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Smart Detection and Scientific Disinfestation Technologies for Food Grain Protection

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Abstract

Smart detection and scientific disinfestation technologies play a crucial role in ensuring the safety and quality of food grains, protecting them from pests, pathogens, and contaminants. These technologies leverage advancements in science and technology to enhance the efficiency, accuracy, and sustainability of food grain protection, benefiting farmers, consumers, and the environment. One of the key challenges in food grain protection is the early detection of pests and pathogens. Smart detection technologies utilize sensors, like optical, acoustic and thermal, to detect signs of infestation or contamination in food grains. By detecting these issues early, farmers can take timely action to prevent further damage and ensure the quality of their harvest. Smart detection technology like electronic noses to detect odors emitted by pests or pathogens in food grains, acoustically to detect the feeding of insects as internal borers, hyperspectral imaging uses advanced imaging techniques to detect subtle changes in the color and texture of food grains, variation in temperature profiling of the infested and uninfested grains are all getting known slowly. Likewise, scientific disinfestation technologies are used to eliminate pests from food grains without compromising their quality. Technologies like physical methods (heat treatment and irradiation), as well as chemical methods (fumigation) can reduce pest load thus gives quality food. Overall, these technologies are essential for protecting food grains from pests, pathogens, and contaminants. By leveraging these technologies, farmers can ensure the safety and quality of their harvests, reduce the use of chemical pesticides, and protect the environment and human health.

1. Introduction

Grains are fundamental staples worldwide, providing vital nutrients like energy, protein, fiber, and essential vitamins and minerals. Despite modern agricultural advancements, post-harvest losses remain a significant issue, with around 30% of cereals lost annually, as reported by the Food and Agriculture Organization (FAO), totaling about 1.3 billion tonnes (FAO, 2011).

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Tackling these losses is crucial to ensuring grain availability, particularly for vulnerable communities, in line with the objectives of organizations such as FAO, the World Food Programme, and the International Fund for Agricultural Development, aiming for 'Zero Hunger' (Ishangulyyev et al., 2019). Additionally, reducing these losses would ease strain on land and water resources, benefiting the environment. Thus, improvements in pre- and post-harvest technologies, particularly in storage methods, are essential.

Traditionally, harvested grains are dried and stored using various structures, from traditional containers to modern silos or warehouses. While traditional methods are cost-effective, they are susceptible to damage from pests and insects (Manandhar et al., 2018). Developing countries are shifting towards bulk storage (warehouse/ silo), offering greater capacity and improved environmental protection, despite facing challenges like pest control. Government regulations, like those outlined by the Food Safety and Standards Authority of India (FSSAI), provide guidelines for warehouse management, including pest control measures like fumigation with phosphine gas or methyl bromide, albeit with precautions due to toxicity risks (FSSAI, 2017). Factors such as ambient moisture, temperature changes, and storage duration significantly impact grain quality during storage. Advanced storage structures like metal silos, equipped with grain aeration augers and ventilators, prolong the shelf life of grains by facilitating controlled respiration and creating unfavorable conditions for pests and insects. Poor storage conditions can lead to mold growth, grain germination, and pest infestations, resulting in compromised grain quality and acceptability (Sirohi and Pandey, 2019; Sirohi et al., 2021).

Elevated temperature and moisture levels accelerate the decline in germination rates, alter grain properties such as color and oil composition, and promote mold proliferation. Fungal contamination by molds such as *Aspergillus flavus*, *Fusarium*, and *Penicillium*, can produce mycotoxins like aflatoxins, ochratoxin A, and patulin. These mycotoxins pose significant health risks, with aflatoxins B1, B2, G1, G2, and M1 being particularly potent carcinogens (Bullerman and Bianchini, 2007; Eskola et al., 2020). Thermal processing for mycotoxin removal is challenging due to the high temperatures required, which can harm grains, rendering them unfit for consumption. Therefore, finding effective methods to eliminate mycotoxins from the food chain remains a significant challenge for food processors.

The global trade of grains, particularly for pesticide-free products, has shown consistent growth, prompting stringent regulations in many countries to control pesticides and contaminants like mycotoxins. As a result, robust post-harvest insect control methods and emerging technologies for grain disinfection and detoxification have been developed. Chemical fumigants have been a go-to solution for disinfection since ancient times due to their effectiveness and cost-effectiveness. However, fumigants such as aluminium phosphide and methyl bromide have limitations owing to their toxicity towards humans and the environment, necessitating high concentrations to eradicate insects across all life stages. Consequently, many fumigants have faced bans or restrictions globally due to health and environmental hazards (Mazima et al., 2018).

In response to these challenges, the scientific community has shifted its focus to advanced tools capable of efficiently and safely eradicating insects at every stage of their life cycle. The evident significance of post-harvest management has prompted the emergence of alternative technologies for disinfecting food grains. These include a range of thermal and non-thermal methods, such as microwave, radio frequency, infrared, ohmic heating, cold plasma, high pressure, irradiation, drying, and pulse light, among others (Du et al., 2020; Sirohi et al., 2021). The pressing nature of the afore-mentioned challenges and the essential role of post-harvest management have spurred the development of these alternative technologies. As a result, the objective of this chapter is to present a comprehensive overview of insect detection techniques, grain disinfection methods and successful technologies currently available in the market.

2. **Insect detection in grains**

Insect detection, crucial across agricultural crops, stored grains, and food processing facilities, serves multiple vital purposes. Primarily, it aids in monitoring and assessing pest infestations, allowing timely intervention to prevent further crop or product damage. Early detection enables effective pest management strategies, reducing reliance on harmful chemical pesticides and minimizing economic losses for farmers and food producers. Moreover, ensuring food safety and quality is paramount; insect detection prevents contamination of food products with insects or their by-products. Such contamination can lead to spoilage, mold growth, and disease transmission, emphasizing the pivotal role of insect detection in preserving food supplies and safeguarding public health. Therefore, detecting insects at an early stage is imperative. Various conventional and innovative methods have been employed for insect detection in stored food grains, which are elaborated on in subsequent subheadings.

2.1 Conventional Methods

Grain storage facilities commonly employ conventional methods such as visual inspection, probe sampling, and insect trap methods. While these techniques are straightforward, they are also time-consuming, labor-intensive, and subjective in nature. Below, we provide a brief overview of some popular techniques:

2.1.1 Detection of insect presence

***Visual inspection**:* Visual inspection is a consistent, qualitative approach commonly employed as a benchmark for comparing quantitative methods. This technique involves visually examining the grains for the presence of eggs, adult insects, and infested grains without the need for drawing grain samples or investigating residual infestation within storage bags. The specific notations for sack usage, storage conditions, and sampling inspection, aiding in the standardization of visual inspection practices are also available (Table 1) (Banga et al., 2018).

Table 1: Insect inspection characteristics in storage structures as per Food Corporation of India

Character	**Specification**	**Number of Insects (in general)**	**As per FCI, GoI**
C	Clear or none	No insects discovered in the course of a prolonged search.	Clear - Lot completely free from any living infestation.
F	Few or light	Small numbers of insects occurring infrequently or irregularly.	Few - Lot having 02 living insects per 500 gm of representative sample.
MN	Moderate numbers	Insects obvious, encountered regularly, sometimes forming small populations or aggregations.	Heavy - Lot having more than 02 living insects per 500 gm of representative sample.
LN	Large numbers	Insects immediately obvious where large numbers are actively crawling over the entire surface of the commodity, i.e., stack or bulk.	
VLN	Very large numbers	Insects are extremely active and numerous that they are audibly present within the confines of the bulk or stack. Live insects or exuviae (cast skins) forming a continuous carpet around the perimeter of the stack or bulk.	

Probe sampling and trap method: Probe sampling and trapping methods are extensively utilized for insect detection in stored grains, despite being labor-intensive and time-consuming. This technique involves extracting grain samples (0.5–1 kg) using probes and then using sieves to separate insects from the grains. TNAU, Coimbatore (India), has pioneered various trap devices for insect monitoring in stored grains. These traps capitalize on insects' natural tendency to gravitate towards airflow, they are probe trap, pitfall trap, two-in one trap for pulse beetles, and others (Mohan et al., 1994). Additionally, the TNAU automatic insect removal bin efficiently eliminates insects and destroys eggs within 10 days, with minimal grain damage observed over a 10-month storage period in paddy and sorghum grains compared to conventional bins.

Visual lures: Visual lures, such as different types of lights (incandescent, fluorescent, and ultraviolet) operating within the wavelength range of 280 to 600 nm, serve as effective tools for detecting and monitoring insects in storage facilities. Insects are attracted to these lights and certain colored objects due to their distinct reflectance properties. By leveraging insects' natural responses to light, visual lures aid in the early detection and management of insect infestations in warehouses, godowns, elevators, and similar facilities (Neethirajan et al., 2007).

Pheromones: Pheromones are chemical substances secreted by insects for communication purposes and play a crucial role in trapping and controlling insect populations. These traps, constructed from various materials, incorporate pheromones, including both sex and aggregation types. They are designed with adhesive-coated surfaces or funnel-shaped structures to effectively capture targeted insects. By utilizing pheromones, insect management efforts can specifically target certain species, aiding in the protection of stored food grains from infestation and damage (Laopongsit and Srzednicki, 2010).

2.1.2 Detection of insect density

Berlese funnel method: The Berlese funnel method employs a standard apparatus comprising a mesh screen. Grain samples are placed in the funnel beneath an incandescent light for a duration of 8 hours, while a container filled with alcohol or water is positioned to capture the insects. Equipped with a screen bottom, the funnels retain the grains while allowing insects to pass through. Dry heat is utilized to dislodge insects from the grains, as it warms them, prompting the insects to move away from the heat source within the funnel (Banga et al., 2018).

Uric acid method: The Uric Acid method, relying on uric acid, the primary component of insect excreta, has emerged as a recommended tracer for detecting insect infestation in stored food grains. This approach provides an indirect means of assessing insect infestation throughout the storage duration. Subsequently, diverse methodologies have been devised to measure uric acid levels, including paper chromatography, fluorometry, colorimetry, gas-liquid chromatography (GLC), thin-layer chromatography (TLC), high-performance liquid chromatography (HPLC), and enzymatic techniques (Rajendran, 2005; Banga et al., 2018). According to the Bureau of Indian Standards (BIS) guidelines from 1970, the colorimetric method is deemed suitable for quantifying uric acid levels, enabling the determination of infestation levels accurately.

Hidden infestation detector: The hidden infestation detector is a straightforward and cost-effective device designed for identifying concealed infestations within grains. Comprising three circular plates stacked atop each other, the apparatus facilitates easy operation. The top and middle plates are hinged to enable convenient lifting, while the base plate is layered with ninhydrin-treated filter paper. To assess its efficacy, sorghum infested with *Sitophilus oryzae*, wheat hosting the angoumois grain moth (*Sitotroga cerealella*), and green gram harboring the cowpea weevil (*Callosobruchus maculatus*) were subjected to testing using this detector. Grain samples with approximately 20% moisture content were placed in the holes of the middle plate, which was then pressed down to crush the grains. The infested grains stained the filter paper, allowing for their identification and subsequent counting. By comparing the results with established methods, the percentage of infestation could be estimated (Dakshinmurthy and Ali, 1984; Kaushik and Singhai, 2018).

2.2 Modern Methods

Modern approaches to detecting infestations in stored food grains offer a convenient and swift solution that can identify both internal and external infestations, even at low densities, with minimal material destruction. This enables prompt action to be taken at the earliest possible stage. These methods utilize various technologies including sensors, cameras, microscopes, radiation sources, volatiles, and sound for insect detection. Compared to conventional methods, these modern techniques require less labor, although skilled labor is essential to operate the sophisticated equipment according to protocols. These technologies can be categorized based on the properties employed for insect detection, such as electrical conductivity, olfactory cues, response to electromagnetic spectrum, and acoustic signals. The details of endeavors made under these different categories are provided in the following sections. Table 2 outlines various studies employing this method for insect detection.

2.2.1 Conductance based method

Electrically conductive roller mill: The electrically conductive roller mill method utilizes the principles of electrical conductance and compression force to identify infestations in stored food grains. This technique employs a single kernel characterization system comprising two resistors and a voltage-divider circuit, where one kernel acts as a resistor. As kernels undergo compression between the rolls, their conductance is measured through voltage. The presence of insects within the kernel results in increased kernel moisture content, enabling the discrimination between sound and infested kernels. However, it's important to note that this method is not suitable for detecting insect eggs, immature larvae, or deceased insects in grains with low moisture content (Pearson and Brabec, 2007).

2.2.2 Olfactory based method

Solid Phase Micro-Extraction (SPME): Solid Phase Micro-Extraction (SPME)

Table 2: Studies utilizing conductance- and olfactory- based method for insect detection

Study	**Description**
Electrically conductive roller mill	
Pearson et al., (2003)	Developed an electrically conductive roller mill called "insect-o-graph" for wheat classification. Detected infested kernels based on system signal characteristics and conductance signal.
Pearson and Brabec, (2007)	Reported detection of infested kernels above 70%, along with larvae and pupae of R. dominica, testing 1 kg of wheat in about 2 min. Tested rice weevil (*S. oryzae* L.) and lesser grain borer (*R. dominica* F.).
Brabec et al., (2010)	Investigated detection of lesser grain borer (LGB) fragments in wheat flour using a conductive roller mill. Found it suitable for testing internally infested insects in low-density grains.
Brabec et al., (2012)	Used modified laboratory mill to detect internal infestation of immature LGB in brown rice and wheat. Detected large, medium, and small LGB larvae in samples within 150 s. Higher detection rate in wheat than brown rice.
Brabec et al., (2017)	Detected maize weevil (*Sitophilus zeamais*) infestation with different development stages in popcorn kernels through a conductive roller mill. Slower feeding mill detected higher percentages of larvae and pupae compared to the faster mill.
Solid phase micro-extraction (SPME)	
Abuelnnor et al., (2010)	Identified distinct volatile compounds from infested wheat flour and wheat grain with T. confusum and S. granarius, respectively, by SPME clenched with gas chromatography-mass spectrometry. Larval and adult insects secreted distinct volatiles useful for early monitoring of infestation.
Senthilkumar et al., (2012)	Detected *T. castaneum* and *C. ferrugineus* by headspace analysis (HS-SPME) coupled with GCMS.
Niu et al., (2016)	Used SPME coupled with GC-FID and GC-MS to establish relationships between storage period and grain quality, and grain quality and insect infestation of *R. dominica* in wheat.
Electronic nose	
Evans et al., (2000)	Used e-nose to discriminate between infested and non-infested samples of different fungal species by detecting secondary volatile metabolites.

Zhang and Wang, (2007)	Utilized e-nose to assess the detection of storage age and insect (*R. dominica* F.) damage incurred in wheat.
Wu et al., (2013)	Employed e-noses to discriminate and detect insect infestation, differentiate between insect species, and predict insect population with some successes.

has emerged as a promising technique for detecting odors associated with insect infestation and evaluating grain quality, gaining increasing popularity in recent years. This method not only facilitates early infestation detection but also assists in determining storage age and distinguishing between different varieties of food grains. SPME employs headspace techniques to isolate volatile compounds vaporized from samples. These compounds are subsequently condensed and analyzed using gas chromatography-mass spectrometry (GC-MS) to quantify the volatiles present. The efficiency and sensitivity of the SPME method depend on extraction time and temperature parameters. Higher temperatures and longer extraction times favor the collection of a greater number of analytes (Laopongsit et al., 2014).

Electronic nose (E-nose): E-nose operates on the principle of electronic aroma detection (EAD), revolutionizing aroma detection with its diverse sensor types and instruments. Consisting of three key components—an odour sensor set, a data pre-processor, and a data interpretation system—the E-nose detects volatile compounds emitted from stored food grains headspace. These sensors detect volatile compounds by modifying their electrical properties and are equipped with a pre-defined database for distinguishing specific volatiles (Wu et al., 2013). E-nose technology holds significant promise for swiftly and automatically identifying insects in stored grains. However, careful attention is necessary in selecting sensor arrays tailored to detect specific volatile organic compounds (VOCs) to achieve desired outcomes. The selection of sensors aims to optimize overall instrument performance and offer diverse selectivity profiles for specific applications (Phaisangittisagul et al., 2010).

2.2.3 Electromagneticspectrum based methods

Machine vision: Machine vision, also known as computer vision, is a cutting-edge technology that combines mechanics, optics, electromagnetic sensing, and digital image processing (Patel et al., 2012). Its functioning revolves around identifying and categorizing objects through information extracted from images captured by cameras. The machine vision process encompasses three key stages: image acquisition, image processing or analysis, and recognition and interpretation. Image acquisition entails capturing real-world images using cameras, scanners, or videos and converting them into digital data. Pre-processing steps refine image quality by reducing noise and emphasizing significant features. Feature extraction involves recognizing image attributes across various complexities, while image segmentation divides images into relevant regions based on object characteristics, crucial for subsequent accurate data extraction. Image recognition and interpretation provide valuable insights for process or machine control (Narendra and

Hareesh, 2010). Machine vision excels in monitoring and assessing grain varieties, detecting foreign materials, mold, and insect infestation in bulk grains, particularly live insects in stored food grains (Aviara et al., 2022).

X-ray imaging: It is an innovative method employing non-contact sensors to examine large samples while yielding significant insights (Yacob et al., 2005). Soft X-ray imaging, known for its swiftness and non-destructive nature, is utilized to detect minute insects in stored food grains, grade agricultural produce, and evaluate the internal quality of commodities such as mangoes, even uncovering hidden insect infestations. The imaging system consists of an X-ray source, X-ray converter, imaging apparatus, and a shielded casing for image capture. Images are captured by the imaging medium, shielded from external radiation by the casing. Soft X-rays, with wavelengths ranging from 0.1 to 10 nm and energy levels between 0.12 and 12 KeV, are employed for internal inspection, generating X-ray images swiftly within 3 to 5 seconds (Kotwaliwale et al., 2014). Various studies employing this technique for insect detection are summarized in Table 3.

Thermal imaging**:** Thermal imaging, a technology often associated with night vision, enhances object visibility in low-light environments by detecting the infrared radiation emitted by objects and translating it into a visible

Table 3: Studies utilizing electromagnetic spectrum-based method for insect detection

Study	**Description**
X-ray imaging	
Kotwaliwale et al., (2007)	Assessed quality of Pecan (*Carya illinoinensis*) using soft X-ray ranging from 15 to 50 kVp and five current levels (0.1–1.0 mA) across two orientations. Identified insect damage and underdeveloped nutmeat. X-ray images revealed shell, nutmeat, air gap, defects, and insect presence.
Karunakaran et al., (2003)	Utilized soft X-ray to detect *Cryptolestes ferrugineus*, *T. castaneum*, Indian meal moth (*Plodia interpunctella*), *S. oryzae*, and *R. dominica* in wheat kernels. A parametric classifier accurately identified infested kernels by various stages of *S. oryzae* and larvae of *R. dominica* with over 98% accuracy.
Chelladurai et al., (2014a)	Employed soft X-ray and near-infrared (NIR) hyperspectral imaging to capture images of soybeans infested by *C. maculatus* alongside uninfested kernels. Extracted features for analysis and classified various infestation stages using LDA, QDA, and PCA models. The integration of X-ray and hyperspectral features enhanced classification accuracy, particularly for egg and larvae stages.

Thermal imaging	
Manickavasagan et al., (2008)	Infrared thermal imaging detected *Cryptolestes ferrugineus* infestation in wheat kernels, identifying insect developmental stages. Respiration rate correlated strongly with temperature distribution on infested kernel surfaces. Classification accuracy for infested and sound kernels ranged from 77.7% to 83.5% for quadratic functions and from 77.6% to 83.0% for linear functions.
Chelladurai et al., (2012)	Employed thermal imaging to assess moong beans infested by *Callosobruchus maculatus*. LDA model achieved classification accuracy of 55.24% to 77.84%, while QDA model achieved 75.45% to 91%. QDA model identified over 80% of moong beans as infested by initial stages of *C. maculatus*.
Khairunniza-Bejo and Jamil, (2013)	Captured thermal images of fungal-infected paddy over time using a mid-infrared thermal camera. Utilized average pixel values as features to assess moisture content, noting higher values in fungal-infected paddy than in non-fungal samples.
Electronic grain probe insect counter (EGPIC)	
Flinn et al., (2009)	Evaluated a commercial electronic grain probe trap in two wheat bins (32.6 tonnes) over 2 years. Developed a regression model, comparing it with insect density estimated by EGPIC. Found 40–75% variation in predicted insect density versus EGPIC. Integrated "Stored Grain Advisor Pro" expert system with EGPIC to estimate *C. ferrugineus*, *R. dominica*, and *T. castaneum* density from trap catch counts. Although efficient, it struggled to differentiate *R. dominica* and *T. castaneum* due to similar size.
NIR spectroscopy	
Ridgway and Chambers, (1996)	NIR reflectance spectroscopy was employed to detect internal infestation by *Sitophilus granarius* in wheat.
Maghirang et al., (2003)	Using an automated NIRS system (400–1700 nm), live pupae and larvae of *Sitophilus oryzae* were detected with an accuracy ranging from 92% to 93%.
Perez-Mendoza et al., (2003)	In a comparison with the standard floatation method for detecting wheat flour, NIRS proved to be a rapid method, taking less than 1 minute per sample. It detected in bulk samples without requiring any preparation.

Chelladurai et al., (2014b)	Employed soft X-ray imaging and NIR hyperspectral imaging to detect *Callosobruchus maculatus* and classify infested versus sound soybean kernels.
Chu et al., (2014)	Utilized Fourier Transformation Near-Infrared (FT-NIR) technology to detect moldy maize kernels, achieving 86.7% validation accuracy with characteristic wavelengths at 1466 nm, 1530 nm, 1926 nm, 2321 nm, and 2384 nm.

image. The amount of infrared energy an object emits, known as its heat signature, directly correlates with its temperature, resulting in what is termed a thermogram. This imaging system typically consists of detectors, lenses, thermal imaging cameras, and tools for data collection. It proves highly useful in managing stored food grains, enabling the identification of damaged grains, foreign materials, and both internal and external grain infestations (Nanje Gowda and Alagusundaram, 2013). Particularly effective in scenarios where temperature variations are utilized for process assessment or quantification, thermal imaging offers distinct advantages over other methods like fluorescence and hyperspectral imaging, including cost-effectiveness and the ability to determine material properties. Various studies employing thermal imaging for insect detection are summarized in Table 3.

***Electronic grain probe insect counter (EGPIC)*:** The Electronic Grain Probe Insect Counter (EGPIC) is an automated passive grain probe engineered for remote monitoring and detection of insect pests in stored food grains, offering real-time infestation data display. Its components include a probe, system circuitry, data logger, and user interface. To minimize the risk of grain dust explosions, electrical components and circuitry are positioned outside the storage structure, with only low-voltage, high-impedance sensor leads passing through the grains from the beam generation/detection circuitry to the sensor head. Sensors within the EGPIC transmit gathered data to a computer for signal analysis, generating time-stamped detection records (Shuman and Epsky, 2001). When an insect disrupts the infrared beam across the sensor head, an infrared diode generates a signal received by the infrared phototransistor, causing a slight decrease in light intensity reaching the phototransistor. The electronic circuitry identifies this reduction and converts it into a time-stamped insect count before the insects exit the probe. EGPIC offers continuous monitoring of insect levels at any depth within the grain (Banga et al., 2018). Various studies utilizing this method for insect detection are summarized in Table 3.

***NIR spectroscopy*:** Near-infrared spectroscopy (NIRS), quantifies the concentration of biological materials like water, protein, and starch by analyzing the reflectance, interactance, or transmittance of dispersed light within the range of 780–2500 nm (Elizabeth et al., 2002). Renowned for its non-destructive, swift, precise, and cost-efficient nature, this method proves adept at detecting both internal and external characteristics in fruits, vegetables, cereals, and pulses. In reflectance mode, the light reflected or dispersed from the object's surface is measured (Xing and Guyer, 2008). Interactance mode comes into play when assessing transmittance proves challenging, but accessing internal information remains crucial. Various studies, as summarized in Table 3, demonstrate the utility of NIR spectroscopy in insect detection, highlighting its efficacy in this domain.

2.2.4 Acoustic detection

Acoustic technology relies on detecting sounds generated by insect movement and feeding to estimate the type and density of insects within stored grain. This method has proven effective in early-stage detection of both internal and external insects, primarily through their feeding sounds. Acoustic sensors capture mechanical or acoustic waves, which, as they pass through a material or object, undergo changes in velocity or amplitude due to material properties and obstacles (Eliopoulos et al., 2015). Transducers then convert these changes into digital or analog signals, often utilizing piezoelectric substrates. Detecting hidden insects within grain kernels involves amplifying and filtering their movement and feeding sounds. However, challenges such as classifying targeted sounds from other sources, sensor sensitivity, signal-to-noise ratio, and sensor range can limit the applicability of acoustic devices. Technological advancements, including improved sensors and digital signal processing software, have bolstered the sensitivity and reliability of acoustic detection. Spectral and temporal pattern features are crucial in distinguishing background noise from targeted noise. Standard speech recognition tools like Gaussian mixture models and hidden Markov models aid in separating insect sounds from background noise, thus refining detection accuracy (Mankin et al., 2009). Various studies employing this method for insect detection are summarized in Table 4.

2.3 Insect Detection Methods: Advantages and Limitations

Efficiently managing stored grains requires dependable insect detection methods to mitigate the risks of infestation. Table 5 offers a comprehensive overview of the various techniques mentioned above for insect detection, detailing their individual advantages and limitations. Grasping the capabilities and constraints of these methods is essential for devising suitable strategies to uphold grain quality and reduce economic losses.

Novel smart detection devices

A novel SmartProbe technology for early insect pest detection and environmental monitoring (Figure 1) (patent pending, UC Davis) has been developed. The SmartProbe operates by remotely monitoring insect activities and environmental conditions, including temperature and relative humidity, within storage and processing facilities. The smart probe attracts insects, captures their images, and periodically sends them to a server for processing and analysis using sophisticated algorithms (Pan and Khir, 2023).

EFOS, a leading provider of commercial solutions, has developed an

Table 4: An overview of various studies employing acoustic technology for insect detection.

Study	Description
Hagstrum et al., (1996)	Acoustically detected *R. dominica*, *T. castaneum*, and *S. oryzae* in stored wheat grains, reaching over 90% detection accuracy, particularly at the bin's base. This method offers a fast and convenient means for insect detection and population estimation
Pittendrigh et al., (1997)	Internal feeding and movement sounds of *Sitophilus zeamais*, rice weevil (*S. oryzae*), and granary weevil (S. granarius) were acoustically detected at low intensity (15–35 dB) and frequencies of 2–6 kHz.
Fleurat-Lessard et al., (2006)	Developed an automatic system for inspecting insects in bulk wheat grains. Achieved over 95% likelihood of detecting primary pests like S. oryzae within 2 minutes, covering a 20 cm range in a 65 kg sample. Detected *R. dominica* and modeled insect activity-density relationship across temperature ranges.
Mankin and Moore, (2010)	Researched revealed that insect sounds consist of short broadband impulses (1–10 ms) grouped in trains, while background noise manifests as continuous signals with symphonic peaks.
Leblanc et al., (2011)	Developed a real-time acoustic insect detection probe for identifying sounds from diverse insect species and stages in long-term storage. Achieved over 90% confidence in predicting live concealed insects in a 30 kg grain mass.
Njoroge et al., (2016)	Studied acoustic signals in stored maize to differentiate *Prostephanus truncatus* and *S. zeamais*, categorizing frequency profiles and observing impulse bursts for species and stage comparison.

innovative model leveraging cloud computing image processing technology (Figure 2). The model, which incorporates a bucket/funnel type of trap, is uniquely tailored to address the challenges posed by larger moth species that are present in high numbers. Notably, it has demonstrated exceptional efficacy in remotely identifying key agricultural pests such *as Helicoverpa armigera, Autographa gamma*, and various species of *Spodoptera*. This advanced solution represents a significant advancement in pest management strategies, offering farmers and agricultural practitioners a reliable tool to monitor and mitigate the impact of these destructive insects on crop yields (Lima et al., 2020).

3. **Grain disinfestation**

Effective post-harvest management involves a diverse array of

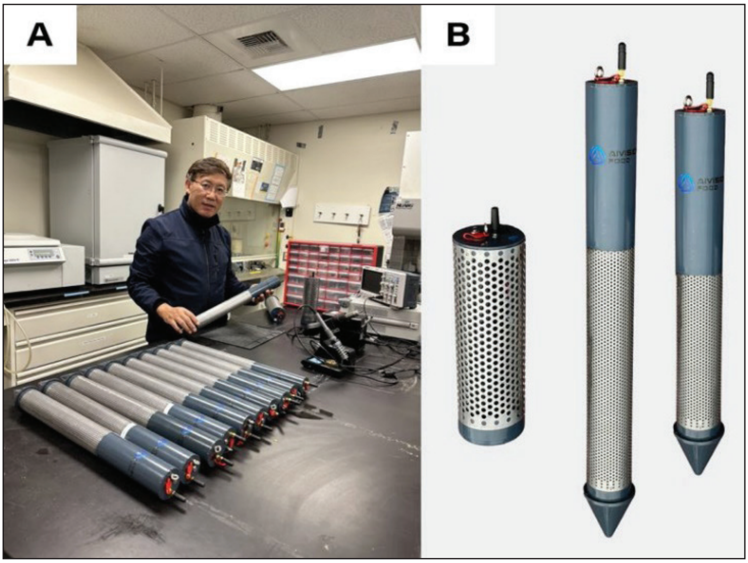

Figure 1: SmartProbe device used in bins/boxes, silos/stockpiles and hanging in processing and storage facilities

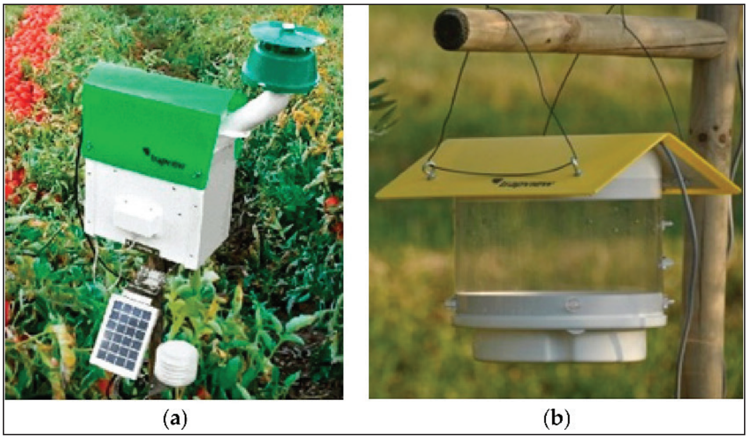

Figure 2: Automatic trap for monitoring and moth species (a) and fruit flies (b), *EFOS, Trapview, Slovenia*

methods to preserve grain quality and minimize losses. Table 6 presents a comprehensive overview of various physical, chemical, and biological techniques employed in grain processing and storage. These methods, detailed with their respective processes, storage conditions, modes of action, and referenced studies, underscore the multifaceted approach to post-harvest grain management.

3.1 Conventional Methods

Conventional methods of grain disinfestation involve various

Table 5: Advantages and limitation of various insect detection methods

Insect Detection Methods	Advantages	Limitations
Conventional methods		
Grain probes and insect probe traps	• Widely used and inexpensive • Effective for finding insect density.	• Labor-intensive • Limits temporal availability of data • Unable to detect internal insects • Placement restrictions for traps
Pheromones	• Provides an indication of pest density • Species specific	• Trap catches influenced by environmental factors • Short term
Visual lures	• Can be effective indoors.	• exposure hazards
Berlese funnel method	• Cheap and commonly used.	• Slow • Unable to identify internal infestations
Modern methods		
Electrically conductive roller mill	• Suitable for detection of hidden infestation • Inexpensive	• Time-consuming as it inspects a single grain • Not suitable for large capacity • Unable to detect egg, larvae stages and dead insects • Not suitable for low moisture content sample
Solid phase micro extraction	• Dynamic headspace increases sensitivity • High sensitivity	• Costly • Detects only adult insects and not suitable for immature insects • Requires a skilled person
E- Nose	• Automatic • Non-destructive • Suitable for hidden infestation and mold • Rapid	• Expensive • Necessity of long-term training of device • Use of complicated data fusion techniques • Expensive sensors affected by environmental factors and need replacement after some time

Insect Detection Methods	**Advantages**	**Limitations**
Machine Vision within visible range	• Suitable for identification and classification of varieties, insect infestation, grain discoloration • Used for grading of agricultural produce	• Expensive • Inadequate to detect dead and internal insects • Unable to classify species of insects
X-ray imaging	• Direct method • Non-destructive • High accuracy • Adequate to detect internal and external insects	• Inadequate to detect insect egg • High cost • Requires skilled workers • Need safety measures to operate
Thermal Imaging	• Suitable to detect all stages of insects • Identify infested and uninfested grains	• Time-consuming • Unable to categorize mixed variety of grains • Expensive camera • Cannot identify development stages of insects
Electronic Grain Probe Insect Counter	• Automatic • Real-time monitoring • Suitable for bulk storage at any depth	• Sophisticated system requires a skilled person to operate • Expensive • Unable to detect dead insects
NIR Spectroscopy	• Rapid method • Detect hidden insect infestation	• High cost and required trained person • Inadequate to detect low levels of infestation • Requires calibration and care of equipment
Acoustic based method	• Non-destructive • Automatic • Detect internal and external insects • High sensitivity • Suitable for reliable decision-making in silos • Estimate density of insects	• Cannot detect eggs and dead insects • Requires sound and vibration-insulated structure • Detects within a suitable range • Sophisticated equipment

Table 6: Various methods for grain disinfestation

Method	Sub-method	Mechanism of Action
Physical	Microwave heating	Electromagnetic energy (915MHz-2450MHz) converted into thermal energy, typically with 3–7% moisture content.
	UV heating	UV light (100–400nm wavelength) acts as a germicide.
	Infrared heating	Energy transfer through electromagnetic radiation (780nm–1mm wavelength).
	Sunlight	Exposure with varying time; maintains moisture content before safe storage.
	Irradiation	Exposure to ionizing radiation (0.02–10kGy) emitted by a radioactive source.
Chemical	Fumigation	Exposure to a lethal concentration of highly toxic gas to insects (e.g., aluminum phosphide).
	Insecticides	Application of insecticides on grain surfaces (e.g., malathion).
	Vaporizers	Vaporized form of chemicals to eliminate pests from grains (e.g., methyl bromide, hydrogen cyanide).
	Ozone	Oxygen and electric discharge for ozone generation
Biological	Fungi, molds, and bacterial control	Environmental parameters regulation (moisture, relative humidity, etc.). Predators, parasitoids and pathogens

techniques aimed at eliminating or controlling insect infestations in stored grains. Some of these methods include:

Fumigation: This method involves the use of chemical fumigants such as phosphine to kill insects within stored grain. Fumigation requires sealing the grain storage area and introducing the fumigant in gaseous form to penetrate the grain mass and kill insects at all life stages. In India, aluminium tablets are used for the purpose.

***Heat treatment*:** Heat Treatment, a pivotal technique in insect management, involves subjecting grains to elevated temperatures for a specified duration, aiming to eradicate insect infestations. This method employs various heat sources such as hot air, steam, or microwave treatment. Renowned for its efficacy, heat treatment not only controls insect populations but also safeguards grain quality. Notably, the Rice Weevil (*Sitophilus oryzae*), Red Flour Beetle (*Tribolium castaneum*), and Granary Weevil (*Sitophilus granarius*) exhibit susceptibility to temperatures ranging from 50°C to 60°C (122°F to

140°F) for durations spanning 5 to 30 minutes. Similarly, the Indian Meal Moth (*Plodia interpunctella*) can be effectively managed within temperatures of 50°C to 55°C (122°F to 131°F) over a period of 20 to 30 minutes. Moreover, the Lesser Grain Borer (*Rhyzopertha dominica*) demonstrates vulnerability to temperatures between 50°C to 60°C (122°F to 140°F) for durations of 5 to 30 minutes.

***Cold treatment*:** Employing cold treatment involves subjecting grains to prolonged exposure to low temperatures to manage insect infestations. The chilling effect of cold temperatures disrupts insect activity and reproduction, ultimately leading to mortality. In the realm of pest management research, diverse temperature-based approaches have emerged as effective strategies for combatting insect pests in stored grains. Rice Weevil (*Sitophilus oryzae*), Granary Weevil (*Sitophilus granarius*), and Lesser Grain Borer (*Rhyzopertha dominica*) can be suppressed by exposing grains to temperatures as low as -5°C (23°F) for a duration up to three weeks. Similarly, *Tribolium castaneum* succumbs to temperatures plummeting to -10°C (14°F) over a period of four days, particularly impacting both larvae and adults. Additionally, the vulnerability of the Indian Meal Moth (*Plodia interpunctella*) becomes apparent at temperatures hovering around 0°C (32°F) for a four-day duration, leading to the eradication of eggs and larvae.

***Mechanical methods*:** Within pest management strategies, mechanical approaches such as sieving, winnowing, and air aspiration stand out as effective means to physically extract insects and their eggs from grains. Despite being labor-intensive, these methods yield notable efficacy, particularly when integrated with other control measures. *Sitophilus oryzae*, *Tribolium castaneum, Rhyzopertha dominica* and *Sitophilus granarius* can be efficiently managed through sieving, which proves highly adept at removing adult weevils and beetles. Similarly, *Plodia interpunctella* exhibits positive responses to trapping methods, effectively entrapping adult moths.

***Biological control*:** Biological control, a sustainable approach in pest management, harnesses the power of natural enemies such as predators, parasites, or pathogens to mitigate insect populations in stored grains. While environmentally friendly, this method necessitates careful selection and introduction of biological control agents. For instance, the Indian Meal Moth (*Plodia interpunctella*) population can be controlled by deploying *Trichogramma wasps*, effectively curbing moth populations. Furthermore, the utilization of predatory beetles has demonstrated efficacy in reducing beetle populations, particularly evident in managing the Lesser Grain Borer (*Rhyzopertha dominica*).

Hygiene and sanitation: Maintaining hygiene is essential for effective pest management in stored grain facilities. Regular cleaning of storage facilities, proper grain handling, and the prompt removal of spilled or infested grains are key components of good sanitation and hygiene practices, crucial for preventing and reducing insect infestations. By implementing preventive measures, stored grain pests can be effectively managed. For instance, regular cleaning of storage facilities disrupts the available food sources for *Sitophilus oryzae*, hindering their proliferation. Proper sealing of grain containers prevents the entry and exit of *Tribolium castaneum*, thereby curbing infestations. Controlling moisture levels in storage areas deters *Sitophilus granarius* by diminishing favorable conditions for their survival. Additionally, maintaining cleanliness in storage areas reduces potential breeding sites for *Plodia interpunctella*. Eliminating spilled grains removes food sources for *Rhyzopertha dominica*.

3.2 Modern methods of grain disinfestations

The disinfestation of insects in grains holds significant importance as a unit operation during the storage and handling of grains. Comprehensively examined various non-chemical methods for disinfecting storage insect pests and highlighted heat or thermal treatment as a particularly effective approach for eliminating insect pests and rendering viable eggs inactive (Paul et al., 2020). Various thermal techniques, including Microwave, Radiofrequency, Infrared, Ohmic heating, and drying. Similarly, non-thermal techniques includes cold plasma, electrodynamic drying, ozonation, pulsed light, irradiation, ultrasound and assisted technologies have been employed in the disinfection of food grains (Sirohi et al., 2021). These methods are characterized by their rapidity and lack of residue, making them effective means of controlling pests in stored grain (Qaisrani and Beckett, 2003).

Microwave technology: Utilizing short-wavelength electromagnetic radiation, has been discovered as an effective method (Sharma and Zalpouri, 2022). Nonetheless, employing microwave treatment can also result in detrimental impacts on seed germination and grain quality due to non-uniform heating, stemming from fluctuations in cold and hot spot temperatures (Dalmoro et al., 2018). The mechanism of microwaves, operating on the basis of the dielectric effect, selectively heats regions containing dielectric fluids, such as water, thus forming hot spots. Strategies to counteract the negative impacts of microwaves involve implementing mode stirrers, agitating particles with hot air, and meticulously controlling surface temperature and microwave power (Ye et al., 2017). The moisture content within grains significantly influences microwave disinfestation, with higher moisture levels in the outer grain layer compared to the inner layer resulting in intensified heating, thereby enhancing disinfection efficacy. Heat uniformity could be maintained by employing a microwave fluidized bed for grain agitation, offering advantages over conventional fluidized bed dryers in retaining grain quality.Vasilev et al., (2019) utilized regression modeling to investigate the relationship between microwave power, processing time, temperature variance within moist grains, and moisture content, revealing substantial impacts of moisture content on heating dynamics. Building upon this research, Taheri et al., (2020a) delved into the microwave treatment of lentil seeds, exploring various power levels and air temperatures while monitoring changes in seed quality markers such as antioxidant enzyme activity, macronutrient composition, and cooking characteristics. Further elucidating the effects of microwave exposure on seed properties, Taheri et al., (2020b) identified specific power levels capable of altering peroxidase activity and germination rates in lentil seeds, proposing the potential superiority of microwave fluidized bed systems for enzymatic inactivation over traditional microwave methods. Extending the application of microwaves in food processing, Hassan et al., (2021) reported findings indicating that microwave heating below 60°C could selectively influence fatty acid composition in corn grains, with increased oleic acid and decreased linoleic acid levels, presenting microwave heating as a viable strategy for enhancing industrial quality control and disinfection protocols.

***Radio frequency*:** Within the electromagnetic spectrum, radio frequency (RF) waves emerge as a formidable force, wielding wavelengths of up to 11 meters and frequencies spanning from 1 to 300 MHz (Hassan et al., 2019). RF technology, illuminating its unparalleled capacity to penetrate dielectric materials and induce volumetric heating through mechanisms such as ionic polarization and dipole rotation. The dielectric potential of grains escalates with an increase in moisture content, attributed to enhanced dipole rotation and ionic mobility. Interestingly, radiofrequency exhibits selectivity towards insects due to their comparatively higher moisture content and electrical conductivity in contrast to food grains, thereby subjecting them to elevated dielectric heating. Jiao et al., (2017) demonstrated that a brief exposure lasting 5 minutes to mild radiofrequency heating effectively controlled immature rice weevils, encompassing eggs and adults, across diverse rice varieties. Yang et al., (2018) outlined that subjecting rice moth to radiofrequency treatment at 57°C led to comprehensive disinfestation without altering the fat, protein, or moisture content of milled rice, while also improving sensory attributes and cooking quality. Ling et al., (2020) underscored the significance of prolonged exposure durations and elevated temperatures in achieving 100% mortality rates for various insects infesting food grains. Their research indicated that the longest lethal time recorded was 29 minutes at 50°C, while the highest lethal temperature observed within a 5-minute timeframe was 54°C.

Infrared: Infrared radiation, positioned between microwaves and the visible spectrum with wavelengths ranging from 0.5 to 100 μm, possesses the ability to penetrate materials. When it interacts with water molecules, it induces vibrational movement, thereby generating heat. Due to its remarkable efficacy in microbial destruction, it has become the preferred method for disinfection within the grain industry compared to traditional chemical approaches. The catalytic infrared emitter has proven effective in combating rice weevils, grain beetles, and saw-toothed grain beetles. Typically, a brief exposure of just 60 seconds is sufficient to manage both externally and internally infested stored grains (Ramaswamy et al., 2012). Exposure to infrared radiation raises the surface temperature of grains even in the absence of conductors. Table 7outlines various applications of infrared radiation in grain disinfection.

***Ohmic heating*:** Ohmic heating, also known as direct electrical resistance heating, electro-heating, or Joule heating, represents a thermal process

Table 7: Various application of infrared in grain disinfestation

Application	Description	References
Thermal Inhibition Mechanism	• Infrared heating damages bacterial cells' components including proteins, ribosomes, cell walls, RNA, and DNA. • Proteins, cell walls, and RNA are more susceptible to infrared heating compared to conductive heating.	(Ha and Kang, 2013; Meenu et al., 2018)
Infrared Treatment for Microbial Reduction	• Selective far-infrared heating reduces microbial contamination in food products such as corn meal and mung beans. • Infrared heating exhibits antibacterial effects against *E. coli* and *B. subtilis*.	(Hamanaka et al., 2006; Meenu et al., 2018)
Infrared Treatment for Grain Sterilization	• Infrared radiation increases the surface temperature of grains, effectively reducing microbial content. • Modified infrared systems, including catalytic infrared emitters, are used for insect control in stored grains.	(Ramaswamy et al., 2012)
Infrared Tempering Treatment	• Infrared tempering treatment, followed by tempering, reduces moisture content and microbial contamination in rice. • Infrared treatment offers advantages for storage and disinfection.	(Wang et al., 2014)

distinct from conventional heating methods, wherein direct electric current passes through various food materials for heating purposes (Lyng et al., 2018). This process achieves homogeneous heating of food materials through volumetric heating, utilizing their inherent electrical resistance to convert electric current into heat energy (Soisungwan et al., 2020). The application of an electric field during ohmic heating induces electroporation of cell membranes in the food material, thereby enhancing heat diffusion, mass transfer, and the extraction rate of specific compounds of interest (Kumari et al., 2016). Additionally, ohmic heating lowers the enthalpy of heat and gelatinization temperature of food (Kaur and Singh, 2016). Recognized as one of the most environmentally friendly food processing methods, ohmic heating is characterized by energy efficiency as it eliminates intermediate steps between the food and electricity source, thereby reducing food and environmental heat losses. It facilitates rapid heating of food while preserving its nutritional value and color (Lyng et al., 2018). Table 8 delineates the various advantages and disadvantages associated with this method.

3.3 Drying

Superheated steam drying: Superheated steam (SS) drying has emerged as an advanced technology aimed at increasing the mortality rate of microorganisms and insects in stored grains. Ultra Superheated Steam Technology (USHD) utilizing high-frequency induction heating, reaching temperatures of 300–500°C. This technology generates ionized gaseous particles, free radicals, hydrogen peroxide, superoxide anion radicals, and singlet oxygen. Application of USHD on maize kernels, chickpeas, red wheat, and peanuts yielded significant positive effects on their disinfestation. Treatment with USHD at temperatures exceeding 500°C for 15 seconds was identified as particularly beneficial for preserving grain quality for up to two years.

***Hybrid drying techniques*:** The infrared drying technique ranks as the second most commonly employed method, often combined with other drying techniques due to its enhanced drying efficiency. One such study investigated the combined effects of gamma radiation, infrared radiation, and microwave radiation on the mortality of *Rhyzopertha dominica* species in wheat (Kirkpatrick et al., 1973). The combination of gamma and infrared radiation resulted in the highest mortality rate, reaching 99%, followed closely by a 96% mortality rate with the combination of gamma and microwave radiation. Another study investigated the effectiveness of combining microwave radiation with vacuum treatment to assess the mortality of insects in stored rye, corn, and wheat (Tilton and Vardell, 1982). At lower doses, there was only a minor reduction in the adult insect population, but as the treatment dosage increased, complete control over the insect population was achieved.

***Electrohydrodynamic drying*:** Electrohydrodynamic (EHD) drying, also known as Electroaerodynamic drying (EAD), represents an innovative, environmentally friendly, and non-thermal method for drying food products, eliminating the necessity for additional heat (Defraeye and Martynenko, 2018). The EHD process operates on the principle of corona wind, wherein a high-voltage electric field applied to an emitter electrode induces a flow of gaseous ions, creating an airflow termed corona wind, which enhances the convective mass transfer rates for moisture removal from food surfaces. This process results in increased mortality of insects due to their vigorous movement and subsequent exposure to corona wind effects. The ionization of air occurs as gaseous ions collide with neutral air molecules, producing corona wind that moves towards a grounded electrode. Studies on the application of EHD drying in food grains are limited, but research indicates promising results for wheat and rapeseed drying, with increased drying rates observed with higher applied voltages. Initially developed for drying sensitive foods, EHD drying is now being explored for mushrooms, fruits, vegetables, and cereal grains due to its potential benefits. However, commercial EHD dryers are not yet available, with only working prototypes currently in existence (Sirohi et al., 2021). Shayesteh and Barthakur, (1996) conducted a study on stored products to assess the mortality rates of various stages of *Tribolium confusum* (TC) and *Plodia interpunctella* (PI) using the EHD system. The treatment involved exposure to both negatively and positively charged ions along with neutral air ions. Remarkably, the negative ions exhibited a significant positive impact on the mortality of TC pupae and PI larvae.

3.5 Non-thermal technologies

Cold plasma**:** Non-thermal or 'cold' plasma, utilized in food decontamination, operates at near-room temperatures, minimizing thermal impact on food items. Cold plasma can be generated under various pressures and energy sources such as radio frequency (RF), microwaves (MW), and pulsed AC or DC electric currents. The properties of the plasma formed can be manipulated by adjusting factors like voltage, pulse shape, gas composition, and pressure levels. The resulting reactive plasma species, including free radicals and UV photons, play a pivotal role in microbial decontamination of food grains. Cold plasma has demonstrated effectiveness against various life stages of red flour beetles (*Tribolium castaneum*), by applying cold plasma at 2500 V with a 3.7 cm electrode gap for 15 minutes can result in 100% mortality of eggs, larvae, and adults of *T. castaneum* (Ramanan et al., 2018).

Irradiation**:** Irradiation encompasses the exposure of food items or food commodities to γ-rays, x-rays, or electron beam ionizing radiations, which are generated either by radioactive sources or machines. The underlying principle in radiation is referred to as radiolysis, wherein electrically charged or neutral ions are produced following the absorption of radiations. Moisture plays a crucial role in food irradiation, as water serves as a medium for free radicals to move and interact with other food components, thereby promoting secondary effects of irradiation. Enu and Enu, (2014) studied the maximum recommended radiation doses are up to 10 KGy, with doses less than 1 KGy recommended for disinfestation of food grains from insects and larvae. UV radiations, including UV-A, UV-B, and UV-C, are also accepted in the food processing industry and water treatment. UV radiation oxidize biological molecules, proteins, nucleic acids, and membrane lipids by damaging DNA and cellular membrane structure (Bravo et al., 2012). The effectiveness of treatment is influenced by radiation intensity and the species involved. Higher intensities often lead to oxidative changes, impacting sensory and nutritional aspects. Gamma radiation and electron beams have also been explored for their efficiency in reducing fungal contamination in food items such as peanuts and grains. Bhuiya et al., (1991) found a radiation dose of 0.5 KGy led to the complete mortality of *Callosobruchus chinesis*, while a dose of 0.2 KGy eradicated 99.5% of the adult stage of *Sitophilus oryzae* and *Sitophilus zeamais* within 21 days.

Ozonation treatment**:** Serving as an oxidizing agent, ozone has found diverse applications in sanitization, deodorization, and food preservation. Ozone exists as a natural gas with the highest oxidation-reduction potential (-2.07 V), surpassing hydrogen peroxide, hypochlorous acid, and chlorine. Consequently, ozone exhibits a high potential to induce oxidative stress, damaging cell membranes and causing DNA rupture, resulting in insect mortality (Kaur et al., 2022a, 2022b). Despite its pungent smell and decreased stability with increasing pH, ozone is recognized as a 'generally recognized as safe' (GRAS) chemical for sanitizing food and agricultural products in various forms, including ozone mist, ozonated water, or ozone gas. Wang et al., (2016) found ozone disinfection is particularly advantageous in grain fumigation as it leaves no toxic residue, unlike chemical fumigants. Studies have demonstrated the efficacy of ozone in reducing insect infestation and improving the color characteristics of wheat flour. Ozone treatment has also been shown to affect the chemical composition and germination capability of grains, with varying effects on milling properties, pasting properties, and color. However, despite its potential, commercial ozone dryers are not yet available, with only working prototypes in existence. To optimize ozone fumigation, factors such as bed thickness, moisture content of grains, and ozone half-life need to be carefully considered. While ozone treatment may affect the quality of grains by oxidizing lipids, starch, and proteins, overall, there has been no significant decrease in quality or nutritional value observed in treated grains.

***Nano formulations and nano sensors*:** Nanotechnology involves the study and application of minuscule entities, typically on the nanometer scale, across various fields of research. In agriculture and food production, nanotechnology offers a wide array of potential applications, ranging from enhanced crop yields to more efficient pest management strategies. Nano formulations of insecticides come in various forms such as nano capsules, nano emulsions, nanoparticles, and nano suspensions (Urkude, 2019). Encapsulation of pesticides represents a groundbreaking advancement in pest management systems, requiring lower dosages compared to conventional methods. In this approach, the core pesticide material, whether solid or liquid, is enveloped in a continuous film of polymeric material, typically composed of polysaccharides or polyesters like chitosan, alginates, starch, or polyethylene glycol. By reducing the size of the pesticide to the nano scale (less than 1 μm) and releasing it under specific conditions of moisture, pH, and temperature, slower release and better penetration of the active ingredient into plant tissues or cuticles are achieved. Examples of nano insecticides include temephos, imidacloprid, cypermethrin, and neem oil (Bhan et al., 2015; Giongo et al., 2016). Controlled delivery systems enable the release of the active ingredient at the target site, be it plants, insects, or pathogens, over an extended period, thereby enhancing pesticide efficiency and reducing the frequency of application. Nanoparticles of silica oxides (SiO2) have proven effective in insect and pest control, while silver nanoparticles exhibit efficacy against various life stages of pests. Nano-suspensions offer advantages over powdered insecticides, such as improved stability, dispersibility, and bioavailability, along with reduced dust drift. They are easier to prepare and more effective against hydrophilic insects. Furthermore, nano sensors are emerging as valuable tools for monitoring the storage environment of grains, detecting changes in moisture levels, air composition, temperature, and other factors influencing grain quality and integrity.

***Pulsed light*:** Short pulses of high-intensity UV light have shown effectiveness in deactivating pathogenic microorganisms in low moisture foods like grains. Pulsed UV-A light, ranging from 315 to 400 nm wavelength, exhibits bactericidal effects by damaging the DNA/RNA strands of bacteria.

Table 8: Modern technology includes thermal and non – thermal methods used for grain disinfestation

S. No.	Technology	Principle	Advantages	Limitations	Applications
Thermal methods					
1	Microwave	Absorption of radio waves by water, fats, and sugars, generating heat	Rapid and efficient, preserves product quality	Constraints with metals, challenges in heat control, water evaporation	Drying, blanching, sterilization, tempering, cooking, baking
2	Radio frequency	Electric field production and movement of charged particles	Accelerated healing and drying, uniform heating, energy efficiency	Expensive equipment and operating costs	Drying, post-baking, thawing, pasteurization, sterilization, cooking
3	Infrared	Direct heating through electromagnetic radiation absorption	Efficient heat transfer, homogeneous heating, reduced energy consumption	Limited penetration power, high heat exposure	Roasting, frying, cooking, dehydration, pathogen inactivation
4	Ohmic Heating	Generation of heat through electric current passage	High conversion efficiency, rapid temperature attainment	Monitoring and control difficulties, installation cost, limited applicability	Peeling, thawing, blanching, evaporation, dehydration

S. No.	Technology	Principle	Advantages	Limitations	Applications
5	Superheated Steam Drying	Conversion of saturated steam to superheated steam under constant pressure	Enhanced product quality, safe operation, minimal environmental impact	Complex systems, longer drying times, feed/discharge difficulties	Drying, roasting, blanching, cell inactivation
Non-thermal methods					
1	Cold Plasma	Generation of highly reactive species through gas-electric field interaction	Chemical reactivity, low operating costs, short treatment times	High investment and complexity, incomplete microorganism eradication	Surface treatment of produce and packaging materials
2	Electrohydrodynamic Drying	Corona discharge generation with electrophoresis and dielectrophoretic forces	Lower production costs, improved rehydration, superior quality	High investment, equipment complexity, texture alteration	Supercritical drying, food dehydration
3	Ozonation	Ozone gas production via electrical voltage for microorganism and pollutant reaction	Rapid microorganism elimination, strong germicidal properties	Expensive, limited water solubility, potential hazards	Sanitization, deodorization, food preservation

S. No.	Technology	Principle	Advantages	Limitations	Applications
4	Pulsed Light	DNA/RNA damage in microorganisms via intense light pulses	Fast microbial eradication, short treatment duration	Uneven exposure, sample discoloration, limited penetration	Food and surface disinfection
5	Ultrasound	Cavitation-induced localized temperature and pressure changes	Efficient energy transfer, reduced thermal gradients	Texture modification, undesired compound formation	Emulsification, sterilization, extraction, freezing
6	Irradiation	Application of ionizing radiation for chemical-free treatment	Reduced chemical usage, sprout control	High cost, volume requirement, ineffective against viruses	Food preservation, sprout control
7	High Hydrostatic Pressure	Application of high pressure for food processing	Minimal nutrient loss, rapid processing	Batch processing, spore resistance, equipment complexity	Food preservation, protein denaturation

Wavelengths of 365 and 395 nm have shown greater effectiveness for wheat flour decontamination than 455 nm.Intense pulsed light treatments have also been effective for reducing pathogens in wheat flour and barley kernels. A patented pulsed light-based technology for controlling insects and mites in food objects utilizes surface coloring chemicals in insects to act as heat sinks for ultraviolet photons, causing selective heating and lethal damage to the insects. Developing continuous pulsed light systems with necessary modifications could enable wider industrial application and acceptance.

***High hydrostatic pressure*:** High hydrostatic pressure (HHP), also known as ultra-high pressure processing, involves applying pressures ranging from 100 to 600 MPa (and possibly up to 900 MPa) through a liquid medium to achieve sterilization. Classified as a non-thermal process, HHP induces a slight adiabatic temperature rise due to pressure increase. This technology shows promise for inactivating anti-nutritional factors while preserving food characteristics.

***Assisted technologies*:** Various thermal and non-thermal techniques have been employed for disinfecting food grains. However, individual methods may not always suffice practically or environmentally. Hence, combining thermal and non-thermal technologies with other processing methods can be effective in both disinfection and preservation of grain quality.

Conclusion

The pursuit of effective methods for detecting insect infestation in stored food grains and ensuring their disinfection is marked by a diversity of approaches, each offering unique advantages and challenges. From traditional visual inspections to cutting-edge acoustic detection techniques, the spectrum of methods reflects a continual search for precision, efficiency, and sustainability in agricultural practices. As we navigate through this array of technologies, it becomes evident that no single method provides a comprehensive solution. Instead, an understanding of each approach is essential for informed decision-making and the development of integrated strategies that address the multifaceted challenges of insect management and grain disinfection.

- Traditional methods such as visual inspection and sampling probes offer simplicity and accessibility but are limited in scope and efficiency.

- Recent advancements in technology, including solid-phase microextraction and electronic nose detection, show promise for enhanced sensitivity and rapid detection.

- Non-destructive techniques like X-ray imaging and thermal imaging offer potential for internal and external detection but come with cost and operational considerations.

- Acoustic detection emerges as a promising tool for bulk storage surveillance due to its non-destructive nature and superior sensitivity.

- Disinfestation strategies encompass a range of thermal and non-thermal techniques, each with their advantages and challenges, highlighting the need for tailored approaches.

- Synergistic combinations of non-thermal disinfestation methods offer potential for enhanced efficacy and sustainability in grain processing.

In essence, the exploration of insect detection and grain disinfection methodologies underscores the complexity of agricultural challenges and the importance of holistic approaches that balance technological innovation with practical considerations and environmental sustainability. As a way forward, continued research and collaborative works are essential in developing integrated solutions that ensure the safety, quality, and security of stored food grains.

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