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Article

Gamma irradiation pilot project: Enhancing food safety and export quality in Indonesia

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Abstract: This study aims to evaluate the feasibility of establishing a gamma irradiator pilot project in Indonesia to reduce food loss and food waste, as well as to enhance the value of export commodities. Gamma irradiators have the potential to extend shelf life, improve food safety, and reduce losses during distribution and storage. The research methodology involves weighting to assess the feasibility of location selection, incorporating secondary data analysis and economic value-added analysis. The results indicate that the PUSPIPTEK Serpong location meets all mandatory criteria and nearly all non-mandatory criteria, making it a suitable site for this pilot project. The operation of the gamma irradiator in Serpong has successfully increased the volume of irradiation services, though its utilization is predominantly for export purposes. The main challenges include a negative public perception of irradiated food and a lack of education on its benefits. This study concludes that gamma irradiators are effective in reducing food loss and food waste, as well as increasing the value-added of export commodities. Strong government support and continuous education programs are necessary to improve public acceptance. Future research could focus on long-term evaluations of the impact of gamma irradiators and the development of more effective educational programs.

Keywords: gamma irradiation; pilot project; food loss and waste; value-added exports; Indonesia; consumer acceptance

1. Introduction

A gamma irradiator is a facility or machine that uses gamma rays to sterilize various objects. Gamma rays are electromagnetic radiation with strong penetrating power, capable of passing through solid materials and killing microorganisms such as bacteria, fungi, and viruses. The use of gamma rays in various applications has proven effective in ensuring the cleanliness and safety of products in both the food and medical sectors (Maherani et al., 2016). In this context, gamma irradiation offers an attractive solution to various challenges faced by developing countries like Indonesia (Handayani and Permawati, 2017).

Indonesia has opted for gamma irradiation technology over electron beam (EB) and X-ray irradiation for several key reasons, particularly considering the economic and infrastructural context of the country. One significant factor is the high initial investment required for electron beam technology. Electron beam irradiators demand advanced and costly electron accelerators, which present a substantial financial burden, especially for widespread implementation (Farkas and Mohácsi-Farkas, 2011; Tanzila Sultana et al., 2021). Additionally, the installation and operational complexities of electron beam systems, including precise control and calibration, increase the operational costs and make them less feasible for regions outside Java where technical infrastructure and expertise are limited (Roberts, 2016).

Similarly, while X-ray irradiation offers deep penetration and is effective for a wide range of food products, its commercial use is limited due to several drawbacks. X-ray irradiation involves very high energy levels (5–7.5 MeV), which can exceed what is necessary for effectively killing microorganisms. This excessive energy can damage the food's structure and significantly reduce its quality, making it unsuitable for many food preservation applications (Maherani et al., 2016). Additionally, the dose rate of X-ray photons is considerably higher, which can cause further degradation of food quality (Pillai and Shayanfar, 2017). The operational costs for X-ray generators are high, and maintaining compliance with safety regulations adds further complications (Farkas and Mohácsi-Farkas, 2011). Furthermore, the technology is less explored and implemented in commercial food preservation compared to gamma and electron beam irradiation, partly due to these technical and economic challenges (Maye et al., 2023).

Given these challenges, gamma irradiation emerges as a more practical and economically viable option for Indonesia. Gamma irradiators, typically using Cobalt-60, provide the necessary penetration and efficacy for treating food products without the prohibitive costs and complexities associated with EB and X-ray technologies. This makes gamma irradiation a suitable choice for ensuring food safety and extending shelf life while being adaptable to the diverse geographic and economic conditions across Indonesia.

Food sterilization using gamma irradiation is crucial as it can extend the shelf life of food without the need for chemical preservatives. This technology allows food to be more durable and safer for consumption, which is particularly beneficial in the context of inter-island food transportation in Indonesia (Prabowo and Pudjianto, 2023). In the medical sector, equipment such as syringes, bandages, and surgical instruments can be sterilized using gamma irradiation, which is essential for preventing the spread of infectious diseases in hospitals. Additionally, gamma irradiation can be used to disinfect other materials like books, clothing, and spices, effectively eliminating bacteria and fungi that might be contaminated.

Indonesia, as an archipelagic country, faces significant challenges in inter-island food transportation. It is estimated that 30% of food commodities spoil during transit or are not transported, necessitating solutions for food preservation (Munir and Fadhilah, 2023). Gamma irradiation technology offers a potential solution to this issue by extending the shelf life and ensuring the safety of food. This approach is not only environmentally friendly but also can reduce food waste and enhance national food security. The issues of food loss and food waste impact not only food security but also the economy and environment of Indonesia (Kinanti et al., 2021).

Additionally, there is significant international market potential for the export of gamma-irradiated products from Indonesia, such as cocoa, spices, herbal medicine, and other irradiated food products. Global demand for products free from microbial contamination is increasing, especially in developed countries that enforce stringent food safety regulations (Maherani et al., 2016). With gamma irradiation, Indonesian products can achieve longer shelf lives, reduce waste, and improve supply chain efficiency. This international market potential presents a substantial opportunity for Indonesia to increase national revenue through the export of high-quality, irradiated products.

Several studies indicate that gamma irradiation can significantly reduce food loss and have positive impacts on the economy and environment (Parlato et al., 2014). For instance, reducing food loss is estimated to increase Indonesia's GDP by 0.37% (approximately 88 trillion IDR) by 2030 compared to the business as usual (BAU) scenario. Additionally, reducing food loss has positive environmental impacts, such as decreasing GHG emissions by approximately 14.19 Mt CO2eq by 2030 and reducing the need for agricultural land by 3.37% by 2030 (Malahayati and Masui, 2021).

Other studies show that the application of gamma irradiation technology to food products can enhance their quality and safety, thereby improving their competitiveness in the international market (Ravindran and Jaiswal, 2019). The international market potential for gamma-irradiated products is substantial. Demand from Asian countries such as Japan, South Korea, and Singapore, as well as European countries and the United States, presents significant opportunities for irradiated food products from Indonesia (Farkas and Mohácsi-Farkas, 2011; Roberts, 2016). The advantages of Indonesian products, including high quality and competitive pricing, coupled with advanced irradiation technology, further boost their competitiveness in the international market.

Gamma irradiation can play a crucial role in enhancing Indonesia's exports. By extending shelf life and ensuring food safety, Indonesian products can meet the stringent standards of international markets. This is essential for increasing Indonesia's competitiveness in the global market and strengthening the national economy. This technology can be applied to various key export commodities of Indonesia, such as fruits, vegetables, spices, and seafood. Thus, gamma irradiation not only helps reduce domestic food loss but also opens new opportunities for exporting high-quality products.

The effectiveness of gamma irradiation has been demonstrated in various previous studies. For instance, research indicates that gamma irradiation can significantly reduce the number of pathogenic microorganisms in food products without compromising their nutritional or sensory quality (Ravindran and Jaiswal, 2019; Tejedor-Calvo et al., 2020). Other studies have found that gamma irradiation can extend the shelf life of seafood products up to twice as long as conventional preservation methods (Hocaoğlu et al., 2012).

Given this background, the present study aims to analyze the feasibility of the Indonesian government's policy on the development of a gamma irradiator pilot project from various aspects, including planning and implementation, social and economic impacts, and technological innovation. The construction of this pilot plant is expected to address food loss and food waste issues in Indonesia, enhance the value of abundant commodities in Indonesia, and expand export markets. This study also aims to identify the appropriate location for the pilot project, assess the challenges that may be encountered during implementation, and formulate strategies to overcome these challenges.

This research will focus on several key questions: Has a feasibility study been conducted showing that this pilot project will be successful and economically beneficial? How is the location of the gamma irradiator pilot project determined to meet safety requirements and avoid negative environmental impacts? What is the future of gamma irradiation in Indonesia?

The study is expected to provide valuable contributions to the literature on policy and infrastructure development. Additionally, it is hoped to offer a comprehensive overview of the readiness and potential success of gamma irradiator development in Indonesia and its contribution to food security, food waste reduction, and increasing national revenue from the export of gamma-irradiated commodities.

2. Methodology

This study employs a weighting method to assess the feasibility of location selection and the potential utilization of gamma irradiators to reduce food loss and enhance the export value of various commodities.

2.1. Gamma irradiation process

The gamma irradiation process utilized in this study was conducted using a Cobalt-60 gamma irradiator, known for its high penetration capability and effectiveness in sterilizing various types of food and medical products. The Cobalt-60 source emits gamma rays with energy levels ranging from 1.17 to 1.33 MeV. The irradiator equipment used was a commercial gamma irradiator, Model MCB, manufactured by Izotop Hungary (Hermana et al., 2023). This equipment is equipped with advanced safety and control features to ensure precise dosage and uniform exposure. This facility is equipped with state-of-the-art irradiation technology and adheres to international standards for radiation safety and quality control. The doses applied to the different food groups were determined based on the guidelines provided by the Codex General Standard for Irradiated Food and tailored to the specific requirements of each food type to ensure optimal preservation and safety (Commission, n.d.).

2.2. Secondary data analysis on food loss and food waste and economic potential of gamma irradiation

The secondary data analysis begins with collecting statistical data related to food loss and food waste in Indonesia. This data is sourced from the Central Bureau of Statistics (BPS) for various agricultural commodities such as fruits, vegetables, and grains. Additionally, export data for these commodities is gathered from the Ministry of Trade to understand the export value of agricultural commodities and their processed products from Indonesia.

Trends in food loss and food waste are analyzed over time to identify the products most susceptible to spoilage. A comparison is made between the export values of irradiated and non-irradiated commodities in other countries to determine the potential increase in export value from irradiated products.

Next, an economic value-added analysis is conducted to assess the financial benefits of using gamma irradiation. First, the economic value lost due to food loss and waste during storage and distribution is calculated. This lost value is compared with the cost of gamma irradiation to extend the shelf life of products, thereby determining the potential cost savings.

Subsequently, the economic value lost due to product damage during transportation and storage is calculated. A comparison is made between this lost value and the cost of gamma irradiation to reduce product damage, estimating the potential increase in revenue that can be obtained from using gamma irradiation.

Finally, the additional export value that can be gained from the enhanced quality of irradiated products is calculated. Factors such as higher selling prices, access to new markets, and compliance with international standards are considered in this analysis. By considering all these factors, the potential increase in export revenue from the use of gamma irradiation is calculated.

2.3. Criteria and weighting in selecting the pilot project location

a) Mandatory criteria (40%)

Mandatory criteria include factors that must be met to ensure the location is feasible and can support the project's operations effectively. The first factor is the area size, which has a weight of 20%. The selected location must have a minimum land area of 2 hectares to ensure there is enough space for the construction and operation of the facility. Land availability is given a weight of 10%, emphasizing the importance of ensuring the land is accessible and can be used for the project. The site's location, with a weight of 5%, considers the strategic geographical position of the land to facilitate access and distribution. The site's status, also with a weight of 5%, evaluates the land ownership status to ensure there are no legal or administrative issues that could hinder the project. The licensing process, which has a weight of 10%, includes obtaining permits from the Nuclear Energy Regulatory Agency (BAPETEN) and Environmental Impact Analysis (AMDAL) (Siregar and Utomo, 2019) from the Ministry of Environment and Forestry (KLHK). This criterion ensures that the location meets all the legal and regulatory requirements needed for the construction and operation of a nuclear facility.

b) Non-mandatory criteria (60%)

Non-mandatory criteria include additional factors that enhance the feasibility and efficiency of the selected location. This category has a total weight of 60%, with several sub-criteria within it. First are site conditions, with a weight of 20%. Soil conditions, which are an important part of this category, are given a weight of 8%, evaluating the soil-bearing capacity to ensure it is strong enough to support the facility's structure. Additionally, the availability of laydown areas, with a weight of 4%, ensures there is enough space for temporary storage and heavy equipment maneuvering during construction.

Accessibility is also a crucial factor in the non-mandatory category, with a total weight of 20%. Road access is given a weight of 5%, assessing the ease of access to the location by road. Proximity to highways is also important, with a weight of 5%, to ensure quick and efficient access. Proximity to seaports and airports, each with a weight of 5%, ensures that the location is easily accessible for the shipment of materials and equipment needed.

Environmental factors are also evaluated in the non-mandatory criteria, with a weight of 10%. Mangroves and protected wildlife are given a weight of 5%, ensuring that the location does not disrupt important ecosystems or protected species. Demographics and population distribution are also given a weight of 5%, to ensure that the location does not negatively impact the local population.

Next, supporting facilities are evaluated, with a total weight of 10%. The availability of electricity with a minimum capacity of 1 MVA is given a weight of 5%, ensuring that the facility's energy needs can be met. The specified electricity capacity of 1 MVA is determined based on the combined power requirements of the gamma irradiator and the supporting equipment. A gamma irradiator used in this study typically requires significant power to operate efficiently and safely. The irradiator itself, along with cooling systems, ventilation, lighting, and control systems, contributes to the overall electricity demand. This capacity allows for the smooth functioning of the irradiator and associated systems without risking power shortages or interruptions. Additionally, it accounts for potential future expansions or additional equipment, ensuring flexibility and scalability for increased operational demands or technological upgrades. Water sources for cooling, with a weight of 5%, are also important for the facility's operation.

Finally, construction support factors, with a total weight of 10%, include proximity to quarries (stone mines) and batching plants as well as piling. Each is given a weight of 5%, ensuring that construction materials and support services are easily accessible from the location.

The allocation of 40% for mandatory criteria and 60% for non-mandatory criteria in assessing the feasibility of the gamma irradiator pilot project location is based on a comprehensive evaluation of the critical factors influencing the success of the project. The mandatory criteria, which account for 40% of the total weight, include essential factors such as land area, land availability, site location, site status, and the permitting process. These criteria are fundamental to ensure the project can be initiated and sustained without legal, regulatory, or logistical hindrances. The selection of these criteria as mandatory is aligned with international best practices and regulatory requirements, ensuring the project meets the essential standards for safety and operability (Hermana et al., 2023; Siregar and Utomo, 2019).

On the other hand, the non-mandatory criteria, which make up 60% of the total weight, encompass additional factors that enhance the feasibility and efficiency of the project. These include site conditions, accessibility, environmental considerations, availability of supporting facilities, and construction support factors. Although these criteria are not strictly essential, they significantly contribute to the optimal functioning and long-term success of the facility. By allocating a higher weight to non-mandatory criteria, the assessment ensures that the selected location not only meets the basic requirements but also provides a conducive environment for efficient operations and future expansion (FNCA, 2014; Maherani et al., 2016).

The chosen weighting reflects the balanced approach needed to evaluate both the essential and supportive factors comprehensively. This methodology ensures that the location selection process is robust, taking into account the critical mandatory requirements while also emphasizing the importance of additional factors that enhance operational efficiency and sustainability.

2.4. Methodology limitations

In developing the methodology for the gamma irradiator pilot project, there are several limitations to consider. Given that this project is multi-purpose and designed to meet various market criteria both in Indonesia and internationally, some aspects are not included in this analysis.

First, the calculation of investment costs is not included in this methodology. The primary focus of this analysis is on the potential utilization for reducing food loss and food waste, increasing national revenue through the export of certain commodities, and selecting locations based on mandatory and non-mandatory criteria, without accounting for the detailed costs of facility construction. Although investment costs are important in the project implementation, this aspect is excluded from the analysis scope to maintain consistency and focus on the utilization study and location evaluation.

Second, the detailed aspect of selecting gamma irradiator technology from various global vendors is also not included here. Choosing the right technology is a complex process requiring in-depth technical evaluation, including reliability, efficiency, and compatibility analysis with the specific needs of the project. However, for the purpose of this methodology, the analysis does not include comparison and evaluation of technologies from different vendors. The focus remains on the study of the utilization of gamma irradiators in Indonesia and location criteria that support the project's operational success.

With these limitations, the research methodology remains focused on studying the potential utilization of gamma irradiators in Indonesia and evaluating critical location criteria to support optimal project operations while ensuring market needs and regulations are met. Investment costs and technology selection will be analyzed further in subsequent stages of the project planning and implementation process.

3. Results and discussion

Based on the latest data from the Forum for Nuclear Cooperation in Asia (FNCA, 2014) and recent updates from Vietnam (IIA, n.d.), the number of gamma irradiators in several ASEAN countries, excluding Indonesia, is shown in **Table 1** below.

Table 1. Number of gamma irradiators in ASEAN countries and their uses (FNCA, 2014; IIA, n.d.).

Country	Number of gamma irradiators	Primary uses
Vietnam	5	Food irradiation, medical sterilization, research
Malaysia	2	Food preservation, medical sterilization, industrial applications
Thailand	5	Food safety, medical sterilization, industrial applications
Philippines	2	Medical sterilization, industrial applications

From the table above, it is evident that countries such as Vietnam, Malaysia, the Philippines, and Thailand have more developed gamma irradiator infrastructures compared to Indonesia. These countries use gamma irradiators for various important applications, such as food irradiation, medical sterilization, and research and development.

On the other hand, when the Indonesian government initiated the gamma irradiator pilot project in 2014 (BATAN, 2015), Indonesia only had one commercial gamma irradiator located near Jakarta. This irradiator is owned by foreign investors and focuses on products intended for export.

Ironically, Indonesia faces acute food loss and food waste issues. According to data from the Central Bureau of Statistics (BPS) and several other sources, food loss and food waste in Indonesia amount to 23–48 million tons per year, equivalent to 115–184 kg per capita per year. According to the Ministry of National Development Planning/Bappenas, this food waste could feed 61–125 million Indonesians in need or 29%–47% of the population (Bappenas, 2021).

The commodities that experience the highest food loss in Indonesia are rice, corn, and sweet potatoes. Conversely, the commodities that suffer the most from food waste are rice, fruits, and vegetables. Food loss and food waste in Indonesia result in economic losses amounting to IDR 231–551 trillion per year, equivalent to 4%–5% of the GDP. Additionally, food loss and food waste contribute to increased greenhouse gas emissions (Bappenas, 2021). According to the Food Waste Index 2021, Indonesia is the largest food waste producer in Southeast Asia, with total food waste reaching 20.93 million tons annually (UNEP, 2021).

While corn and sweet potatoes are among the commodities that suffer significant food waste, it is important to recognize that gamma irradiation is not universally applicable to all types of food. These particular commodities typically have lower rates of irradiation application due to their unique preservation methods and storage conditions. For instance, corn and sweet potatoes are often stored in controlled environments where traditional methods such as drying or temperature control are more commonly used to prevent spoilage (Farkas and Mohácsi-Farkas, 2011; Roberts, 2016).

Gamma irradiation is most beneficial for commodities that are highly perishable and susceptible to microbial contamination, such as fresh fruits, vegetables, meat, and seafood. For example, fruits like mangoes and papayas benefit significantly from irradiation as it extends their shelf life and ensures safety from pests and microorganisms (Maherani et al., 2016). Similarly, the irradiation of meat products helps in reducing pathogens and extending shelf life, making it a more suitable application for gamma irradiation (Hocaoğlu et al., 2012; Tejedor-Calvo et al., 2020).

Focusing on these commodities allows for a more targeted approach where the benefits of gamma irradiation can be maximized. It also aligns with international practices where irradiation is applied primarily to high-risk, perishable products that require enhanced preservation techniques to reduce food loss and waste effectively.

This issue underscores the urgency of constructing more gamma irradiators in Indonesia to address food loss and food waste. By adopting gamma irradiation technology, Indonesia can extend the shelf life of food, reduce product spoilage, and enhance food quality and safety. Furthermore, the application of gamma irradiation can help Indonesia achieve sustainable development goals by mitigating economic losses and environmental impacts associated with food loss and food waste.

Table 2 presents the maximum radiation doses recommended for different food groups and their specific purposes. This detailed categorization ensures that the appropriate dose is applied for each type of food, optimizing the benefits of gamma irradiation for food preservation and safety.

Table 2. Maximum radiation dose for food irradiation by food group (BPOM, 2004).

Food group	Purpose	Maximum dose (kGy)
Group 1—Tubers	Inhibit sprouting	0.2
Group 2—Fresh fruits and vegetables (excluding Group 1)	Delay ripening	1.0
	Eradicate insects	1.0
	Extend shelf life	2.5
	Quarantine control	1.0
Group 3—Cereals, processed cereal products, legumes, oilseeds, pulses, dried vegetables, dried fruits	Eradicate insects	1.0
Group 4—Raw fish and seafood and their products (fresh or frozen), frozen frog legs	Reduce specific pathogenic microorganisms	5.0
	Extend shelf life	3.0
	Control parasitic infections	2.0
Group 5—Poultry and meat and their products (fresh or frozen)	Reduce specific pathogenic microorganisms	7.0
	Extend shelf life	3.0
	Control parasitic infections	3.0
Group 6—Dried vegetables, spices, dried herbs, and herbal teas	Reduce specific pathogenic microorganisms	10.0
	Eradicate insects	1.0
Group 7—Dry animal-derived foods	Eradicate insects	1.0

The results and discussion clearly indicate the critical need for developing gamma irradiator infrastructure in Indonesia. Implementing the gamma irradiator pilot project will significantly reduce food loss and food waste, enhance food security, and strengthen the national economy. Additionally, this technology will support efforts to reduce greenhouse gas emissions, aligning with Indonesia's commitments to environmental protection and climate change mitigation.

Food loss and food waste in Indonesia are complex issues involving various factors across the entire food supply chain. The primary causes of food loss and food waste in Indonesia are as follows:

- Inefficient transportation and logistics infrastructure (Mangla et al., 2019; Raut et al., 2018). Poor transportation infrastructure, such as damaged roads and lack of cooling facilities, is a major cause of food spoilage during distribution. Inefficiencies in the logistics chain, such as inadequate storage facilities, also contribute to food loss during transportation. Long delivery times due to traffic congestion and unstable road conditions prolong delivery times and increase the risk of food spoilage. Additionally, a lack of coordination among supply chain actors, such as farmers, traders, distributors, and retailers, can lead to stockpiling and food spoilage. Inadequate standardization and regulation related to food storage, packaging, and transportation exacerbate these issues.
- Poor post-harvest practices (Chegere et al., 2022; FAO, 2011). The lack of infrastructure and technology for harvesting, storing, and transporting crops leads to high spoilage and wastage rates. Farmers often lack adequate

knowledge and skills to manage crops and post-harvest processes effectively, making the produce more susceptible to pests and diseases. Furthermore, limited market access for farmers to sell their produce results in unsold harvests that rot and are wasted.

- Wasteful consumer behavior (Eriksson and Spångberg, 2017). Consumer behavior significantly contributes to food waste. Consumers frequently purchase excessive amounts of food, leading to uneaten food being discarded. They also tend to select food based on appearance, resulting in the disposal of cosmetically imperfect but still edible food. A lack of consumer awareness regarding the importance of reducing food waste and its negative environmental and economic impacts exacerbates this problem.
- Other factors (Cattaneo et al., 2021). Natural disasters such as floods, droughts, and earthquakes can damage crops and harvests, increasing food loss. Government policies that do not support food waste reduction, such as subsidies for certain food products, can also worsen the problem. Moreover, the lack of awareness and knowledge among industry players about the importance of reducing food loss and food waste during transportation and storage contributes to the issue.
- Food loss and food waste in Indonesia are driven by interrelated factors. Poor transportation and logistics infrastructure, inadequate pre-harvest practices, wasteful consumer behavior, and other factors such as natural disasters and unsupportive government policies all play roles in the high levels of food loss and waste. Addressing these issues requires a comprehensive and coordinated approach involving all stakeholders in the food supply chain. Implementing technologies like gamma irradiators can be part of the solution to reduce food loss and enhance food security in Indonesia.

3.1. Efforts of the Indonesian government in addressing food loss and food waste

The Indonesian government has undertaken several significant measures to address food loss and food waste (Asriyana Suryana et al., 2023):

- National strategy. The government has established a national strategy for the reduction of food loss and food waste, encompassing various coordinated initiatives aimed at reducing wastage throughout the food supply chain.
- Infrastructure and technology. Enhancement Investments have been made to improve infrastructure and technology for food storage and processing. This includes the construction of cold storage facilities and the development of technologies that can extend the shelf life of food products.
- Public education. Educational programs have been launched to raise public awareness about the importance of reducing food loss and food waste. The government collaborates with various organizations to disseminate information and increase public awareness about the negative impacts of food wastage and ways to reduce it.

Although these three measures have been significantly implemented over the past five years, there are crucial aspects that have not yet been fully addressed and should be pursued in parallel:

- Strengthening coordination among supply chain actors (Spang et al., 2019; Teigiserova et al., 2019). Improved coordination between farmers, traders, distributors, and retailers is needed to ensure smooth food flow and reduce wastage. This includes effective communication and efficient logistical arrangements.
- Standardization and regulation (Ishangulyyev et al., 2019). Adequate standards and regulations regarding food storage, packaging, and transportation are required. Clear standards can help reduce damage during distribution and storage processes.
- Enhancing farmer knowledge and skills (Chegere et al., 2022). Education and training for farmers need to be enhanced to improve their knowledge and skills in managing crops and post-harvest processes. With better knowledge, farmers can reduce crop damage and increase production efficiency.

With collaborative efforts from various stakeholders and strong policy support from the government, it is hoped that food loss and food waste in Indonesia can be significantly reduced. This will improve food security and nutrition, help preserve the environment, and reduce the economic losses caused by food wastage.

3.2. Comparison of food product export values in ASEAN countries

In terms of food product exports, Indonesia lags behind Thailand and Vietnam. **Table 3** below shows the export values of major commodities in ASEAN countries in 2022.

Table 3. Export values of major commodities in ASEAN countries (2022) (ASEAN, 2023).

Country	Major export commodities	Export value (USD billion)
Thailand	Rice, rubber, tapioca, shrimp	35.1
Vietnam	Rice, coffee, shrimp, seafood	34.5
Indonesia	Palm oil, shrimp, coffee, tea	24.9
Malaysia	Palm oil, rubber, wood products	22.8
Philippines	Bananas, palm oil, shrimp	11.7
Cambodia	Rice, corn, wood products	4.8
Myanmar	Soybeans, corn, rice	3.9
Laos	Coffee, wood, wood products	1.6
Brunei Darussalam	Oil and gas products	1.2
Singapore	Electronics, chemical products	0.1

From the table, it is evident that Indonesia relies heavily on palm oil exports. However, the export value of Indonesia's food products is still behind that of Thailand and Vietnam, which have higher export values.

Specifically, for fruits, vegetables, processed foods, spices, and seafood, the comparison of food product export values in ASEAN countries based on product categories in 2022 is shown in **Table 4** below.

Table 4. Food product export values in ASEAN countries by product category (2022) (ASEAN, 2023).

Product	Largest exporting country	Export value (USD billion)
Fruits	Thailand	6.5
Vegetables	Thailand	4.2
Processed Foods	Thailand	7.1
Spices	Indonesia	1.3
Seafood	Vietnam	10.3

Several conclusions can be drawn from this table:

- Thailand is the largest exporter of fruits, vegetables, and processed foods in ASEAN. With an export value of USD 6.5 billion for fruits, USD 4.2 billion for vegetables, and USD 7.1 billion for processed foods, Thailand leads in these categories.
- Vietnam is the largest exporter of seafood in ASEAN, with an export value reaching USD 10.3 billion.
- Indonesia is the largest exporter of spices in ASEAN, with an export value of USD 1.3 billion.

Although Indonesia is the largest exporter of spices, the export value of its other food commodities remains behind that of Thailand and Vietnam. This indicates that Indonesia needs to enhance the competitiveness and diversification of its food export commodities to compete with other ASEAN countries. This effort includes improving infrastructure, technology, and better coordination across the entire food supply chain.

3.3. Indonesian government strategy in infrastructure and technology improvement

One of the strategies to address food loss and food waste is the enhancement of infrastructure and technology. In terms of transportation, the government has extended the Trans Java, Trans Sumatra, Trans Kalimantan, Trans Sulawesi, and Trans Papua toll roads. Over the past 10 years, 26 airports have been built, and 51 ports have been rehabilitated. To improve inter-island connectivity, 36 maritime toll routes have been established, aiming to reduce commodity price disparities between major islands and remote islands, especially in Eastern Indonesia (Mandasari et al., 2019).

Drawing lessons from other ASEAN countries, the Indonesian government has begun to introduce gamma irradiator technology as a solution to food loss and food waste problems and to enhance the export of food commodities (BATAN, 2015).

Food safety enhancement is crucial for high-risk products such as meat and dairy and significantly contributes to overall food security. Gamma irradiation technology plays a crucial role in pest control, particularly in the context of phytosanitary treatment for tropical fruits. This technology is used to reduce insect and pest populations in fruits such as mangoes, papayas, and guavas, which are often subject to international quarantine regulations. By effectively eliminating pests, gamma irradiation ensures that these fruits can be safely exported without the risk of introducing invasive species to other countries (Farkas and Mohácsi-Farkas, 2011; Maherani et al., 2016)

However, it is important to note that the commercial application of gamma irradiation for pest control is primarily limited to tropical fruits and is not widely used for grains or other agricultural products. This limitation is due to the specific requirements and regulations for phytosanitary treatments in international trade, which focus on preventing the spread of pests through high-risk commodities like fruits. The effectiveness of gamma irradiation in maintaining the quality and safety of these products has been well-documented, ensuring compliance with international standards and facilitating market access (Roberts, 2016; Tanzila Sultana et al., 2021).

Therefore, while gamma irradiation is a valuable tool for reducing losses due to pest attacks during storage and transportation of tropical fruits, its application for other agricultural products remains limited. Future research and development could explore the potential for expanding the use of this technology to a broader range of commodities, addressing specific pest control challenges in different agricultural sectors.

Gamma irradiation also preserves the nutritional and organoleptic quality (taste, aroma, and texture) of food products. By preventing changes in color, taste, and texture, this technology ensures consumer satisfaction with the products they purchase while maintaining the nutritional value of the food. Moreover, gamma irradiation enables the export of commodities to countries with strict quarantine regulations. By ensuring that products are free from pests and pathogens, this technology opens new market access and enhances the competitiveness of Indonesian products in international markets.

Furthermore, gamma irradiation increases the added value of products by extending shelf life and improving quality. This not only reduces economic losses due to food loss but also enhances potential revenue from the sale of high-quality products.

Here is a simple example of the field application of gamma irradiation technology to reduce food loss and food waste in Indonesia: Gamma irradiation can be used to extend the shelf life of mangoes produced in Java. By using this technology, mangoes can be sterilized from microbes and enzymes that cause spoilage, extending their shelf life by 2–3 weeks (Maherani et al., 2016). This allows mangoes to be distributed to Papua without damage during the long journey. As a result, the mangoes remain fresh and consumable upon arrival, reducing waste and increasing the availability of fresh fruit in regions far from the production centres (FNCA, 2014). Fish is a food commodity vulnerable to bacterial contamination and harmful microorganisms, which can cause foodborne diseases. Gamma irradiation can be applied to fish produced in Sulawesi to kill pathogens and parasites, thus enhancing food safety (Ravindran and Jaiswal, 2019). With this technology, fish can be distributed to Sumatra without the risk of foodborne diseases. Consumers in Sumatra can enjoy safe and high-quality fish, while producers in Sulawesi can expand their markets. Transporting beef often requires refrigeration facilities to prevent spoilage during the journey (Roberts, 2016). While gamma irradiation is promising in extending the shelf life of beef by reducing pathogenic microorganisms such as E. coli and Salmonella, it is only one aspect of a comprehensive preservation strategy. Proper handling, storage, and other food safety interventions are still necessary to ensure the overall quality and safety of irradiated (Farkas and Mohácsi-Farkas, 2011; Hashim et al., 2024; Roberts, 2016; Tejedor-Calvo et al., 2020). With this technology, beef produced in Bali can be irradiated to kill harmful bacteria and microorganisms, thus extending its shelf life. The beef can then be distributed to East Nusa Tenggara with less dependence on refrigeration facilities, reducing transportation costs and the risk of spoilage during the journey (Maherani et al., 2016; Tejedor-Calvo et al., 2020)

With the application of gamma irradiation technology, Indonesia can effectively reduce food loss and food waste, enhance food safety, and extend the shelf life of various food commodities. This not only benefits producers and consumers but also contributes to national food security and reduces the environmental impact of food waste.

3.4. Added value and market expansion with gamma irradiation

The use of gamma irradiation technology can significantly add value to Indonesia's exported commodities while opening new market access that requires irradiation for imported fruits. **Table 5** shows the potential export commodities of Indonesia that can be enhanced with gamma irradiation.

Table 5. Potential export commodities of Indonesia that can be enhanced with gamma irradiation (Badan Pusat Statistik, 2023).

Commodity	Export value (USD)	Major destination countries
Mango	1.2 billion	China, Vietnam, Japan, South Korea
Pineapple	500 million	China, USA, Japan, Singapore
Papaya	300 million	China, Vietnam, Japan, South Korea
Onion	200 million	Thailand, Vietnam, Singapore, Malaysia
Potato	150 million	Japan, South Korea, Taiwan, Singapore
Mushroom	100 million	Japan, South Korea, Taiwan, Singapore
Beef	2 billion	China, Vietnam, Japan, South Korea
Fish	7 billion	Japan, USA, China, EU
Egg	500 million	Japan, South Korea, Taiwan, Singapore
Cocoa	2 billion	USA, Germany, Netherlands, Belgium

3.4.1. Benefits of gamma irradiation on export commodities

- Added value enhancement

The application of gamma irradiation on export commodities such as mangoes, papayas, and others can extend product shelf life, maintain quality, and ensure safety from pests and pathogens. This technology not only helps reduce food loss and food waste but also increases product value. For example:

- Mangoes and papayas: Gamma irradiation can extend shelf life by several weeks, enabling wider distribution without quality degradation. This is crucial for markets like China, Japan, and South Korea, which have strict import requirements for fruits.
- Beef and fish: Gamma irradiation kills harmful bacteria and pathogens, ensuring the products remain safe and fresh during long-distance shipments to major destination countries like China, Japan, and the European Union.

- Market Expansion

Many countries require imported fruits to be irradiated before entry to prevent the spread of pests and plant diseases. The following **Table 6** outlines some countries with such irradiation requirements:

Table 6. Countries requiring irradiation for imported fruits (Maherani et al., 2016).

Region	Country	Irradiation requirements
Asia	Japan	All imported fruits, except bananas, must be irradiated
	South Korea	All imported fruits, except pineapples, must be irradiated
	Taiwan, China, Singapore	All imported fruits, except bananas, oranges, and grapefruits, must be irradiated
America	USA	Certain imported fruits, such as mangoes, grapefruits, and papayas, must be irradiated
	Canada	Certain imported fruits, such as mangoes, grapefruits, and papayas, must be irradiated
Europe	European Union	All imported fruits from non-EU countries must be irradiated
	Australia	All imported fruits, except bananas, oranges, and grapefruits, must be irradiated
	New Zealand	All imported fruits, except bananas, oranges, and grapefruits, must be irradiated

By meeting these irradiation requirements, Indonesia can access new markets and increase export volumes to these countries. For instance, irradiated mangoes and papayas can easily enter the Japanese and South Korean markets, while other products like fish and beef can penetrate the European Union markets more efficiently.

The implementation of gamma irradiation technology on Indonesian export commodities will not only increase product value through extended shelf life and improved quality but also open access to new markets with irradiation requirements. Thus, gamma irradiation can be a strategic tool to enhance Indonesia's competitiveness in the international market, reduce food loss and waste, and boost national income from the agricultural and fisheries sectors.

3.4.2. Savings and benefits from using gamma irradiation on Indonesian export commodities

The use of gamma irradiation on Indonesian export commodities can provide significant savings and increase overall economic benefits. Several studies have shown the positive impact of this technology on enhancing export value and reducing food loss and waste. The following narrative explains the potential savings and benefits of using gamma irradiation on certain commodities.

A study found that gamma irradiation can increase the export value of mangoes by up to 20% (Tanzila Sultana et al., 2021). By extending product shelf life and ensuring safety and quality, gamma irradiation can enhance product competitiveness in the international market.

Suppose the economic loss due to food loss and food waste of mangoes in Indonesia reaches Rp 10 trillion per year. If gamma irradiation can extend the shelf life of mangoes by 2 weeks and increase their selling value by 20%, the potential cost savings can reach Rp 2 trillion per year. The cost of gamma irradiation for mangoes ranges from Rp 500 to 2500 per kg. Assuming an average irradiation cost of Rp 1000 per kg and an average mango consumption in Indonesia of 10 kg per person per year, the total irradiation cost for the entire Indonesian population reaches Rp 10 trillion per year.

In this example, although the total irradiation cost for the entire Indonesian population reaches Rp 10 trillion per year, the potential cost savings from reducing food loss and increasing the selling value of mangoes reaches Rp 2 trillion per year. This indicates that despite the high irradiation cost, the economic benefits are more significant. Reducing food loss and increasing export value not only boosts farmer and exporter income but also contributes to national economic stability and food security.

Overall, the use of gamma irradiation on Indonesian export commodities can be an effective solution to reduce economic losses due to food loss and food waste. By extending shelf life, maintaining product quality, and meeting international market requirements, this technology can open new market opportunities and enhance the competitiveness of Indonesian products in the global market.

The Indonesian government recognizes that there should be gamma irradiators at major ports on the main islands (Hermana et al., 2023). However, the government also understands the hesitation from the private sector to take the initiative in building such facilities. This hesitation is due to several key factors.

Regulations related to the use of nuclear technology, including gamma irradiators, often pose challenges. Some companies may be concerned about licensing, safety, and environmental impact. Additionally, public perception of nuclear radiation also affects the acceptance of this technology. Concerns about health and environmental impacts make the public skeptical about using gamma irradiators (Ridwan et al., 1979).

Moreover, the construction and operation of gamma irradiators require significant initial investment. Private companies may be reluctant to take financial and technical risks to build and operate these facilities. The high costs and uncertainty about return on investment make many companies hesitant to get involved.

The domestic market for irradiated products is also relatively low (Hermana et al., 2023). This is due to several factors, such as a lack of consumer education about the benefits of irradiation and competition with cheaper non-irradiated products. The lack of awareness about the benefits of gamma irradiators results in lower demand for irradiated products than expected.

Considering these obstacles, the government decided to build a pilot gamma irradiator project (BATAN, 2015). The goal is to demonstrate the benefits of this technology, address negative perceptions, and encourage private-sector participation in the future. The government hopes that with the establishment of this pilot facility, there will be increased awareness and acceptance of gamma irradiation technology and increased market demand for irradiated products.

3.5. Selection of the gamma irradiator pilot project location

When the Indonesian government initiated the construction of a gamma irradiator pilot project in 2014, several key requirements had to be met (BATAN, 2015):

- Safety and security. As an irradiation facility, this project must strictly adhere to safety and security regulations to protect the public and the environment. High safety standards are essential to avoid radiation risks and ensure safe operations.
- Multi-purpose. The facility must serve as an exemplary model capable of addressing various challenges in Indonesia, making it a multi-purpose installation. This means the facility must handle various types of products and irradiation applications, including food, medical, and industrial uses.
- Timely completion. The construction must not be delayed due to non-technical issues. The government is committed to avoiding administrative and bureaucratic obstacles that could hinder the project's progress.
- Government funding and management. The government fully funds the construction of this facility and will manage it entirely once completed. This ensures adequate financial support and coordinated management of the project.
- International collaboration. To assure the public and enhance the project's credibility, international collaboration is established with countries experienced in constructing gamma irradiators. This collaboration helps ensure the facility meets international standards and gains the necessary technical expertise.

As a pilot project that needs to be utilized promptly, the government considered two potential locations: Tanjung Priok Port in Jakarta and the science and technology Area of PUSPIPTEK in Serpong, approximately 30 km from Jakarta. The selection of these locations is strategic due to their respective advantages in terms of accessibility and infrastructure.

3.5.1. Mandatory criteria analysis for Tanjung Priok location

For the mandatory criteria analysis, all criteria must be met with a score of 100%. Based on the analysis, the Tanjung Priok location failed to meet all mandatory criteria, thereby disqualifying it as a proposed location.

Tanjung Priok, being the main port in Indonesia, has sufficient land to meet the minimum area requirement of 2 hectares. This indicates that the available land in Tanjung Priok meets the area criterion. Additionally, the land in Tanjung Priok is owned and managed by various parties, including the Ministry of Transportation, PT. Pelindo (a state-owned enterprise), and private entities. Despite this, suitable land is available for the project, fulfilling the land availability criterion.

The position and location of the land in Tanjung Priok are very strategic, automatically meeting various needs at the port, including accessibility and distribution. Therefore, the site location in Tanjung Priok is considered appropriate and meets the established criteria. The land ownership status in Tanjung Priok involves various parties; however, no significant issues are hindering the land's use for this project, thus meeting the site status criteria.

However, the main challenge in Tanjung Priok is the permitting process. The Tanjung Priok location fails to meet the stringent and complex permitting criteria primarily due to several regulatory and administrative challenges. One of the significant hurdles is obtaining the necessary permits from multiple authorities. The Nuclear Energy Regulatory Agency (BAPETEN) requires comprehensive documentation and strict adherence to safety protocols for facilities involving radiation. The environmental impact analysis (AMDAL) from the Ministry of Environment and Forestry also presents a rigorous process that evaluates the potential environmental impacts of the facility. This process involves detailed studies, public consultations, and multiple stages of approval, which can be time-consuming and complex.

Additionally, the Tanjung Priok area is a major port with heavy industrial and logistical activities. This setting increases the complexity of ensuring that the gamma irradiator facility does not interfere with existing operations and complies with local zoning and land use regulations. The land ownership status in Tanjung Priok involves multiple stakeholders, including government agencies and private entities, which complicates the process of securing clear and uncontested rights to use the land for the project.

Given these challenges, the permitting process at Tanjung Priok is not only lengthy but also fraught with potential legal and administrative hurdles. Therefore, despite the strategic advantages of the location, the difficulties in navigating the permitting landscape make it an unsuitable choice for the gamma irradiator pilot project.

Given that all mandatory criteria must be met with a score of 100%, the Tanjung Priok location fails to meet the stringent and complex permitting criteria. Therefore, Tanjung Priok cannot be selected as a proposed location for the gamma irradiator pilot project.

Table 7. Mandatory criteria weighting for Tanjung Priok location.

Criteria	Weight (%)	Score (%)	Weighted score
Land area	20	100	20
Availability	10		
Site location	5	100	5
Site status	5	100	5
Permitting process	10	50	5
Total mandatory	40		35

As shown in **Table 7**, the score for the permitting process criterion only reaches 50% and does not meet the mandatory requirement of 100% for all criteria, Tanjung Priok is automatically disqualified as a proposed location for the gamma irradiator pilot project.

Subsequently, an analysis of the alternative location, the science and technology area of PUSPIPTEK Serpong, is needed to ensure that all mandatory criteria can be met with a score of 100%.

3.5.2. Analysis of the PUSPIPTEK science and technology area location for mandatory criteria

The following is a weighting analysis for the mandatory criteria of the PUSPIPTEK science and technology area as a candidate location for the gamma irradiator pilot project.

As the largest science and technology area in Indonesia, PUSPIPTEK has sufficient land to meet the minimum area requirement of 2 hectares. This indicates that PUSPIPTEK can provide adequate land for this project, fulfilling the area criterion.

The land at PUSPIPTEK is owned and managed by the Ministry of Research and Higher Education, ensuring that the land is suitable and available for this project. With clear ownership status and no significant obstacles, PUSPIPTEK meets the land availability criteria.

The position and location of the land at PUSPIPTEK are highly strategic, being close to laboratory facilities and a nuclear research reactor. The proximity to these facilities provides significant added value to the project, ensuring that this location is strategic and suitable for various nuclear technology research and development purposes.

The land ownership status at PUSPIPTEK is clear and managed by the Ministry of Research and Higher Education, with no significant issues hindering the use of the land for this project. With unproblematic ownership status, PUSPIPTEK meets the site status criteria.

The permitting process at PUSPIPTEK is also an added advantage. The Environmental Impact Analysis (AMDAL) is already available as it is part of the existing nuclear facilities, and the permitting process for construction, commissioning, and operation will be expedited following other nuclear and radiation facilities in the area. This ensures that the permitting process can be completed quickly and efficiently, meeting the established criteria.

Overall, the PUSPIPTEK Serpong location meets all mandatory criteria well, making it a very suitable site for the construction of the gamma irradiator pilot project, as shown in **Table 8**.

Table 8. Mandatory criteria weighting for PUSPIPTEK science and technology area location.

Criteria	Weight (%)	Score (%)	Weighted score
Land area	20	100	20
Availability	10		
Site location	5	100	5
Site status	5	100	5
Permitting process	10	100	10
Total mandatory	40		40

From the analysis above, the total weighted score for the mandatory criteria at the PUSPIPTEK science and technology Area location is 40 out of 40. This location meets all mandatory criteria with a score of 100%, making it highly suitable for consideration as the site for the gamma irradiator pilot project.

Although the PUSPIPTEK Serpong area is suitable from a mandatory criteria perspective, a non-mandatory analysis is needed to determine the strengths and weaknesses of this location.

3.5.3. Analysis of non-mandatory criteria for the PUSPIPTEK Serpong science and technology area

- Site conditions. The soil conditions at PUSPIPTEK Serpong are favorable, having been used for various research and technology development facilities. The site also offers ample space for laydown and temporary storage, providing sufficient room for maneuvering heavy equipment during construction. Additionally, the location has a proven track record of supporting high-tech projects, demonstrating its infrastructure readiness and soil suitability.
- Accessibility. Road access to PUSPIPTEK Serpong is excellent, with an adequate network of roads for transporting materials and personnel. The location is also close to highways connecting Serpong to Jakarta and other nearby cities, facilitating distribution and logistics. Although not directly adjacent to a seaport, efficient land transport access to Tanjung Priok Port and other ports is available. Proximity to Soekarno-Hatta International Airport also eases air transport for quick deliveries and international logistics.
- Environmental. There are no mangrove plants or protected wildlife in the area, thus avoiding any negative impact on critical ecosystems. The site is situated within a science and technology area, separate from dense residential areas, reducing the risk of negative impacts on the local population.
- Facility. Adequate electricity supply is available, ensuring sufficient power for facility operations. Water sources are also accessible for cooling and operational needs.
- Supporting. The location is close to a quarry that provides construction materials. Additionally, the proximity to the batching plant and piling facilities supports construction activities.

Table 9. The weighting of non-mandatory criteria for the PUSPIPTEK science and technology area location.

Criteria	Weight (%)	Score (%)	Weighted score
Site conditions	20	100	20
-Soil conditions	8	100	8
-Laydown area	4	100	4
-Other factors	8	100	8
Accessibility	20	100	20
-Roads	5	100	5
-Highway	5	100	5
-Sea ports	5	80	4
-Airports	5	100	5
Environmental	10	100	10

Table 9. (*Continued*).

Criteria	Weight (%)	Score (%)	Weighted score
-Mangroves and wildlife	5	100	5
-Demography and population distribution	5	100	5
Facility	10	100	10
-Electricity	5	100	5
-Water source	5	100	5
Supporting	10	100	10
-Quarry	5	100	5
-Batching plant and piling	5	100	5
Total non-mandatory	60		59

From the analysis above, as shown in **Table 9**, the total weighted score for the non-mandatory criteria at the PUSPIPTEK science and technology area location is 59 out of 60. This location almost entirely meets all non-mandatory criteria, making it an excellent candidate for the gamma irradiator pilot project.

With these considerations, and following the selection of vendors and technology, construction of the gamma irradiator pilot project began in 2016. The project's design and construction were 85% contributed by Indonesian human resources, with the remaining input from Hungary. As with the construction of nuclear and radiation facilities, various challenges such as seismology and geotechnics arose, but all were successfully addressed.

3.6. Challenges and future of gamma irradiators in Indonesia

The gamma irradiator pilot project commenced operations in 2017(Hermana et al., 2023), exactly two years after it was initiated by the government, as shown in **Figure 1**. The operation has been running smoothly, with data from the facility's management indicating an increase in irradiation service volume from 626 tons in 2018 to 1126 tons in 2020. However, a significant challenge faced in the utilization of this irradiator is that 65% of the irradiated commodities are for export purposes, with the remaining 35% for domestic needs. Initially, the project emphasized domestic utilization over export purposes.

This discrepancy is attributed to the perception among some members of the public that irradiated food commodities are as dangerous as radioactive materials, leading to widespread fear. There is even a belief that irradiated food is more hazardous than chemically preserved food, which often lacks proper regulation. Therefore, continuous public education programs about the safety and benefits of gamma irradiation are essential. This concern is not unique to Indonesia; other countries introducing irradiation technology for food have encountered similar issues.

The lack of consumer knowledge and education about gamma irradiation technology and its benefits causes many consumers to misunderstand and associate irradiation with dangerous radioactivity. This misinformation can lead to fear and distrust of irradiated products.

Figure 1. Exterior view of the gamma irradiator pilot project facility.

Risk perception is also a significant factor. Consumers tend to be more concerned about the risks associated with new technology, including gamma irradiation, than the risks recognized by experts. These concerns are related to potential negative side effects of irradiated food, such as long-term health risks or changes in the nutritional properties of the food.

Distrust in this technology often stems from ineffective communication between scientists, producers, and consumers. Consumers unfamiliar with the irradiation process are more likely to be influenced by misinformation or myths.

To address this distrust, it is crucial to educate consumers about the safety and benefits of gamma irradiation technology. Clear and accurate information can help change negative perceptions and increase consumer acceptance of irradiated products.

Clear and transparent labelling on irradiated products is vital to provide consumers with the necessary information to make informed decisions. The RADURA symbol is an example of an effort to identify irradiated products and provide consumers with a sense of security.

Social and cultural factors also play a significant role in the acceptance of new technology. Some consumers may be influenced by negative perceptions from their social environment or cultural norms that emphasize the consumption of “natural” foods. Therefore, educational programs involving various stakeholders, including community leaders and influencers, can be very effective in changing these perceptions.

Retailers play a crucial role in introducing and marketing irradiated products to consumers. By offering choices to consumers and explaining the benefits of irradiated food, retailers can help increase consumer acceptance and trust. Partnerships between the government, producers, and retailers can enhance transparency and provide consumers with a sense of security.

Encouragingly, the successful construction and operation of the pilot project have spurred interest from several regions to build similar facilities. The Provincial Government of East Kalimantan, for instance, aims to construct a gamma irradiator similar to the one in Serpong (Bridr Kaltim, n.d.). The construction of the irradiator facility in East Kalimantan is necessary to stimulate economic growth, particularly to enhance the national economy and competitiveness, and to support the establishment of the new capital city (IKN) Nusantara in East Kalimantan Province. The irradiation service capacity analysis is determined using data obtained from previous studies. The target market encompasses the regions of East Kalimantan, South Kalimantan, Central Kalimantan, North Kalimantan, and parts of Sulawesi, including Gorontalo. The local government of East Kalimantan estimates that irradiation services will be utilized for approximately 72,156.67 tons per year. Other regions, such as West Kalimantan, Bali, West Sumatra, and Bangka Belitung, are projected to follow suit (Hermana et al., 2023; Satmoko, 2020).

Although the gamma irradiator pilot project has yet to show significant reductions in food loss and food waste or increases in export commodities, the emerging interest from several regions in building gamma irradiators is expected to have a positive impact on Indonesia's policies in the next ten years.

4. Conclusion

This study aimed to analyze the feasibility of establishing a gamma irradiator pilot project in Indonesia, identify the appropriate location, evaluate the social and economic impacts, and assess the challenges encountered during implementation. The primary objectives were to reduce food loss and food waste, enhance the value of export commodities, and strengthen national food security.

The study found that gamma irradiators have significant potential in addressing food loss and food waste in Indonesia, as well as in improving the quality and value of export commodities. The pilot project established at PUSPIPTEK Serpong demonstrated an increase in irradiation service volume from 626 tons in 2018 to 1126 tons in 2020. The location analysis indicated that PUSPIPTEK Serpong met all mandatory criteria and nearly all non-mandatory criteria, making it an excellent location for this pilot project.

These findings are crucial as they show that gamma irradiators can significantly reduce economic losses due to food loss and food waste. This technology can also open new market opportunities for irradiated Indonesian commodities, meet stringent international market standards, and enhance the competitiveness of Indonesian products. Establishing such facilities in various regions can stimulate regional and national economic growth and support food security.

Based on the results, it can be concluded that gamma irradiators are effective in reducing food loss and food waste and in enhancing the value of export commodities. PUSPIPTEK Serpong is an ideal location for the gamma irradiator pilot project. The main challenges in utilizing this technology are the public perception of the safety of irradiated food and the lack of knowledge about its benefits. Strong government support and continuous educational programs are essential to increase public and private sector acceptance of gamma irradiation technology.

Future research should focus on long-term evaluations of the impact of gamma irradiators on food loss, food waste, and the added value of export commodities. Developing more effective educational programs to enhance public acceptance of gamma irradiation technology is also necessary. Comparative studies between various irradiation technologies and their efficiency in reducing food loss and food waste can provide additional insights. Additionally, research on the social and economic impacts of building gamma irradiator facilities in different regions of Indonesia will be highly beneficial.

Thus, this study provides a strong foundation for the development and implementation of gamma irradiator technology in Indonesia to reduce food loss and food waste and to enhance the competitiveness of export commodities in the international market.

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References

ASEAN. (2023). Asean Statistical Yearbook 2023. Available online: https://www.aseanstats.org/wp-content/uploads/2023/12/ASYB-2023-v1.pdf (accessed on 2 June 2023).

Asriyana Suryana, E., Wiryadi Effendi, M., & Luna, P. (2023). Challenges and Strategies for Food Waste Reduction Policy in Indonesia. Forum Penelitian Agro Ekonomi, 41(1), 1–14.

Badan Pusat Statistik. (2023). Statistical Year Book of Indonesia 2023. Available online: https://www.bps.go.id/publication/2020/04/29/e9011b3155d45d70823c141f/statistik-indonesia-2020.html (accessed on 4 June 2023).

Bappenas. (2021). Study Report: Food Loss and Waste in Indonesia, Supporting the Implementation of Circular Economy and Low Carbon Development. Available online: https://grasp2030.ibcsd.or.id/2022/07/07/bappenas-study-report-food-loss-and-waste-in-indonesia-supporting-the-implementation-of-circular-economy-and-low-carbon-development/

BATAN. (2015). BATAN Strategic Plan 2015–2019. Available online: https://karya.brin.go.id/id/eprint/1052/1/Salinan Perka Renstra Rev 3.1.pdf (accessed on 6 June 2023).

BPOM. (2004). Guidelines Food Irradiation Authorization in General or Based on Food Group. National Agency of Drug and Food Control.

Bridr Kaltim. (n.d.). Kick-Off Meeting for the Implementation of Feasibility Study of Gamma Irradiator Nusantara (Indonesian). Available online: https://brida.kaltimprov.go.id/artikel/kick-off-meeting-pelaksanaan-feasibility-study-iradiator-gamma-nusantara (accessed on 12 June 2023).

Cattaneo, A., Sánchez, M. V., Torero, M., et al. (2021). Reducing food loss and waste: Five challenges for policy and research. Food Policy, 98, 101974. https://doi.org/10.1016/J.FOODPOL.2020.101974

Chegere, M. J., Eggert, H., & Söderbom, M. (2022). The Effects of Storage Technology and Training on Postharvest Losses, Practices, and Sales: Evidence from Small-Scale Farms in Tanzania. https://doi.org/10.1086/713932, 70(2), 729–761. https://doi.org/10.1086/713932

Commission, C. A. (n.d.). Codex General Standard for Irradiated Food. Available online: https://www.fao.org/input/download/standards/16/CXS_106e.pdf (accessed on 7 June 2023).

Eriksson, M., & Spångberg, J. (2017). Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets. Waste Management, 60, 786–799. https://doi.org/10.1016/J.WASMAN.2017.01.008

FAO. (2011). Global food losses and food waste—Extent, causes and prevention. In: Food Loss and Food Waste: Causes and Solutions. Edward Elgar Publishing.

Farkas, J., & Mohácsi-Farkas, C. (2011). History and future of food irradiation. Trends in Food Science & Technology, 22(2–3), 121–126. https://doi.org/10.1016/J.TIFS.2010.04.002

FNCA. (2014). FNCA Consolidated Report on Radiation Safety (Issue March). Available online: https://www.fnca.mext.go.jp/english/rwm/FNCA_RS002.pdf (accessed on 2 June 2012).

Handayani, M., & Permawati, H. (2017). Gamma irradiation technology to preservation of foodstuffs as an effort to maintain quality and acquaint the significant role of nuclear on food production to Indonesia society: A Review. Energy Procedia, 127, 302–309. https://doi.org/10.1016/j.egypro.2017.08.112

Hashim, M. S., Yusop, S. M., & Rahman, I. A. (2024). The impact of gamma irradiation on the quality of meat and poultry: A review on its immediate and storage effects. Applied Food Research, 4(2), 100444. https://doi.org/10.1016/j.afres.2024.100444

Hermana, F., Saptowati, H., Satmoko, A., et al. (2023). Merah Putih Gamma Irradiator; Nuclear Technology Innovation of Indonesian Pride (Indonesian). Available online: https://books.google.co.id/books?hl=en&lr=&id=J_DnEAAAQBAJ&oi=fnd&pg=PA1&dq=info:nBH35WXvrJoJ:scholar.google.com&ots=Ip3hzXKnzM&sig=ykEKdb14xssGKdrF89hyRXy2ahQ&redir_esc=y#v=onepage&q&f=false (accessed on 10 June 2023).

Hocaoğlu, A., Sükrü Demirci, A., Gümüs, T., et al. (2012). Effects of gamma irradiation on chemical, microbial quality and shelf life of shrimp. Radiation Physics and Chemistry, 81(12), 1923–1929. https://doi.org/10.1016/J.RADPHYSCHEM.2012.07.017

IIA. (n.d.). New irradiation center in Vietnam. Available online: https://iiaglobal.com/iia-news/new-irradiation-center-in-vietnam/ (accessed on 15 June 2023).

Ishangulyyev, R., Kim, S., & Lee, S. H. (2019). Understanding food loss and waste-why are we losing and wasting food? Foods, 8(8), 297. https://doi.org/10.3390/foods8080297

Kinanti, A. A. P., Heidra, T. C., & Masjud, Y. I. (2021). The Raising Concern of Food Waste and Food Loss in Indonesia to Achieve a Sustainable Consumption. FIRM Journal of Management Studies, 6(2), 124. https://doi.org/10.33021/firm.v6i2.1164

Maherani, B., Hossain, F., Criado, P., et al. (2016). World market development and consumer acceptance of irradiation technology. Foods, 5(4), 1–21. https://doi.org/10.3390/foods5040079

Malahayati, M., & Masui, T. (2021). Potential impact of introducing emission mitigation policies in Indonesia: how much will Indonesia have to spend? In: Mitigation and Adaptation Strategies for Global Change. Springer Netherlands. https://doi.org/10.1007/s11027-021-09973-2

Mandasari, V., Wahjyuni, E. T., & Wahyuni, E. T. (2019). Infrastructure Development by Public-Private Partnership in Indonesia: A Systematic Literature Review. CSID Journal of Infrastructure Development, 2(2), 153–160. https://doi.org/10.32783/csid-jid.v2i2.90

Mangla, S. K., Sharma, Y. K., Patil, P. P., et al. (2019). Logistics and distribution challenges to managing operations for corporate sustainability: Study on leading Indian diary organizations. Journal of Cleaner Production, 238, 117620. https://doi.org/10.1016/J.JCLEPRO.2019.117620

Maye, K., Rita, M. S., Turla, A. Y., et al. (2023). Beyond Preservation: A Systematic Review on the Impact of Ionizing Radiation on Food Functionality. Philippine Journal of Science, 153(S1), 101–112.

Munir, A., & Fadhilah. (2023). Climate Change and Food Insecurities: The Importance of Food Loss and Waste Reduction in Indonesia. IOP Conference Series: Earth and Environmental Science, 1134(1), 012040. https://doi.org/10.1088/1755-1315/1134/1/012040

Parlato, A., Giacomarra, M., Galati, A., et al. (2014). ISO 14470:2011 and EU legislative background on food irradiation technology: The Italian attitude. Trends in Food Science & Technology, 38(1), 60–74. https://doi.org/10.1016/j.tifs.2014.04.001

Pillai, S. D., & Shayanfar, S. (2017). Electron Beam Technology and Other Irradiation Technology Applications in the Food Industry. Topics in Current Chemistry, 375(1). https://doi.org/10.1007/S41061-016-0093-4

Prabowo, A., & Pudjianto, M. (2023). Logistics Costs of Rice and Soybean: Issues, Challenges, and the Impact of Regulations. Center for Indonesian Policy Studies. https://doi.org/10.35497/563232

Raut, R. D., Gardas, B. B., Kharat, M., et al. (2018). Modeling the drivers of post-harvest losses—MCDM approach. Computers and Electronics in Agriculture, 154, 426–433. https://doi.org/10.1016/J.COMPAG.2018.09.035

Ravindran, R., & Jaiswal, A. K. (2019). Wholesomeness and safety aspects of irradiated foods. Food Chemistry, 285, 363–368. https://doi.org/10.1016/j.foodchem.2019.02.002

Ridwan, M., Sundardi, F., Utama, M., et al. (1979). Radiation processing in Indonesia. Radiation Physics and Chemistry, 14(3–6), 747–757. https://doi.org/10.1016/0146-5724(79)90110-9

Roberts, P. B. (2016). Food irradiation: Standards, regulations and world-wide trade. Radiation Physics and Chemistry, 129, 30–34. https://doi.org/10.1016/J.RADPHYSCHEM.2016.06.005

Satmoko, A. (2020). The Challenge of The Iradiator Gamma Merah Putih (Igmp) As A Commercial Pilot Project. Prosiding Seminar Nasional Inovasi Dan Pendayagunaan Teknologi Nuklir 2020, 1, 18–19.

Siregar, M. A., & Utomo, S. W. (2019). Environmental impact assessment as a regulation and equator principles as an initiative. IOP Conference Series: Earth and Environmental Science, 399(1), 012081. https://doi.org/10.1088/1755-1315/399/1/012081

Spang, E. S., Moreno, L. C., Pace, S. A., et al. (2019). Food Loss and Waste: Measurement, Drivers, and Solutions. Annual Review of Environment and Resources. https://doi.org/10.1146/annurev-environ-101718

Tanzila Sultana, Kazi M Maraz, Arwah Ahmed, et al. (2021). Effect of Irradiation process on mango. GSC Advanced Research and Reviews, 9(2), 108–118. https://doi.org/10.30574/gscarr.2021.9.2.0267

Teigiserova, D. A., Hamelin, L., & Thomsen, M. (2019). Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. Resources, Conservation and Recycling, 149, 413–426. https://doi.org/10.1016/J.RESCONREC.2019.05.003

Tejedor-Calvo, E., Morales, D., García-Barreda, S., et al. (2020). Effects of gamma irradiation on the shelf-life and bioactive compounds of Tuber aestivum truffles packaged in passive modified atmosphere. International Journal of Food Microbiology, 332, 108774. https://doi.org/10.1016/J.IJFOODMICRO.2020.108774

UNEP. (2021). Food Waste Index Report 2021. Available online: https://www.unep.org/resources/report/unep-food-waste-index-report-2021 (accessed on 2 June 2023).