RF-284
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REVIEW ARTICLE Agricultural Reviews

Advances in Irradiation Technology for Plant Disease Resistance: A Review

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10.18805/ag.RF-284

ABSTRACT

Plant diseases pose a significant threat to global food security, leading to substantial yield losses and economic damage. In recent years, irradiation technology has emerged as a promising approach to enhance plant disease resistance. Gamma irradiation, a well-established technique, has been utilized for approximately 60 years to develop new plant varieties with improved resistance to pests and diseases. X-ray is another form of ionizing radiation, has also shown the potential in enhancing plant disease resistance. UV light, including UVB and UVC radiation, has been effective in eliminating microorganisms by damaging their DNA. Electron beam irradiation, a non-ionizing form of radiation, has been investigated for its impact on plant disease resistance. However, the implementation of irradiation technology in agriculture faces challenges such as public perception, regulatory barriers and cost-effectiveness. This review article highlights the advances in irradiation technology for plant disease resistance. It emphasizes the potential of gamma irradiation, X-ray gamma irradiation, UV light, UVB, UVC and electron beam in enhancing plant disease resistance.

Key words: Gamma irradiation, Irradiation technology, Plant diseases, UV light, X-ray.

Plant diseases pose a major threat to global food security, causing significant yield losses and economic damage. Irradiation technology has emerged as a promising approach to enhance plant disease resistance. Gamma irradiation, X-ray gamma irradiation, UV light, UVB, UVC and electron beam are some of the irradiation technologies that have been studied for their effectiveness in plant disease resistance. In this review article, the recent advances in irradiation technology for plant disease resistance have been discussed. The mechanisms of action of different irradiation technologies, their effectiveness in enhancing plant disease resistance, the potential applications of irradiation technology in agriculture and the challenges associated with its implementation.

Gamma irradiation has been used for approximately 60 years to develop new plant varieties with improved resistance to pests and disease (Lourdes *et al*., 2022). Studies have also revealed the positive effects of irradiation on the physical and nutritional properties of different fruits and vegetables (Bisht *et al*., 2021). Gamma irradiation is one of the most widely studied irradiation technologies for plant disease resistance. It has been shown to induce mutations in plant DNA, leading to the development of new plant varieties with improved resistance to pests and disease (Lourdes *et al*., 2022). The X-ray gamma irradiation is another form of ionizing radiation that has been studied for its effectiveness in plant disease resistance. It has been shown to induce changes in the expression of genes involved in plant defense mechanisms (Lourdes *et al*., 2022). Non-chemical methods such as UV radiation have been shown to be effective in keeping the root zone free of pathogens (Jeong and Jeong, 2018). The UV light is a non-ionizing form of radiation that has been studied for its effectiveness in plant disease resistance. UVB and UVC radiation have been shown to be effective in killing microorganisms by damaging their DNA (Jeong and Jeong, 2018). Electron beam irradiation is another form of irradiation technology that has been studied for its effectiveness in plant disease resistance. It has been shown to induce changes in the expression of genes involved in plant defense mechanisms (Lourdes *et al*., 2022). The application of existing irradiation technology could reduce crop losses that can be as high as 50 per cent in developing countries (Intelligence and Report, 2012). Therefore, irradiation technology has the potential to be an effective tool in enhancing plant disease resistance. In this review article, the mechanisms of action of different irradiation technologies and their effectiveness in enhancing plant disease resistance were discussed. The potential applications of irradiation technology in agriculture and the challenges associated with

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How to cite this article: Zulkifli, N.A., Izhar, M.A.A.K., Lau, H.Y. and Azizi, M.M.F. (2023). Advances in Irradiation Technology for Plant Disease Resistance: A Review. Agricultural Reviews.
DOI: 10.18805/ag.RF-284
Submitted: 24-07-2023 **Accepted:** 30-10-2023 **Online:** 25-11-2023

its implementation are studied. The aim of this review is to provide a comprehensive overview of the recent advances in irradiation technology for plant disease resistance.

Irradiation for plant disease control

Gamma irradiation

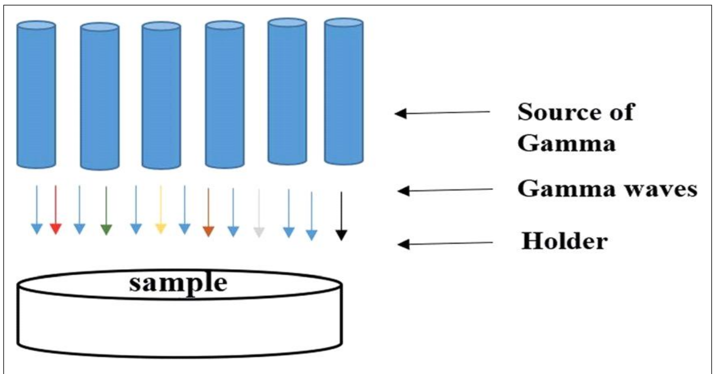
The use of gamma irradiation is a physical method for controlling plant diseases. It does not require the administration of any chemicals. Gamma irradiation has been extensively researched for its potential to manage plant diseases caused by fungi, bacteria, viruses and nematodes. Numerous studies have proven that this technique is effective at combating plant diseases. For instance, gamma irradiation has been found to be effective in controlling powdery mildew, gray mold and downy mildew on cucumbers (Faris *et al*., 2016). The use of gamma irradiation has been shown to be effective in controlling various fungal diseases in other crops such as gerbera (Ghani and Sharma, 2019; Serrano-Fuentes *et al*., 2022).

Fig 1 shows schematic of the gamma radiation process. The gamma radiation process is a method that utilizes high-energy photons emitted by the decay of the radioisotope Cobalt 60 to kill microorganisms on various products. It is commonly used for sterilization, decontamination and materials modification (Adhamash *et al*., 2020).

The irradiation is the most prominent technique for treating seeds due to its ability to kill pathogens that may be present in the seeds without affecting their viability or germination (Jeong *et al*., 2015). Moreover, it can also be deployed to treat plant cuttings, bulbs and other propagating materials to prevent the spread of disease. The efficiency of gamma radiation in eradicating plant ailments depends on various aspects, such as radiation strength, exposure span and pathogen vulnerability (Choi *et al*., 2021). The effectiveness of gamma radiation in managing plant disease depends on the pathogen and material, therefore requiring varying doses. The optimal dose must be carefully determined to effectively control the disease without compromising the quality and safety of the plant products being treated (Gamma Irradiation as a Treatment to Address Pathogens of Animal Biosecurity Concern Final Policy Review, 2014). The effective dose of gamma radiation to control plant disease may vary depending on the specific plant pathogen and the plant material being treated. The optimal dose of radiation required to achieve effective disease control also depends on the radiation sensitivity of the pathogen and the radiation tolerance of the plant material (Gamma Irradiation as a Treatment to Address Pathogens of Animal Biosecurity Concern Final Policy Review, 2014).

Gamma radiation doses ranging from 0.1 to 10 kGy are generally effective in treating plant diseases. The ideal dosage can differ depending on the treated plant material and pathogen e.g. a suitable dosage for the microbial decontamination of plant extract is 6-12 kGy, while for dried plant, it is 9-13 kGy (Khawory *et al*., 2019). Some plant materials require a lower gamma radiation dose to control pathogens than others. The US Food and Drug Administration (FDA) has established dosage guidelines for treating certain plant products with gamma rays *e.g.* a dose of 0.3 kGy is recommended for irradiation of fresh fruits and vegetables to control insect pests. In contrast, a dose of 1 kGy is recommended to irradiate sprouts to control plant pathogens (I-food and Services, 2023). However, it is important to note that excessive doses of gamma radiation can adversely affect the quality and safety of treated plant products. The high doses of radiation can cause changes in taste, texture and nutritional content of treated plant products. Gamma radiation can also damage plant cells and tissues if the dose is too high (Choi *et al*., 2021). Therefore, the optimal gamma radiation dose for treating plant diseases must be meticulously determined in order to achieve effective disease control without compromising the quality and safety of the treated plant products.

The effectiveness of gamma irradiation in controlling plant diseases can be affected by a variety of abiotic and biotic factors. Abiotic factors refer to inanimate environmental factors such as radiation, temperature and humidity that can affect plant growth and survival. Factors such as exposure dose, exposure time and moisture content of plant tissue can influence the efficacy of gamma irradiation in preventing



(Adapted from Adhamash *et al*., 2020).

Fig 1: Schematic of the gamma radiation process.

plant diseases. Biotic factors refer to living organisms such as fungi, bacteria, viruses and insects that can cause plant diseases. Gamma radiation can be used to control these biotic factors by damaging their DNA and preventing them from reproducing (Hong *et al*., 2022). However, the effectiveness of gamma irradiation to control plant diseases can be affected by the type of pathogen, its growth stage and the plant's susceptibility to the pathogen.

Gamma irradiation is non-chemical and does not affect the nutritional value or flavor of the treated plant products. It can also be used to treat a variety of plant materials such as seeds, fruits and vegetables (Bhatnagar *et al*., 2022). Gamma radiation offers numerous advantages including the fact that it is a non-chemical method, which implies no harmful residue on plants. Therefore, this technique is considered asecological method of controlling plant diseases (Gamma Irradiation as a Treatment to Address Pathogens of Animal Biosecurity Concern Final Policy Review, 2014). Moreover, gamma radiation can be implemented at different stages of plant growth, such as pre-sowing, post-harvest and during storage, it a versatile method (Katiyar *et al*., 2022). It can also enhance plant growth and productivity by inducingphysiologic changes in plants. For instance, gamma radiation has been demonstrated to increase the size and nutritional value of fruits and vegetables. The Gamma radiation can also stimulate the production of antioxidant and anti-inflammatory phytochemicals (Jameel and Mohammed, 2021). Despite its advantages, gamma radiation has some limitations. One of the biggest challenges of this technique is the potential damage to plant tissue and DNA. Gamma irradiation can cause mutations in plant DNA thereby, reducing plant growth and yield. Furthermore, high doses of gamma radiation can damage plants physiologically, resulting in changes in plant morphology and structure. Another constraint is the expense of the necessaryequipment for gamma irradiation. Installing and maintaining gamma irradiation systems is costly, making them a less viable option for small farmers (Katiyar *et al*., 2022).

X-ray irradiation

The X-ray irradiation is most commonly used for seed treatment as it can effectively kill pathogens that may be present in seeds without affecting seed viability or germination.

Protocol for X-ray mutagenesis of plant material

Seed Background Induced Mutagenesis in Plants Dates Back to the Beginning of the 20, 2010. The previous study examined the potential of X-ray irradiation for the inactivation of *Aspergillus* spp.in cannabis flowers (Frink *et al*., 2022). The study published in MDPI discussed the use of gamma radiation for the genetic improvement of underutilized plant varieties, which is a similar technique to X-ray irradiation (Lourdes *et al*., 2022). While, Jan *et al.* (2012) investigated the effect of gamma radiation on morphological, biochemical and physiological aspects of plants and plant products, which is a related topic to X-ray irradiation. It can also be used to treat other plant materials such as fruits and vegetables to reduce post-harvest losses due to disease. This process damages the DNA of plant pathogens such as fungi, bacteria and viruses, preventing their growth and reproduction, thereby reducing the occurrence, severity and spread of plant diseases (Lourdes *et al*., 2022). The X-ray irradiation has been shown to be effective in controlling anthracnose and black spot disease in various crops including pears and strawberries (Jeong and Park, 2017; Yoon *et al*., 2020). Like gamma radiation, X-ray radiation is an environmentally friendly, non-invasive method of disease control that leaves no chemical residue on plants or in the soil. It is also a non-thermal method of disease control, meaning it does not cause heat damage to plants or plant products (Katiyar *et al*., 2022).

The X-ray irradiation can also improve plant growth and productivity by inducing changes in plant physiology. For example, X-ray exposure has been shown to increase the shelf life of fruit and vegetables by slowing down the ripening process (Rezk and Al-khayri, 2019). It can also stimulate the production of phytochemicals that have antioxidant and anti-inflammatory properties, improving the nutritional value of plants.To encounter diseases by use of X-ray irradiation the plants or plant products are exposed to high-energy X-rays in a specially constructed irradiation chamber,the duration and intensity of exposure depend on the type and severity of the condition being treated. After irradiation, plants or plant products are tested for immunity from pathogens (Rezk and Al-khayri, 2019).

The effective dose of X-ray irradiation to treat plant diseases varies depending on the specific plant pathogen and the plant material to be treated (Zappala *et al*., 2013). The optimal dose of radiation required to achieve effective disease control depends on the sensitivity of the pathogen to radiation as well as the tolerance of the plant material to radiation. In general, the effective dose of X-rays to treat plant diseases is in the range of 0.1 to 10 kGy. However, the optimal dose can vary widely depending on the specific pathogen and plant material being treated. The effective dose of X-rays used to treat plant diseases is usually less than the effective dose of gamma rays. This is because X-rays have a higher energy transfer rate than gamma rays, which means they can achieve the same pathogen inactivation with a lower dose of radiation (Shahi *et al*., 2021). The optimal dose of X-ray irradiation for plant disease control must be carefully determined in order to achieve effective disease control without compromising the quality and safety of the plant products being treated.

The choice of the appropriate radiation source, dose and exposure time depends on the specific plant pathogen and plant material being treated. It is important to evaluate the potential risks and benefits of using X-ray irradiation to control crop disease and to consider other disease control strategies that may be more sustainable and environmentally friendly. Both abiotic and biotic factors can influence the effectiveness of X-ray irradiation to control plant diseases. However, X-ray irradiation can also have some disadvantages like high capital and operating costs, safety concerns and regulatory requirements.

The use of X-rays to treat plant diseases should be carefully evaluated, as other disease management strategies (Jeong and Jeong, 2018). Therefore, further research is needed to optimize the use of X-rays to combat plant diseases, particularly with regard to optimizing dose, timing of application and developing cost-effective devices. Excessive doses of X-rays can have adverse effects on the quality and safety of treated plant products (Shahi *et al*., 2021). Therefore, the optimal dose of X-ray irradiation for the treatment of plant diseases must be carefully determined in order to achieve effective disease control without compromising the quality and safety of the plant products being treated.

Ultraviolet irradiation

Ultraviolet (UV) light is a non-chemical means to effectively suppress plant diseases. The UV light technology has been used for over 75 years in various microbiological applications, including hospitals, water purification and food processing, with no reported examples of practical resistance (Gadoury and Peres, 2022). It can be used to control crop diseases by activating plant-defense mechanisms and boosting overall plant defenses against pathogens (Cornell University, 2019). These light can also directly harm plant pathogens and increase disease resistance in plants (Meyer *et al*., 2021). UV light is divided into three categories: UV-A (400-315 nm), UV-B (315-280 nm) and UV-C (280-10 nm) radiation each with a different wavelength and energy level that affects its effectiveness and safety (Meyer *et al*., 2021). The UV-C light can reduce disease incidence in crops and is often applied to diminish postharvest decay of plant products or as a pre-treatment to boost plant resistance (Meyer *et al*., 2021). The benefits of using UV light for plant disease control include its non-toxicity, low cost and ease of application. It is also effective against a wide range of plant pathogens (Meyer *et al*., 2021). There are various types of UV light sources that can be used for plant disease control, including UV lamps, LEDs and natural sunlight(Loconsole and Santamaria, 2021). The UV lamps are commonly used in greenhouse installations and can be placed above or below the plants (Gadoury and Peres, 2022). The LEDs are also used for plant disease control and can be customized to emit specific wavelengths of UV light (Loconsole and Santamaria, 2021).

Natural sunlight is another source of UV light and can be used for outdoor plant disease control. There are different methods of applying UV light to plants, such as direct exposure, reflective surfaces and greenhouse installations. Direct exposure involves placing the UV light source close to the plants, while reflective surfaces can be used to increase the amount of UV light that reaches the plants (Loconsole and Santamaria, 2021). Greenhouse installations involve placing UV lamps or LEDs in the greenhouse to provide continuous UV exposure to the plants. While UV light is an effective non-chemical alternative for controlling plant diseases, it has some limitations. One of the limitations is that UV light cannot penetrate plant tissue, which means that it is only effective on the surface of the plant (Gadoury and Peres, 2022). Therefore repeated treatments may be necessary to ensure that all the pathogens are eliminated (Cornell University, 2019) moreover, UV light can only be used during certain times of the day, such as early morning or late afternoon, when the sun is not too intense (Loconsole and Santamaria, 2021). Another limitation is that UV light can cause damage to plant tissue if used excessively or at the wrong time, which can reduce plant growth and yield (Meyer *et al*., 2021). Despite these limitations, UV light is still a promising tool for controlling plant diseases, especially for high-value specialty crops like strawberries, grapes and greenhouse cucumbers (Cornell University, 2019). When using UV light for plant disease control, safety considerations should be taken into account. The UV light can be harmful to human skin and eyes, so it is important to wear protective clothing, such as gloves, long-sleeved shirts and pants and to avoid direct exposure to UV light (Meyer *et al*., 2021). Therefore, it is important to follow the recommended guidelines for UV light application and to avoid overexposure. UV light can be a safe and effective tool for controlling plant diseases when used properly and with caution. There are several successful applications of UV light for plant disease control in agriculture and horticulture.

The applications of UV light showed similar or better response than available fungicides, resulting in 95 per cent reduction in occurrence of powdery mildew in the fields of strawberries, basil, roses, grapes, strawberries, rosemary and of cucumbers (Cornell University, 2019). Moreover, UV light has been demonstrated to significantly reduce mildew in plants ranging from grapes, rose plants, cucumber, rosemary and strawberries (“UV LED Technology for Emerging Applications in Agriculture,” 2018). The UV light has also been used as a non-chemical means to effectively suppress powdery mildew in nursery operations without risk of resistance. One commercial nursery in Nova Scotia has applied the UV technology on a grand scale, building the largest UV array developed to date and using it to control powdery mildew in nursery operations (Gadoury and Peres, 2022).

Ultraviolet-B (UVB)

The UV-B light has been shown to have a positive effect on disease resistance in many plant-pathogen combinations (Meyer *et al*., 2021). It induces the production of specialized metabolites that contribute to reduced biotrophic disease (McLay *et al*., 2020).like powdery mildews in several plant species (Suthaparan *et al*., 2016). The quality of light is an important factor in plant disease management and UV-B light is effective in controlling plant diseases by suppressing pathogen growth (Smith *et al*., 2022). UV-B light works by inducing the production of flavonoids, which are specialized metabolites that contribute to reduced disease incidence in crops (Meyer *et al*., 2021). Supplemental UV-B light has great potential in reducing disease incidence in crops and controlling plant diseases. In general, supplemental UV-B light has a positive effect on disease resistance in many plant-pathogen combinations, mainly through the induction of the production of specialized metabolites (Meyer *et al*., 2021). The UV-B exposure time and intensity vary depending on the study conducted. In one study Meyer *et al*. (2021) reported that, 6 hours of UV-B light completely suppressed powdery mildew infection in roses, while 4 hours was only partially effective.

In another study Smith *et al*., (2022) exposed plants to UV-B light for 3 hours during the night. Depending on the study the experimental set up was varied some used detached leaves and others used whole plants (Smith *et al*., 2022). The results of the studies suggest that supplemental UV-B light has a positive effect on disease resistance in many plant-pathogen combinations, mainly through the induction of the production of specialized metabolites. However, there is a lot of variation in the experimental setups, making it challenging to compare the effect of UV-B radiation and draw general conclusions (Meyer *et al*., 2021; Smith *et al*., 2022). The efficacy of UV-B light in controlling plant diseases is promising, but further research is needed to determine the optimal UV-B exposure time and intensity for different plant-pathogen combinations. Limitations of the studies include the use of different plant species, pathogens and experimental setups, which make it difficult to compare the results across studies (Meyer *et al*., 2021; Smith *et al*., 2022). The studies reviewed suggest that supplemental UV-B light has a positive effect on disease resistance in many plant-pathogen combinations, mainly through the induction of the production of specialized metabolites. The findings of the studies have important implications for plant pathology and agriculture, as UV-B light has the potential to reduce disease incidence and pest infestation in crops.Overall, the studies provide practical insights and facilitate future research on UV-B radiation as a promising tool to reduce disease and pest incidence in crops.

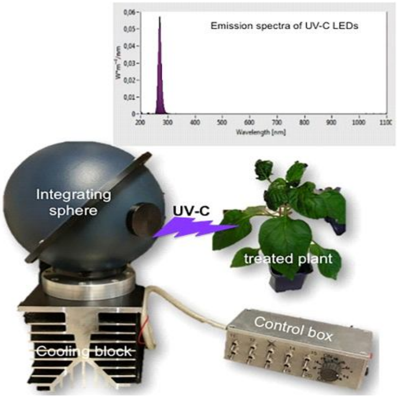
Ultraviolet-C (UVC)

Ultraviolet-C (UVC) radiation is a type of electromagnetic radiation with a wavelength between 100 and 280 nanometers (Santos and de Castro, 2021). The UVC radiation is known to have germicidal properties and is commonly used for disinfection purposes.

Fig 2 shows the device used for supplying UV-C light to plants. In recent years, UVC radiation has also been studied for its potential use in plant disease control (Lualdi *et al*., 2021).

Studies have shown that UVC radiation can stimulate plant resistance to pathogens and pests. The study showed that irradiation for one second is more effective than irradiation for longer periods. The results confirmed that UVC light stimulates plant resistance (Aarrouf and Urban, 2020). The UVC radiation works by damaging the DNA and RNA of microorganisms, including plant pathogens. This damage can lead to the death of the microorganisms or the inhibition of their growth and reproduction (Bhardwaj *et al*., 2021). The UVC radiation can also stimulate the production of reactive oxygen species (ROS) in plants, which can trigger the plant's defense mechanisms against pathogens and pests (Urban *et al*., 2016). In addition to its potential use in plant disease control, UVC radiation has also been found to be effective in promoting plant growth and product quality. In a study by Darras *et al*. (2013) found that UVC radiation can increase the biomass and the number of lateral stems and inflorescences in plants. The study exposed plants to six successive UVC treatments throughout cultivation and found that plants treated with UVC radiation were less sensitive to *Podosphera aphanis, Botrytis cinerea* and *Rhizopus spp*. at the leaf and fruit level than untreated plants (Forges *et al*., 2020). The other previous studies used different methods to investigate the effects of UVC radiation on plant disease control. For example, a study by Aarrouf and Urban (2020) exposed leaves of lettuce, pepper, tomato and grapevine plants to UVC light for either 60 seconds or 1 second, using a specific LED-based device and found that irradiation for one second is more effective than irradiation for longer periods in stimulating plant defenses against several fungal and oomycete diseases.

In another study by Darras *et al*. (2020) evaluated the potential of low doses of UVC applied during plant growth for use in fruit or vegetable and ornamental quality maintenance. They exposed the plants to low UVC doses (≤ 36 J m^{2}) of 254 nm and far UV at 220 nm and induced fungal resistance in strawberry plants with UVC irradiation. The UVC radiation can induce plant resistance to pathogens and pests, reduce the development of diseases in many plant species and improve the nutritional qualities of plant products (Loconsole and Santamaria, 2021). One limitation of the studies is that they used different types of plants and pathogens, UVC exposure times and intensities and experimental setups, which makes it difficult to compare the results across studies (Vanhaelewyn *et al*., 2020). Another limitation is that the studies focused mainly on the effects of UVC radiation on disease control and did not investigate



(Adapted from Santos and de Castro, 2021).

Fig 2: The device used for supplying UV-C light to plants.

the potential negative effects of UVC radiation on plant growth and development.

From these limitation, future research could focus on determining the optimal dose and application method of UVC radiation for different plant species and diseases, as well as investigating the potential negative effects of UVC radiation on plant growth and development. Additionally, more research is needed to compare the efficacy of UVC radiation to other methods of plant disease control, such as chemical treatments and biological control agents. The relevance of the study to the field of plant pathology is significant, as it provides a potential alternative to chemical treatments for plant disease control. The use of UVC radiation has the potential to reduce the use of pesticides and fungicides, which can have negative effects on the environment and human health. The potential applications of UVC radiation in agriculture and horticulture are also significant, as it can help improve crop yields and quality.

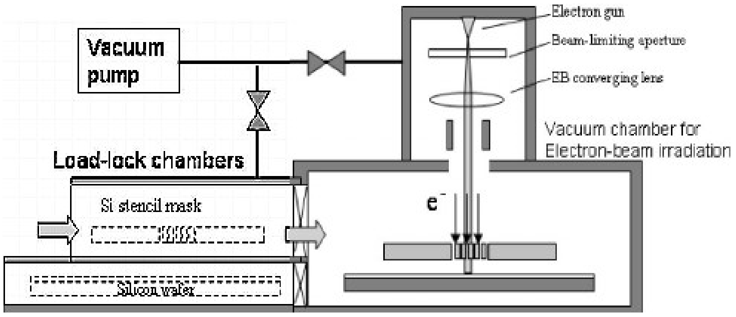
Electron beam

Plant diseases pose a major threat to food security and can cause significant economic losses. Traditional methods of combating plant diseases include the use of pesticides, which can have negative impacts on the environment and human health. The electron beam (e-beam) irradiation is a promising alternative to conventional methods of controlling plant diseases. Electron beam irradiation has been shown to reduce or eliminate pathogens in fruits, vegetables and grains, but its effects on plant disease resistance and quality are still under investigation (Chizh *et al*., 2018; Gautam and Venugopal, 2021; Nguyen *et al*., 2021). Plant health is a crucial part of food safety as it is a key driver of food production, a livelihood in plant-based agriculture and a source of pharmaceuticals (Rizzo *et al*., 2021). However, plant diseases and pests often threaten the availability and safety of crops for human and animal consumption, causing significant economic losses and exacerbating the current food deficit affecting at least 800 million people (Giovani *et al*., 2020).

Plant pathogens are difficult to control because their populations are temporally, spatially and genotypically variable and they often evolve, thereby overcoming resistances that may have been the plant's hard-won achievement (Strange and Scott, 2005).Pesticides are widely used in agricultural production to prevent or control pests, diseases, weeds and other plant pathogens. However, they raise serious concerns about the health risks arising from farmer exposure when mixing and applying pesticides or working on treated fields, as well as residues in food and drinking water for the general population (Nicolopoulou-stamati, 2016). Climate change is also expected to affect plant health, as pests and diseases are expected to invade and infest previously immunized areas (Gitz *et al*., 2016). Disasters and crises, including the COVID-19 pandemic, can also have significant impacts on agriculture and food security (FAO, 2021). Therefore, it is of crucial importance to develop effective and sustainable methods to control plant diseases. Electron beam irradiation is a promising alternative to traditional crop disease control methods, as it has been shown to reduce or eliminate pathogens in fruits, vegetables and grains (Mousavi *et al*., 2020). Further research is needed to fully understand the effects on crop quality and to develop effective and sustainable implementation methods.

Fig 3 shows illustration of the electron-beam irradiation system and the its highlights the importance of understanding the effects of contaminants on surfaces in vacuum chambers, which can affect the quality and effectiveness of electron beam irradiation(Saga and Hattori, 2005). This knowledge can be applied for the development and maintenance of electron beam irradiation facilities for plant disease control to ensure optimal performance.

Several studies have examined the effects of electron beam irradiation on disease resistance and plant quality. A preliminary experiment on mangoes revealed that electron beam irradiation can mitigate the development of post-harvest diseases caused by hydrogen peroxide and plant activities (Truc *et al*., 2021). However, Sci, (2022) found that while electron beam irradiation can reduce or eliminate pathogens, product quality can be compromised. The study of Waskow *et al.* (2021) demonstrated the effect of a low-energy pulsed electron beam on the occurrence and spread of disease. Another study investigated the biological effects of electron beam rotating X-ray beams (EBTTX) on two



(Adapted from Saga and Hattori, 2005).

Fig 3: Illustration of the electron-beam irradiation system.

freesia cultivars and found that EBTTX is a new irradiation technology that potentially can accelerate the reproductive process of plants (Li *et al*., 2021). Some studies have shown that electron beam irradiation has a positive impact on the disease resistance and quality of plants. In another study, by Truc *et al*. (2021)found that electron beam irradiation delay postharvest senescence of kiwi fruit during cold storage by regulating reactive oxygen species. However, it is important to note that product quality can be adversely affected by exposure to electron beam radiation. They also examined the influence of electron beam irradiation on chlorophyll degradation and antioxidant capacity of mango fruits and found that electron beam-treated fruits significantly suppressed the activities of chlorophyll-degrading enzymes, particularly phaeophy tinase and chlorophyllase. Therefore, although electron beam irradiation has the potential to improve plant disease resistance, further research is needed to fully understand its effects on plant quality and to develop effective and sustainable implementation methods.

Electron beam irradiation has several advantages over traditional methods of controlling plant diseases. It is a non-thermal process that does not affect the nutritional value or taste of food which can also be used to treat food and food ingredients to kill microbial pathogens, or in higher doses (Jeong and Jeong, 2018). Furthermore, electron beam treatment combined with antagonistic biological control can be used as a novel sterilization method to prevent replanting diseases in culture soils used for continuous cultivation (Sim *et al*., 2018). Electron beam (E-beam) irradiation offers several benefits for controlling plant diseases. Advantages include that electron beam irradiation does not alter the physical properties of food as it is a non-thermal process and it can also reduce or eliminate pathogens in fruits, vegetables and grains (Nguyen *et al*., 2021). The Electron beam irradiation can alleviate the development of post-harvest diseases caused by hydrogen peroxide and plant defense enzyme activities (Chizh *et al*., 2018; Truc *et al*., 2021). In addition, electron beam irradiation can maintain fruit quality in terms of firmness, slow the decline in titratable acidity and delay respiration rate (Electron beam irradiation for improving safety of fruits, 2011; Mousavi *et al*., 2020). For sterilization, electron beam treatment combined with antagonistic biological control can be used as a novel sterilization method to prevent replanting diseases in culture soil used for continuous culture(Mousavi *et al*., 2020). Next, electron beam irradiation could be an effective intervention treatment to improve seafood safety(Gautam and Venugopal, 2021).

Despite these benefits, it is important to note that product quality can be adversely affected by exposure to electron beam radiation. Therefore, further research is needed to fully understand the effects on crop quality and to develop effective and sustainable implementation methods. Electron beam irradiation is a promising alternative to conventional methods of controlling plant diseases. Although its effects on plant disease resistance and quality are still being studied, it offers several advantages over traditional methods. Further research is also needed to fully understand the potential of electron beam irradiation to control plant diseases and to develop effective and sustainable implementation methods.

In summary, this article review provides a comprehensive overview of the recent advances in irradiation technology for plant disease resistance. It explores the mechanisms of action of different irradiation technologies and their effectiveness in enhancing plant disease resistance. It also discusses the potential applications of irradiation technology in agriculture and the challenges associated with its implementation. This review highlights the potential of irradiation technology as an effective tool in enhancing plant disease resistance and reducing crop losses.

CONCLUSION

Irradiation technology has emerged as a promising approach to enhance plant disease resistance. Gamma irradiation, X-ray gamma irradiation, UV light, UVB, UVC and electron beam irradiations are some of the irradiation technologies that have been studied for their effectiveness in plant disease resistance. The application of existing irradiation technology could reduce crop losses that can be as high as 50 per cent in developing countries.

The effectiveness of irradiation technology in enhancing plant disease resistance is due to its ability to induce changes in the expression of genes involved in plant defense mechanisms. Irradiation technology has also been shown to induce mutations in plant DNA, leading to the development of new plant varieties with improved resistance to pests and disease. Studies have also revealed the positive effects of irradiation on the physical and nutritional properties of different fruits and vegetables.

Despite the potential benefits of irradiation technology in agriculture, there are challenges associated with its implementation. These challenges include public perception, regulatory barriers and cost-effectiveness. Therefore, further research is needed to address these challenges and to explore the potential applications of irradiation technology in agriculture.

ACKNOWLEDGEMENT

This study was supported by a scholarship and research funding from the Malaysian Nuclear Agency for a internship program at the Agrotechnology and Biosciences Division, Malaysian Nuclear Agency. The author wish to thank her degree supervisors, Mr. Mohammad Malek Faizal Azizi and Dr. Lau Han Yih.

Conflict of interest: None.

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