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Smart strategies: Radiations for insect pest management approach

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Abstract

Insecticides have long been considered one of the most effective tools for pest control. However, their extensive use comes with significant drawbacks. Chemical pesticides are costly and leave residues that contaminate soil, air, and water systems, posing serious risks to non-target organisms and natural ecosystems. These environmental and health concerns have led to increasing restrictions on chemical use. In this context, irradiation has emerged as a promising alternative, particularly for replacing chemical fumigation in export commodities. In sterile insect technique (SIT) programs, irradiation is commonly applied using either self-contained or panoramic (non-self-contained) irradiators. The primary ionizing radiation sources used include gamma rays, X-rays, and high-energy electrons. To ensure effective quarantine security, especially for large insect populations, accurate dosimetry is essential when applying these radiation treatments. Irradiation is increasingly favoured because chemical disinfestation methods are subject to strict regulatory limitations due to concerns about environmental contamination and public health. Within integrated pest management (IPM) programs, SIT plays a crucial role in controlling economically important pests in agriculture, veterinary science, and public health. Furthermore, advances in genetic engineering are expected to enhance SIT by enabling the development of transgenic insect strains, thereby improving long-term pest suppression strategies. Thus, genetic approaches are becoming an important complement to SIT in managing large pest populations.

Keyword: Sterile Insect Technique (SIT); Ionizing Radiation; Insect Pest Management; Quarantine Disinfestation; Gamma Irradiation; Integrated Pest Management (IPM); Radiation Dosimetry; Post-Harvest Treatment; Agricultural Biosecurity.

1. Introduction

Since the development of synthetic pesticides during the Second World War, chemical control has been the dominant strategy for managing insect pests. Although pesticides are effective, their extensive use has led to serious environmental pollution. Residues persist in soil, air, and surface water, posing significant risks to non-target organisms and disrupting ecological balance.

Two major challenges currently face pest management professionals: the rapid development of pesticide resistance and the environmental hazards associated with chemical use. In response, irradiation has emerged as a promising alternative, particularly for eliminating the need for chemical fumigation in export commodities (Ahmed, 1991; Marcotte, 1993; Hallman, 2013; Ayvaz & Yilmaz, 2015). Radiation treatments are already considered effective for controlling stored-product pests in commodities such as wheat and flour in several countries, and their application may soon expand to other grains and dry foods (Brower & Tilton, 1983; Kebede, 2021). However, further research is still needed to optimize these methods.

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Despite its long history, the adoption of irradiation for quarantine disinfestation remains limited. One reason is that irradiation does not cause immediate insect mortality, and another is public concern regarding radiation safety (Hallman, 2013; Ayvaz & Yilmaz, 2015). Many consumers associate irradiation with nuclear risks, even though it does not induce radioactivity in treated products, even at high doses (Bakri et al., 2005). As a result, the adoption of irradiation technology in agriculture has progressed slowly.

Improving public awareness about the safety and reliability of irradiation could significantly enhance its acceptance. If consumers are assured of product safety and nutritional quality, they are more likely to accept irradiated food. Irradiation offers several advantages: it reduces post-harvest losses, ensures uniform treatment compared to fumigation, and leaves no chemical residues, making it highly suitable for maintaining quality standards in international trade (Loaharanu & Mainuddin, 1991). It also contributes to improved hygiene in agricultural products.

Future research should focus on determining effective doses for radiation-resistant pests such as Lepidoptera, reducing treatment duration and radiation levels, developing standardized treatments below 400 Gy for key quarantine pests, and generating data on value-added irradiated fresh products (Follett & Wall, 2013). Standardized irradiation treatments will enhance global trade safety by preventing the spread of invasive pests. These treatments aim to sterilize eggs, larvae, and pupae in agricultural commodities. Studies indicate that relatively low doses are sufficient for pests belonging to Coleoptera, Homoptera, and Diptera, whereas Lepidopteran pests require higher doses. Resistance to radiation generally increases with developmental stage, and males tend to be more tolerant than females (Yamada et al., 2022).

1.1. Sources of Ionizing Radiation

Ionizing radiation includes X-rays, gamma rays, electron beams, and neutron radiation (Wikilectures, n.d.) (Hallman, 2013). Naturally occurring radiation, often referred to as background radiation, originates mainly from cosmic sources such as galactic cosmic rays, solar radiation, and radiation trapped in the Earth's Van Allen belts (UNSCEAR, 2010).

Gamma rays are particularly useful because they can ionize atoms without affecting the nucleus, meaning they do not induce radioactivity in exposed materials. In sterile insect technique (SIT) programs, gamma rays, X-rays, and high-energy electrons are the primary radiation sources used (Bushland & Hopkins, 1953; Lindquist, 1955; Baumhover et al., 1955; Klassen & Curtis, 2005; Robinson, 2002).

Comparative studies show that X-rays and gamma rays have similar biological effectiveness for insect sterilization, although operational considerations may differ (Kaboré et al., 2023). Dose rate also plays a crucial role in sterilization efficiency and insect quality (Yamada et al., 2022).

Particle radiation is generally unsuitable for insect sterilization due to its limited penetration despite high energy transfer. Although neutrons can induce sterility effectively, they are not used in SIT because they may render materials radioactive (Hooper, 1971; Offori & Czock, 1975; North, 1975). For practical applications, energy levels are carefully controlled—below 5 MeV for gamma rays and X-rays, and below 10 MeV for electron beams—to maintain insect fitness (Bakri et al., 2005; Elias & Cohen, 1977).

Different types of radiation generally show similar biological effectiveness in inducing sterility (Bakri et al., 2005). Among available sources, cobalt-60 and cesium-137 are the most commonly used radioisotopes in SIT programs (UNSCEAR, 2010).

1.2. Irradiators and Their Design

Irradiators are specialized devices used to expose insects or commodities to controlled radiation doses. Regardless of type, they consist of three essential components: a radiation source with control systems, a material transport mechanism, and shielding to protect human health and the environment (Bakri et al., 2005; Hallman, 2013).

Gamma irradiators typically use cobalt-60 or cesium-137 sources (Bakri et al., 2005). In self-contained irradiators, the radiation source is enclosed within a shielded chamber, often arranged to ensure uniform dose distribution. These systems have limited capacity but provide high dose rates, making them suitable for small-scale SIT applications (Kaboré et al., 2023; Ayvaz & Yilmaz, 2015).

For large-scale operations, panoramic irradiators are used. These systems may include movable cobalt-60 sources or multiple rods arranged in a plane. Because gamma rays are emitted in all directions, high efficiency can be achieved by surrounding the source with multiple containers of insects. However, dose variability within large chambers makes them less suitable for precise dose determination. Smaller irradiators are therefore preferred for research purposes (Hallman, 1998).

Electron and X-ray irradiators rely on particle accelerators. Electron beams allow rapid treatment but have limited penetration, whereas X-rays can penetrate deeper and treat larger volumes (Bakri et al., 2005). The choice of radiation source depends on factors such as penetration depth, cost, throughput, safety, and technical requirements (IDIDAS, 2004).

Gamma irradiators are generally less expensive to operate, whereas electron accelerators are considered safer because they can be switched off when not in use (Cavallaro & Delrio, 1974; Smittle, 1993; EBFRF, 2004). However, X-ray production is relatively inefficient, requiring higher energy input (Farrell et al., 1983). Overall, gamma irradiators remain the most widely used in SIT programs (Bakri et al., 2005).

1.3. Dosimetry

Accurate dosimetry is essential in SIT programs to ensure that insects receive the appropriate radiation dose for sterilization (Parker & Mehta, 2007). Dosimeters are used to measure absorbed doses, monitor processes, and calibrate irradiators (Bakri et al., 2005). Standardized protocols developed by ISO/ASTM guide dose measurement and calculations.

The absorbed dose is measured in Gray (Gy), defined as one joule of energy absorbed per kilogram of material. If the radiation dose is too low, sterility may not be achieved; if too high, insect fitness and competitiveness may be reduced (Robinson, 2002). Therefore, both sterility and biological performance must be considered when determining optimal doses. Field evaluations are necessary to validate laboratory findings (Parker & Mehta, 2007; Horrocks et al., 2021; Basso et al., 2024).

1.4. Radiation Doses and Quarantine Protection

Irradiation is widely used as a quarantine treatment to prevent the spread of pests through trade. Many insect species, particularly those in Diptera, Coleoptera, and Homoptera, can be effectively controlled with relatively low doses without damaging host commodities (Hallman, 1998). Moderate doses are sufficient for many Lepidopteran pests and are tolerated by fruits such as mangoes, cherries, and blueberries.

This approach also supports the development of generic treatments, where a single dose can control multiple pest species without affecting product quality. These treatments must be validated across different species before widespread implementation.

1.5. Advantages of Irradiation

Irradiation offers several advantages over conventional post-harvest treatments. It reduces losses, ensures uniform treatment, and leaves no chemical residues, making it ideal for international trade (Loaharanu & Mainuddin, 1991; Ayvaz & Yilmaz, 2015). It can penetrate deeply into products, reaching pests that are inaccessible to other treatments (Tiryaki, 1990).

Unlike chemical methods, irradiation does not significantly increase temperature or leave residues, thereby preserving the nutritional and physicochemical properties of food. Increasing regulatory restrictions on chemical fumigants further emphasize irradiation as a practical alternative (Loaharanu & Mainuddin, 1991). It also helps maintain hygiene standards and prevents the development of pesticide resistance (Jarrett, 1982).

1.6. Standard Quarantine Approaches

With increasing global trade, the risk of pest introduction has grown significantly (Follett, 2009). To address this, standardized irradiation treatments have been developed. The International Consultative Group on Food Irradiation recommended doses of 150 Gy for fruit flies and 300 Gy for other insects (ICGFI, 1991).

Later guidelines suggested 150 Gy for tephritid fruit flies and up to 400 Gy for most other insect pests (Follett & Weinert, 2009). These treatments effectively sterilize pests without damaging host commodities. Irradiation is now recognized as a safe and effective quarantine method under international standards (FAO, 2000, 2010), providing a reliable alternative to traditional treatments (Follett & Armstrong, 2004).

1.7. Integrated Pest Management (IPM) and SIT

Modern pest management increasingly relies on integrated approaches due to pesticide resistance and environmental concerns. Integrated Pest Management (IPM) combines multiple strategies to control pests while minimizing ecological impact (EPA, 2007).

The sterile insect technique (SIT) is a key component of area-wide integrated pest management (AW-IPM) programs (Klassen & Curtis, 2005; Vreysen et al., 2007; Abd-Alla et al., 2025; Mainardi et al., 2025). It is species-specific, environmentally friendly, and compatible with other control methods such as biological and cultural practices (Carpenter, 2000; Dyck et al., 2005; Schuster & Stansly, 2005). SIT has been successfully applied to several pest species, including fruit flies and moths, and continues to evolve with improved techniques (Bloem et al., 2005; Carpenter et al., 2005; Simmons et al., 2010). Current field employments demonstrate its practical impact, such as mosquito control programs targeting *Aedes aegypti* (Macedo et al., 2026). Pilot studies further confirm its practicability for pest suppression (Cécile et al., 2026).

2. Conclusion

Irradiation-based pest control, particularly through SIT, represents a sustainable and environmentally friendly alternative to chemical methods. Advances in radiation technology, dosimetry, and genetic approaches are enhancing its effectiveness and expanding its applications. With increasing global demand for safe and residue-free agricultural products, irradiation is expected to play a central role in future pest management strategies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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