CHAPTER 1 INTRODUCTION

1.1 Research Background

Indonesia is known as a major producer of various tropical fruits that have strategic value in the national economy. The horticulture sector contributes significantly to Indonesia's Gross Domestic Product (GDP) (Indarwatmi and Kuswadi, 2021). Interest in irradiation as a phytosanitary measure is also showing a clear trend in the Asia-Pacific region, especially for tropical fruits. Among various types of fruit, dragon fruit (*Hylocereus spp*.) is a tropical and subtropical fruit that is currently widely cultivated in Indonesia and in major producing countries such as Vietnam and the Philippines (Aryanta, 2022). According to data from *Badan Pusat Statistik* the volume of fresh dragon fruit export from Indonesia in 2024 reached 1,091,376 kg with Free on Board (FOB) value of USD 670,807. Dragon fruit has shown promising performance in regional exports, confirming its position as a high-value commodity in the international market (BPS, 2025).

The increase in export volume must be balanced with product quality and safety guarantees, especially in meeting the strict phytosanitary (plant health) requirements of importing countries. Phytosanitary treatment is an integral part of global trade protocols aimed at preventing the spread of quarantine pests to new areas (Kim et al., 2015). The main threat of concern is the attack of quarantine pests, especially fruit flies of the genus *Bactrocera* such as *Bactrocera dorsalis*, which are known to infest dragon fruit (Thao and Tuan, 2024). The presence of these pests, even in the egg or larval stages that are not visually apparent in the fruit flesh, can result in the rejection of entire shipments, causing significant economic losses and damaging the reputation as a trusted exporting country (Oliveira et al., 2025).

Traditionally, fumigation with methyl bromide (*MeBr*) gas has been the method of choice for treating quarantine pests (Indarwatmi and Kuswadi, 2021; Pierard, 2025). However, the International Protocol has classified methyl bromide as an ozone-depleting substance, so its use is being phased out or will be banned in the near future (Tong et al., 2015). Concerns about chemical residues that are harmful to health and the environment, which can accumulate and cause chronic diseases such as cancer, further reinforce this decision (Sinambela, 2024). This situation has driven the search for safer, more effective, and environmentally friendly phytosanitary methods (Kim et al., 2015; Oh et al., 2014; Tong et al., 2015). Irradiation has emerged as one of the most promising candidates, and international bodies such as the FAO and IPPC recommend its development as a free residue treatment for agricultural commodities (IPPC, 2025).

Phytosanitari irradiation particularly using electron beams from a Linear Accelerator (LINAC), offers a superior solution (Ly et al., 2021). This technology is capable of inactivating pests by damaging the DNA in eggs or larvae, thereby breaking their life cycle (Pierard, 2025). This process aims to prevent the development or reproduction of pests (IPPC, 2025). The main advantages of irradiation are that it does not cause products to become radioactive because the maximum energy of industrial electron beam is maintained at 10 MeV and does not leave chemical residues (Oh et al., 2014). The electron beam from 10 MeV LINAC accelerator is a viable alternative to gamma irradiation (Cao et al., 2021). Studies on the effectiveness of electron irradiation for target pests (*Bactrocera dorsalis*) have proven that a dose of 400 Gy from a 10 MeV electron beam is sufficient to achieve the required phytosanitary efficacy in dragon fruit, although doses as low as 250 Gy have been observed to eliminate the hatching of eggs and pupation of *Bactrocera dorsalis* on dragon fruit (Thao and Tuan, 2024).

In general, there are several sources of radiation that can be used for phytosanitary purposes, mainly gamma rays from Co-60 or Cs-137 isotopes, electron beams and X-rays converted from electrons (Zolotov et al., 2023). Electron beam and X-rays are considered viable alternatives to Cobalt-60 gamma radiation for industrial and sterilization applications. However, electron beams from LINAC offer several strategic advantages for industrial-scale applications (Pierard, 2025). From a safety and regulatory perspective, LINAC does not use radioactive sources, thereby eliminating the risk of contamination and logistical issues related to the procurement and storage of radioactive sources that decay over (Vargasab and Brisona, 2023). Therefore, electron beam accelerators have an “On/Off switch” feature that provides operational flexibility not available with continuously emitting gamma sources (Pierard, 2025). From an energy efficiency perspective, electron beams have a very high dose rate (approximately 3,000 Gy/s for electron beam vs 0.06 – 0.12 Gy/s for Gamma), which significantly shortens treatment time compared to gamma irradiation (Studenikin et al., 2021). Although X-rays have better penetration, their conversion process from electrons has low efficiency, thus requiring greater input energy to achieve an equivalent dose (Alexander, 2024). Therefore, considerations of penetration, efficiency, safety, and treatment speed make electron beams with energies up to 10 MeV the energy limit approved to avoid inducing radioactivity very balanced and optimal choice for commodities such as dragon fruit, which has medium thickness (IAEA, 2010).

However, the success of irradiation applications is not only determined by the minimum effective dose, but also by the Dose Uniformity Ratio (DUR) throughout the entire product volume (Firmansyah et al., 2025). The ratio of maximum dose to minimum dose is very important quality criterion in radiation processing (ISO/ASTM, 2015; Nikandrovs, 2024). For example, in comparative research of radiation sources, the DUR in a single electron beam system was reported to be 1.60 (Vargasab and Brisona, 2023).

Dragon fruit, with its unique morphology (which can be approximated as ellipsoidal) and internal composition dominated by watery tissue with very high-water content (85.7 g per 100 g), creates complex dosimetry challenges (Aryanta, 2022). The distribution of absorbed electron energy is greatly influenced by the density and atomic composition of the medium it passes through (Cao et al., 2021). In addition, the depth-dose curve of electrons is highly dependent on the inhomogeneity of the irradiated material. Dosimetry studies on complex shaped foods such as mangoes show that irregular shapes can cause significant dose variations between the surface and the interior of the fruit (Tuan et al., 2019). The dose variations make accurate measurements difficult, often requiring a simple ellipsoidal model approach to simplify the geometry in dose simulations for tropical fruits (Oh et al., 2014). Significant dose variations have the potential to cause under dosing in certain areas (especially under the skin where quarantine pests hide), which can allow pests to survive, or over dosing in other areas (Kim et al., 2015).

The risks of overdosing include damage to texture, a decline in sensory quality, and decrease in nutrients such as vitamin C. High doses more than 1000 Gy can even cause greater loss of texture and severe changes in cell wall structure (Oliveira et al., 2025).

Recognizing the high cost and complexity of purely experimental dose distribution evaluation, the numerical simulation approach using the Monte Carlo (MC) method has become the gold standard in radiation treatment planning and optimization. Various Monte Carlo codes such as MCNP, GEANT4, and FLUKA have been widely used in radiation transport research (Firmansyah et al., 2025). For example, studies using MCNP have successfully simulated the distribution of irradiation doses on mangoes, melons, and pineapples for phytosanitary purposes (Alexander, 2024; Kim et al., 2015; Ly et al., 2021; Oh et al., 2014; Vargasab and Brisona, 2023).

Although several Monte Carlo codes are available, the selection of PHITS (Particle and Heavy Ion Transport code System) for food irradiation applications, especially for fruits with complex geometries, has not been extensively explored and compared in detail (Firmansyah et al., 2025). While codes such as MCNP, GEANT4, and PENELOPE have been extensively used in irradiation dose simulations of tropical fruits such as mangoes, pineapples, and melons, PHITS offers a unique combination that is highly relevant to this research. The advantages of PHITS include high flexibility in modeling complex 3D geometries, such as the ability to read CAD (Computer-Aided Design) geometries via tetrahedral meshes and efficient electron transport algorithms (Firmansyah et al., 2025; Sato et al., 2024). PHITS is reliable and proven Monte Carlo software that is continuously being improved, and exploring its capabilities in the context of dragon fruit dosimetry with an ellipsoidal model is an added value and originality of this research.

1.2 Research Purpose

This research aims to develop Monte Carlo simulation model using PHITS to analyze the distribution of 10 MeV electron doses in ellipsoidal dragon fruit for phytosanitary applications. Specifically, the study construct an ellipsoidal geometric model of dragon fruit with scanning horn configuration, and to analyze the profile depth-dose characteristics and fundamental dosimetric parameters under both single-sided and double-sided (flip) irradiation configurations. This research also evaluates the Dose Uniformity Ratio (DUR) against the international phytosanitary standard ISO/ASTM 51649 with limit value of 2.5 and assesses the adequacy of minimum and maximum doses. To validate dose accuracy, the simulation results are compared with experimental measurements at three positions within the fruit like top surface, geometric center, and bottom surface using alanine dosimeter data obtained from actual double-sided irradiation trials.

1.3 Research Benefits

This research produced accurate 3D electron dose distribution data on ellipsoidal dragon fruit model, which can be directly applied to optimize industrial irradiation parameters such as dual beam configuration to ensure phytosanitary effectiveness in accorandce with international standards while maintaining fruit quality. This PHITS simulation also provides a methodological basis for developing irradiation protocols for other complex horticultural commodities, thereby contributing to the improvement of the competitiveness of Indonesian fruit exports.

1.4 Scope of Research

This research is limited to the following scope:

1. Performing numerical simulations of 10 MeV electron dose distribution using the Particle and Heavy Ion Transport code System (PHITS) software.
2. Specifying dragon fruit with a diameter of 7.0 cm, 7.4 cm, 7.7 cm and with weight of 300 g, 350 g, 400 g for each diameter.
3. The simulation object is dragon fruit with an ellipsoid geometry, assumed to be homogeneous and having a density of 1 g/cm³.
4. The research focuses solely on the physical aspects of dose distribution, excluding the biological response of dragon fruit to irradiation.