

Gamma Irradiation of Nigerian Cowpea (*Vigna Unguiculata*): Advances, Challenges and Future Perspectives for Mutation Breeding and Postharvest Preservation

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ABSTRACT

Cowpea (*Vigna unguiculata*) is a nutritionally and economically vital grain legume in Nigeria, where post-harvest losses of up to 16% of production, driven mainly by insect pests continue to threaten food security, income, and seed availability for subsequent planting seasons. Conventional preservation methods are increasingly limited by toxicity concerns, insect resistance, and environmental and public-health considerations, creating an urgent need for safer and sustainable alternatives. Gamma irradiation has emerged as a promising non-thermal technology for both postharvest pest control, owing to its capacity to disinfest stored grain, extend shelf life, and generate genetic variability without rendering food radioactive. This review establishes the current knowledge on gamma irradiation of cowpea, covering the crop's taxonomy, nutritional and economic importance, the biological mechanisms of gamma-ray interaction with seed material and the established use of ionising radiation across the food industry. International and Nigerian empirical studies on legume and cowpea irradiation are critically compared, revealing consistent evidence of dose- and genotype-dependent responses. Within Nigeria, no specific optimum gamma dose has yet been established that simultaneously safeguards storage stability, nutritional integrity, and seed viability across the genotype and agro-ecological diversity of Nigerian cowpea. The review identifies this gap as the central limitation of existing work and outlines future research directions, including alternative and complementary irradiation technologies (electron-beam and X-ray), combined irradiation-storage protocols, omics-based mechanistic characterization, and artificial-intelligence-assisted dose optimization. The review concluded that addressing these gaps will support the development of integrated gamma-irradiation protocols for Nigerian cowpea, with direct benefits for national food security.

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INTRODUCTION

Food is a basic need of humans; hence, food production, preservation, and security are critical for the conservation of lives and socioeconomic development of every country. However, food security has remained a challenge that has become difficult to eradicate due to its complexity and global spread. Owing to the importance of food quality and availability to human health and socioeconomic development, huge resources are expended by individuals, food processing industries, governments all over the globe on food and crop preservation techniques. All these attempts are directed to guarantee food security. The Food and Agriculture Organisation (FAO) had concluded that the benchmark for food security is the accessibility of safe and sufficient food that meets the preference and dietary needs of everyone in the world at all times, irrespective of social, physical and economic status (FAO, 1996; Baiden *et al.*, 2020). Unfortunately, the global food security challenge still transcends all social, cultural and educational groupings, geographical locations and income strata. In 2018, it was reported that about a billion of the world human population suffer from chronic hunger (McCarthy *et al.*, 2018; FAO, 2019). Consequently, a global food production increase of at least 70% was recommended to mitigate hunger (Roy *et al.*, 2024). However, increase in food production may not be the only viable solution to food

security. For example, the competition for land and water usage, global warming, insecurity, loss of soil fertility resulting from continuous usage and cultural inertia related to farm practices are other factors that make consistent increase in food production unsustainable. A multidimensional strategy including increase in food production, limiting post-harvest losses and novel food preservation techniques are sustainable ways of making food available to humans at all times. While, increase in food production may be a long-term solution, the development of efficient food preservation techniques that guarantees a drastic reduction in postharvest losses could be a sustainable solution to global food crises. Food preservation techniques involve all processes directed at preventing spoilage and conserving nutritional value, taste and texture of food items over a longer period of time. In addition, the preservation of food ensures that food borne diseases are eliminated and foods are made available for a longer time. Diverse traditional and modern techniques exist for preventing the physical, chemical and microbial agents that promotes spoilage. These methods include physical, chemical treatment (such as salting, sugaring, and pH-control), biological process (such as fermentation and phage treatment), thermal process (such as drying, smoking, freezing and pasteurisation) and irradiation (Talib *et al.*, 2024). The use of a particular model for the preservation of crops or food items depends on factors such as cost, nature of

food item, duration, and desired quality of food. In recent times, the use of irradiation technique for food preservation has gained wide acceptance (Mshelia *et al.*, 2023). Consequently, irradiating food such as legumes, to elongate their shelf lives while maintaining their nutritional quality is a viable solution to the global food crises.

The high protein and carbohydrate contents, affordability and adaptability to different ecological soil conditions of grain legumes position them to play a key role in ensuring global food security. Among these grain legumes, cowpea (*Vigna unguiculata*) is a unique part of human diet, particularly in developing economies including Nigeria, where it serves as a major source of complex carbohydrate, protein, and essential minerals for a huge proportion of the populations. They also serve as a major source of income for millions of farmers and their families. In many emerging economies in Africa, cowpea is the major source of plant protein where animal protein may not be readily available. These make cowpea a multipurpose legume whose cultivation is attractive from economic and public health perspectives. The cultivation of cowpea in Nigeria is thus important to national economy, public nutrition quality and food security.

Nigeria leads the global cowpea production, accounting for about one-half of the world production (FAOSTAT, 2021). For example, in 2023, Nigeria produced around 4.3 MT out of the 9.8 MT produced worldwide (FAOSTAT, 2023; Omoigui *et al.*, 2025). However, Nigeria does not only dominate the production of cowpea, it also leads in the consumption; consuming more than it produces. The wide gap between consumption and production is fostered by production related factors such as global warming, insecurity and shrinking farmland (Nkomo *et al.*, 2021). Another major factor favouring the high consumption-production ratio is post-harvest losses due to biotic factors. This account for not less than 16% of the production volume (Nwagboso *et al.*, 2024). The biotic agents are mainly insect pest, bacteria, fungi and virus deterioration and compromising storage conditions. These factors affect the nutritional value, seed quality, germination potential, shelf life and market value of cowpea. These threaten food availability and seed for subsequent planting season. Although many conventional preservation techniques exist for safeguarding against these agents of cowpea destruction, however, many of these strategies are limited due to toxicity concerns, insect resistance and fluctuating efficiency. In Nigeria, synthetic pesticides are commonly used to reduce post-harvest losses, public health and environmental safety concerns has however made the exploration of sustainable and safe alternative models attractive for cowpea preservation.

Ionising radiations including gamma photons, electrons and heavy ions of diverse energies have become important tools in medicine for the diagnosis and management of diseases, material characterization and modification among other areas of technology. In agriculture and food processing industry, ionising radiation is increasingly used for food preservation, aid crop germination, and for the control of crop pest and microorganism attack. In addition, irradiation can prevent significant food spoilage by controlling insects, preventing sprouting, deactivating food spoiling microorganisms, and sterilizing food for longer shelf lives (Farkas and Mohácsi-Farkas, 2017; Feng and Kim, 2020). Food irradiation using gamma rays is a technique used to eliminate harmful microorganisms and increase food safety. Since gamma rays do not cause radioactivity, irradiated foods are not radioactive and food quality is preserved unlike other conventional preservation methods (Ahn and Lee, 2018; Friday, 2020;

Mshelia *et al.*, 2023). Despite the growing acceptance of food irradiation, it is yet to be adopted in a large scale in Nigeria to reduce hunger and preserve diverse crops cultivated locally. Nigeria is saddled with a wide range of socio-economic problems such as insecurity, uncontrolled urbanisation leading to shrinkage of farmlands, inadequate irrigation facility, farmer-herder clashes, and general insecurity, all of which have slowed down farming activities (Nwozor, 2023; Ani *et al.*, 2022). While the nation attempts to eradicate some of these socioeconomic problems and boost food production, preventing post-harvest losses of cowpea in particular, and other food crop will drastically reduce hunger and ensure local food security. In addition, an isolated increase in food production will enviably result in a surge in post-harvest losses unless efficient and sustainable preservation methods are adopted.

Gamma irradiation has been successively applied for grain preservation using diverse irradiation conditions. However, there is yet to be an optimised dose that preserve nutritional quality, guarantees storage stability, and retains germination potential for cowpea species cultivated in Nigeria. Most of the existing investigations on cowpea irradiation in the past scarcely focus on the simultaneous determination these parameters. Rather, they have focused more on insect disinfection using gamma rays of wide dose spectrum without the consideration of the optimum dose that simultaneously guarantees food quality and effects of the irradiation on future generation of the seeds (Saleh *et al.*, 2021; Bhat *et al.* 2024; Robichaud *et al.*, 2021). Above all, some of these studies use different varieties of cowpea that are localised to other parts of the world. Therefore, the combined responses of insect control, germination potential and stability of nutritional quality of Nigerian cowpea to gamma irradiation has not been fully understood. Cowpea varieties differ in physical and morphological properties such as moisture content, biochemical composition and radiosensitivity (Lumoth *et al.*, 2025; Adly *et al.*, 2024; Diallo *et al.*, 2025). These properties could influence the gamma interaction attributes of different varieties of cowpea. Generalising optimal gamma doses from previous investigations on cowpeas species cultivated in different ecological environments may be misleading and inefficient.

The present review examines the state of food irradiation in Nigeria, particularly for cowpea and grains. It examines simple research results from different parts of the world and effort geared towards building a working food irradiation facility in Nigeria. This review was motivated by the need to fill existing knowledge gaps in food irradiation in Nigeria as a contribution to mitigate hunger and guarantee food security in Nigeria and beyond.

Cowpea: Taxonomy, Origin, Nutritional Content and Economic Overview

Taxonomy, Origin, and Cultivation of Cowpea in Nigeria

Cowpea belongs to one of the largest and economically viable plant family-*Fabaceae* (Leguminosae). Cowpea belongs to the Kingdom: *Plantae*, Division: *Magnoliophyta*, Class: *Magnoliopsida*, Order: *Fabales*, Family: *Fabaceae*, Genus: *Vigna*, and Species: *Vigna unguiculata* (L.) Walp (Padulosi and Ng, 1997; Ezra *et al.*, 2024).

Within the species *Vigna unguiculata*, several subspecies have been identified based on morphological and genetic characteristics (Ezra *et al.*, 2024). Cowpea (*Vigna unguiculata* (L.) Walp.) is an annual warm season legume widely cultivated in Nigeria and Africa. Although there are many controversies surrounding its origin, many scholars accepted that it originated from West and Central Africa

(Lazaridi and Bebeli, 2023; Panzeri *et al.*, 2022). It is believed to have been introduced to other parts of the world through trade and other forms of interactions. In Nigeria, cowpea is cultivated almost everywhere. It is widely referred to as beans, while some of its local names are *wake*, *ewa* and *ikedi* in Hausa, Igbo and Yoruba language, respectively. However, its cultivation is more prominent in the rain forest of Western Nigeria and the Sudan, Sahel and Guinea savannah regions of the North. Grown in commercial and subsistence agriculture, cowpea is often intercropped with other crops such as maize. Furthermore, the ability of cowpea to survive in high temperature ecology with little rain and poor soil conditions makes it attractive for cultivation in regions where other legumes fail to survive. These have contributed to the widespread of cowpea cultivation and consumption. However, the wide geographical spread of cowpea has resulted in the morphological and genetical variations of cowpea. Today, many varieties of cowpea with different seed colour, size, growth pattern, maturity time, and resistance to diverse environmental factors including pests and diseases, yield, and suitability for specific soil type exist (Olapade *et al.*, 2002). These varieties come majorly from international scientific collaborations; national programmes aimed at breeding new varieties and farmers' choices. Broadly speaking, variety of cowpea can be classified as local and improved varieties.

Local varieties are simply identified bases on physical attributes of seed such as colour, size, and firmness of attached seed coat as well as seed place of origin (Olapade *et al.*, 2002). Consequently, some common local varieties common in the Southern part of Nigeria include *manyan fari*, *kananado fari*, *kananado yari*, *banjara karadua*, *akidi*, *olo-1*, and *olo-2* (Olapade *et al.*, 2002). These variety differ in the seed physical properties, density, water absorption capacity and swelling after cooking. On the other hand, improved varieties are developed in Nigeria by the International Institute of Tropical Agriculture at Ibadan and Zaria. These institutions also collaborate with research institutes scattered across the country to develop new varieties. Some of the well-known developed varieties include SAMPEA 5–20 (Olasan *et al.*, 2023; Kim *et al.*, 2025). These varieties are known to have disease resistance, shorter maturity period, and differences in physical appearances. These variations can influence the insect infestation, stability, response to radiation and ultimately the shelf life of the crop.

Nutritional Composition of Cowpea

Globally, legumes such as cowpea, groundnut, soybean, faba bean, field pea, common beans, spring vetch, and lentils have high nutritional quality and economic value. This has led to their worldwide cultivation, distribution and consumption (Ali *et al.*, 2013; FAOSTAT, 2023; Omoigui *et al.*, 2025). Aside the nutritional advantage, which is common to all legumes, cowpea has agricultural, ecological, environmental and economic advantages over other crops and legumes. Cowpea provides immense income for farmers and for individuals within the value chain of its application across Africa and other countries all over the World. Although cowpea originated from Africa, its global acceptance arises from its ability to be cultivated in broad soil types and with

low inputs. Its agricultural and environmental importance is connected to its drought resistance and ability to thrive in diverse soils and regions. Healthwise, cowpea is important in human diet to prevent risk factors for cardiovascular and metabolic diseases (Gonçalves *et al.*, 2016). In addition, nearly all of the plant including the green pod, green beans, leaves and matured beans are directly consumed or processed into other product that serve as food for humans and livestock. These factors encouraged the growth in the global production of cowpea by a factor of about seven between 1981 and 2013 (Singh, 2014). The production rate of cowpea has continued to grow since then.

Nutritionally, the protein contents of cowpea seed and leaves are within the range 203–394 g/kg and 215–437 g/kg, respectively (Ali *et al.*, 2013). Also, cowpea is known to be rich in essential amino acids (such as phenylalanine tyrosine, asparagine/aspartic acid and tamine/glutamic acid, among others), low in crude fat and fatty acids (31–304 g/kg), high in carbohydrate (504–658 g/kg), dietary fibre (160–209 g/kg) and high micronutrients (Ali *et al.*, 2013). The summary of the nutritional and chemical composition of different edible parts of cowpea plant is given in Table 1, as summarised from several studies (Abebe and Alemayehu, 2022). Clearly, different parts of cowpea contain main and micro nutrients needed by humans and animal for survival and healthy living. This makes cowpea an essential part of animal and human nutrition worldwide.

Contribution of Cowpea Cultivation to the National Economy

An essential component of traditional cropping systems, cowpeas are tropical leguminous crop indigenous to Africa, cultivated in the semi-arid territories of West Africa and the Savanna (Adegboye *et al.*, 2023). It ranks as the second most significant grain legume crop, following the groundnut (Akinola *et al.*, 2023). It has been reported that cowpea is an important food crop throughout Sub-Saharan Africa (Agyemang *et al.*, 2023) and is one of the major sources of plant-based protein in developing countries including Nigeria. Its leaves and seeds have high-quality protein and vitamins, which is an excellent food supplement in developing countries (as shown in Table 2.1). Nigeria produces cowpeas as a mono-crop or as an intercrop with maize all over the country.

Cowpeas constitute an economical source of vitamins, minerals, and protein compared to animal-based sources, which are both scarce and expensive. One contributing factor to the prevalent malnutrition in developing countries is insufficient dietary protein intake. As a result, increasing the number of cowpeas consumed provides an affordable protein source for the majority of Nigerian households. Millions of poor people in low-income countries rely on Cowpeas for their livelihood and as protein supplement (Okoro *et al.*, 2021). Hence, it is a key staple food crop for ever-increasing population both in the rural and urban areas. Being a leguminous crop, cowpea has ability to fix atmospheric nitrogen in the soil, thereby improving soil nutrients (Aliyu *et al.*, 2022). This reduces the cost of purchasing additives such as fertilizers to enhance soil nitrogen content.

Table 1: Average Nutritional Content of Different Parts of Cowpea Evaluated Based on Several Studies

Parameters	Fresh aerial part	Dehydrated aerial part	Haulms	Hay	Pod husk
DM (%) DM (as fed)	20.9	92.5	95	91.2	51.6
CP (%DM)	18.1	17.1	13.7	14.8	12.7
CF (%DM)	24.1	–	29.9	32.6	31.8
NDF (%DM)	38.6	43.2	49	49	54.2
ADF (%DM)	27.1	32.8	35.4	37.2	41.1
Lignin (%DM)	4.6	8.4	8.5	8	–
EE (%DM)	2.8	–	2.2	1.7	0.7
Ash (%DM)	11.3	15.8	11	13.7	7.9
GE (MJ/kg DM)	18.1	12.6	17.9	17.5	18.2
Macro minerals (g/kg DM)					
Calcium	12.5	–	11.4	13.1	–
Phosphorous	2.4	–	2.6	3.9	–
Potassium	19.1	–	15.1	33.2	–
Sodium	–	–	0.7	2.6	–
Magnesium	3.1	–	5.6	6.6	–
Micro minerals (mg/kg DM)					
Manganese	–	–	129	97	–
Zinc	46	–	33	56	–
Copper	30	–	8	6	–
Iron	1690	–	1	–	–
Amino acids percent of protein					
Arginine	4.6	–	–	–	–
Histidine	1.8	–	–	–	–
Iso-leucine	4.3	–	–	–	–
Leucine	7.4	–	–	–	–
Lysine	3.3	–	–	–	–
Phenylalanine	4.6	–	–	–	–
Alanine					
Valine	5.3	–	–	–	–
Cystine	0.9	–	–	–	–
Glycine	4.8	–	–	–	–
Methionine	1.4	–	–	–	–
Threonine	4	–	–	–	–
Tryptophan	1.3	–	–	–	–
Tyrosine	3.2	–	–	–	–

Where, ADF: acid detergent fiber; CF: crude fibre; CP: crude protein; DM: dry matter; EE: ether extract; GE: gross energy; NDF: neutral detergent fibre. (Source: Abebe and Alemayehu, 2022).

Economically, cowpea serves as cheap carbohydrate and protein source for farmers and their families in Nigeria. In addition, farmers get good income by selling the seed to other farmers, traders and directly to consumers, while the leaves and pods are sold for animal feed production. Consequently, cowpea serves as a good source of income within the value chain of the product within and outside Nigeria. Nigeria can also earn a lot of foreign exchange from cowpea if the production is made to exceed consumption through increased cultivation and drastic reduction in post-harvest losses. Presently, more than 80% of the global production of cowpea comes from Africa with Nigeria accounting for about 50% of the global cowpea production (Moussa *et al.*, 2011; FAOSTAT, 2021). With increased production and reduction in post-harvest losses, cowpea can diversify the nation's economy and improve the standard of living of Nigerians—many of whom are presently low-income earners.

Post-Harvest Storage Losses in Cowpea

Nature and Magnitude of Cowpea Storage Losses

Postharvest losses (PHLs) within the food supply chain (i.e., from the point of harvest to consumption) can be very high if harvesting and storage is not well managed. Generally, PHLs

come in two forms, namely, qualitative and quantitative losses (Chaboud and Daviron, 2017). Qualitative losses include all forms of distortion that lowers the nutritional quality of a food item. Conversely, quantitative losses involve when the amount of matter (energy (in calories) or mass (in kilogram) in a food item declines with time (Sheahan and Barrett, 2017). While the latter PHL is easier to determine, the former requires more sophisticated method to quantify. The prevention of both PHLs can mitigate hunger, nutrient deficiencies and food-borne diseases. In Africa, more than 4 billion American dollars' worth of food items are lost to qualitative and quantitative PHLs according to the World Bank (Zorya *et al.*, 2011; Ariong *et al.*, 2023). This amount could be more, as many losses in Africa and Nigeria, in particular are not often well documented.

The magnitude of PHLs depends on post-harvest handling, environmental factors and storage modalities. Studies have shown that traditional storage method could only guaranty food quality and quantity within the first sixty days after harvesting (Ariog *et al.*, 2023). For longer storage and availability, more sophisticated and sustainable storage method is required. In Nigeria, studies on food losses due to postharvest handling have resulted in huge financial losses to

farmers (Ogundele, 2022; Ojo *et al.*, 2025, Bappah and Adejoh, 2024; Ibrahim *et al.*, 2022). The losses did not only translate to loss of revenue to farmers; it threatened the availability of food. Although, not much has been done on the empirical evaluation of PHLs in cowpea in Nigeria, however, Ojo *et al.* (2025) established that about 22% loss of cowpea to PHLs among farmers in Oyo State, while Ogundele (2022) estimated national PHLs of about 31%. These clearly show that a safe and sustainable method for post-harvest (PH) handling and storage is required to guarantee food safety and availability.

Major Insect Pests of Stored Cowpea

Post-harvest storage of cowpea is inhibited by biological agents or pests which affects seeds and pods and subsequently reduce the food quality and quantity. Sometimes, the impact of these pests is enormous, that it discourages peasant farmers from planting cowpea in the following planting season. The destruction of cowpea seeds by pest also prompts farmers to sell at low and unprofitable prices (Eze *et al.*, 2021). Although, many factors are responsible for PHLs of cowpea in Nigeria, the major losses are attributed to insect infestation and environmental damage.

One major biological agent contributing to cowpea destruction is the cosmopolitan insect known botanically as *Callosobruchus maculatus* F. (Coleoptera: Bruchidae). This insect commonly called the bean beetle or cowpea weevils have huge appetite for legumes (Umeozor, 2005). The weevil's reproduction rate is high and starts with mature females laying their eggs on the coating of the seed. The larvae develop within the seed, leading to loss of seed mass and quality as seen in Figure 2.1 (Akuba *et al.*, 2023). This attack also leads to the reduction in the nutritional and market values of the seeds. The attack by these weevils begins from the field and extends to storage facilities resulting in huge losses. Field losses due to *C. maculatus* attack on cowpea have been estimated to be within 5% (Sanon *et al.*, 2005). On the other hand, storage losses could be as high as between 50% and 100% (Adedire *et al.*, 2011; Udo and Henry, 2013). High moisture content in cowpeas makes them susceptible to mold and spoilage. Traditional preservation techniques are often insufficient, and financial constraints prevent farmers from investing in better storage and pest control solutions (Adamu *et al.*, 2020).

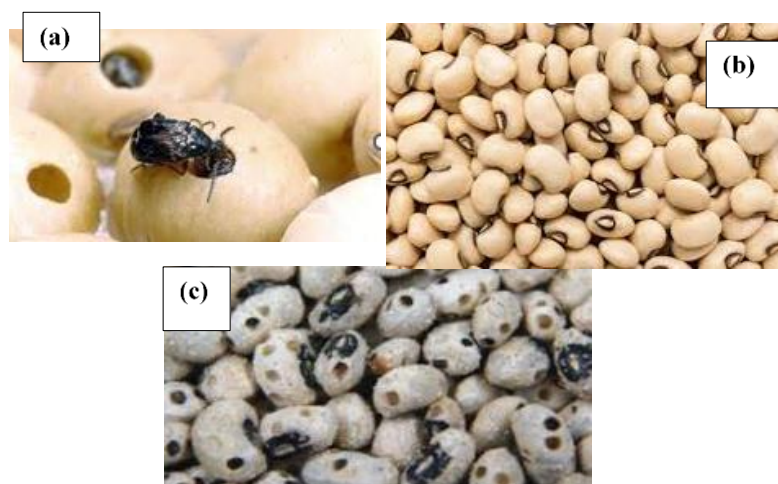


Figure 1: (a) *C. maculatus* on bean seed (b) *C. maculatus*-free bean seeds and (c) *C. maculatus*-infested seeds

Limitations of Existing Cowpea Storage Practices in Nigeria

Different storage mechanisms have been adopted for extending the shelf-life and availability of cowpea worldwide. Research has shown that the major insect that infests and destroys cowpea in Africa is the *C. maculatus* (Bakoye *et al.*, 2020). Consequently, most storage and preservation strategy are aimed at eliminating the attack of this insect. Consequently, postharvest storage (PHS) of cowpea aims at eliminating the possibility of attack from this insect.

In developing countries like Nigeria, the inadequacy and efficiency of storage facilities and methods, respectively, contributes majorly to PHLs. Existing traditional methods have become ineffective to mitigate insect infestation for a long time. One common method for preventing the procreation of bean beetle is the use of insecticides and fumigants (Akuba *et al.*, 2023). However, this method is discouraged due to the potential environmental and health risks posed to humans and animals by synthetic chemicals. In view of these risks, biological and other safer methods are encouraged for insulating cowpea from insect infestation.

Although, *C. maculatus* are known to withstand high heat energy and humidity (Beck *et al.*, 2013), Ajayi *et al.* (2021) have shown that the exposure to solar radiation for 24 h eliminated the eggs of *C. maculatus*. While the use of irradiation is common in Africa among peasant farmers, this method may not be effective due to non-uniformity of solar irradiance and air current may fluctuate and influence the heat need to cause 100% mortality of *C. maculatus* eggs. This affects the standardization of the method. Moreso, the effect of the sun on developed weevil and how long the cowpea last before further infestation and effect on the growth potential of F1 generation of the cowpea have not been ascertained. Moreso, the use of solar irradiation is not standardised and replication may be scientifically difficult.

In 2020, Bakoye *et al.* showed that the use of hermetic bags with trade names such as AgroZ™, PICS™, EVAL™, and Supergrain™ bags to store cowpea reduced *C. maculatus* drastically compared to the popular woven bags for a period of eight months. However, the germination potential of the seeds was reduced. Also, the bags may not be cheap and reuseable, this affects the cost and availability of cowpea.

Ionising Radiation in Food Preservation

Gamma-Ray Interaction with Seed Material

Gamma irradiation has the potential to change plant's biological processes via its ability to interact with cellular atoms and molecules thereby generating free radicals and thus changing certain essential cellular makeup. The resulting biological response is dose-dependent among other factors. While lower doses potentially produce stimulatory effects while higher doses may become toxic (Katiyar *et al.*, 2022). Because seed tissues contain substantial amounts of water, the energy deposited by ionizing radiation can subsequently initiate chemical changes in the aqueous cellular environment. This provides an important pathway through which the initial physical interaction of gamma radiation can be translated into chemical and biological effects within the seed. This pathway is shown in Figure 2.

Water Radiolysis and ROS Generation

Gamma radiation, when irradiated upon a seed such as cowpea deposits its energy within its cellular environment. In

the presence of water molecules, a chemical change begins to occur. Water Hydrolysis is the process of ionization and decomposition of water molecules by ionizing radiation. This results in highly reactive species, including hydroxyl radicals ($\text{OH}^\bullet$), hydrogen atoms ($\text{H}^\bullet$), hydrogen peroxide (H_2O_2) and solvated electrons (Gudkov *et al.*, 2019).

These species, collectively associated with reactive oxygen species (ROS), have the capacity to react with nearby cellular molecules. When their concentrations exceed a seed's antioxidant capacity, ROS can generate oxidative stress which results in lipid peroxidation, protein modification and ultimately, nucleic acid damage (Gudkov *et al.*, 2019).

At lower levels, the presence of ROS, radiation-induced changes in cellular redox status may also participate in signaling and regulatory responses. A low-dose gamma irradiation can enhance antioxidant capacity and influence hormone-signaling pathways, providing a possible basis for some of the stimulatory responses observed in irradiated plants (Katiyar *et al.* 2022).

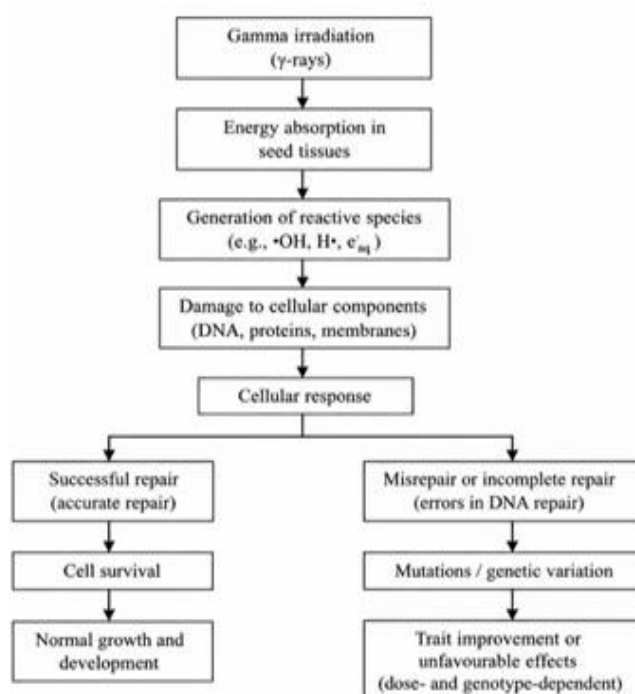


Figure 2: Mechanism of gamma irradiation and its biological effect

DNA Damage, Repair and Mutation Induction

Ionizing Radiation (IR) is able to cause damage to the plant's DNA via either a direct or an indirect pathway. Directly, incident IR is able to interact with DNA molecules thereby ionizing them and consequently producing lesions (cuts) which may be a single or double strand breaks. Indirectly, the ROS via water radiolysis can react with the DNA consequently producing oxidative lesions such as oxidized bases, abasic sites and strand breaks (Szurman-Zubrzycka *et al.*, 2023).

The DNA damage may not immediately lead to a mutation. Plant cells possess a DNA damage response (DDR) system which detects DNA lesions and goes into a repair mode. Upon a successful repair, cellular activity can resume but when the repair fails, it can lead to cell death. However, when the damage is not accurately repaired, persistent lesions may assist in fostering genomic instability (Szurman-Zubrzycka *et al.*, 2023).

Errors during repair can result in chromosomal abnormalities and mutations that may subsequently become fixed in the population (Gudkov *et al.*, 2019). This produces a pathway through which heritable genetic variation can arise.

Biochemical and Enzymatic Responses

The oxidative changes generated due to irradiation can also change cellular biochemical processes, giving rise to the need for the seed to activate protective and metabolic responses. Low-dose gamma irradiation has reported to be been associated with increased antioxidant capacity and enzyme activity, as well as changes which occur in plants' hormone-signalling pathways (Katiyar *et al.*, 2022).

These biochemical actions are known to provide a potential link between radiation-induced molecular changes and the physiological traits of seeds that have been irradiated. In 2018, Kumar *et al.* reported changes in α -amylase and peroxidase activity in cowpeas following gamma irradiation,

with stimulatory responses observed at lower doses and declining activity at higher doses thereby suggesting the irradiation dose dependent nature of the biochemical response.

The response therefore maybe a balance between radiation induced stress and the seed's potential to activate its protective and metabolic processes. At certain expected levels of exposure, changes which occur in antioxidant and hydrolytic enzyme is expected to support the metabolic processes required during germination, although where excessive, irradiation can be overwhelming to cellular protection and cause impairment to biochemical function. The biochemical changes produced in this manner provides the instant conduit through which the molecular effects of irradiation can manifest as changes during germination and/or seedling growth and vigour (Kumar *et al.*, 2018)

Physiological Responses

The biochemical and enzymatic changes which have been described above are given expression at the whole-seed level via the changes in physiological indicators. Gamma irradiation have been known to influence certain parameters such as germination, seedling emergence, root and shoot development, survival and seedling vigour. It's important to note that the severity and direction of the response highly depends on the amount of irradiation dose. It is also worth noting that higher doses may result in progressive reductions in morphological performance. (Katiyar *et al.*, 2022; Jayashri *et al.* 2022; Atchaya *et al.* 2023). The physiological response is therefore the observable outcome of the processes preceded by irradiation.

Food Irradiation and Technologies

Food Irradiation

Food irradiation is a nonthermal process whereby selected food items and products are exposed to a predetermined dose of ionizing radiation to improve quality and assure wholesomeness without compromising sensory or nutritional attributes. It involves the exposure of food items in bulk or packaged form to defined quality of ionising radiation. Ionising radiation quality is defined by the nature and energy of the radiation. Common radiation used in food irradiation include, electron beams, gamma and X-ray photons of different energies (Farkas, 1998; Farkas, 2006; Farkas and Mohacs -Farkas, 2011). Depending on factors such as absorbed radiation dose and post irradiation treatment, storage losses, increased shelf life and insulation from microbial actions are some of the effects of irradiation of food items (Arapcheska *et al.*, 2020). Unlike in the past, the safety of irradiated food is no more in doubt. In all irradiation processes, the safety of operation as well as the health of the consumers of the products is always paramount. For example, in 1980, a joint United Nations Food and Agriculture Organisation (FAO), International Atomic Energy Agency (IAEA), and the World Health Organization (WHO) Experts Committee on the wholesomeness of irradiated food declared that irradiation of any food up to overall average dose of 10 kGy causes no toxicological hazard and introduces no special nutritional or microbiological problem (Arapcheska *et al.*, 2020). Also, the microbiological safety of irradiated food was further considered at a meeting of the Board of the Committee of Food Microbiology and Hygiene of the International Union of Microbiological Societies held in Copenhagen in December 1982 in order to produce a second opinion. The Board was satisfied and came to the conclusion that there was no cause for concern on irradiated food (Reddy and Gundewadi, 2018). Today, food Irradiation is considered to

be an important addition to the methods of control of food-borne pathogens and not meant to present any additional health hazard. The effect of ionising radiation amongst other things is to kills most of the bacteria in treated food; replaces potentially hazardous chemical fumigation used to preserve food; destroys insects that infest grains, herbs and spices; increases the shelf life of many foods; reduces sprouting in stored yams, potatoes and onions; delays ripening in some fruits; provides extra safety for prepared meals; and leaves the taste and texture of foods intact. In summary, the application of food radiation processing technology has been found to assure the availability of seasonally produced crops and minimizes food losses as well as reduces the incidence of illness caused by food borne pathogens (Arapcheska *et al.*, 2020).

Ionising Radiation Effects on Food and Food Products

Ionizing radiation induces a chemical transformation through the mechanisms of primary and secondary radiolysis. Variables such as temperature, type of facility, availability of oxygen, absence of oxygen, absorbed dose and radiation dose rate influence these reactions. In General, the majority of micronutrients (primarily water-soluble and fat-soluble vitamins) and macronutrients (proteins, fats, and carbohydrates) show minimal nutritional alteration with an application up to 10 kGy of ionising radiation (Fabian *et al.*, 2018).

Nevertheless, ionizing radiation doses beyond 10 kGy can give rise to slight rancidity in lipids and structural degradation of fibrous carbohydrates (Molina and De-Ancos, 2019). Food compositions and their physical state (fresh or frozen, solid, liquid, or powdered) also affect the radiation-induced reactions (IAEA, 2017). An optimal dosage is determined by balancing the item's requirements with its tolerances. Generally, the radiation dose in food irradiation is divided into three broad categories ((Arapcheska *et al.*, 2020). The dose categories and their applications are summarised as:

- i. Low-dose (< 1 kGy): used to stop the sprouting in tubers, disinfestation of seeds, slow fruit ripening and preserve vegetables.
- ii. Medium-dose (1 - 10 kGy): for eradicating pathogens and prevent food spoilage.
- iii. High-dose (> 10 kGy): used for the sterilization of food intended for immunocompromised patients such as people infected with HIV.

Ultimately, uncontrolled ionising radiation can positively and negatively change the qualitative and technical attributes of cereals and cereals products when tested at radiation levels ranging from 1 to 10 kGy. The effect of different irradiation on food items is a function of irradiation dose of irradiation, nature of the food and preparation method. Ionizing radiation serves as an effective and efficient pest control method, as it leaves no residues in the treated foods after irradiation, it prevents pest insects from developing resistance and does not alter the nutritional content or physicochemical properties at a controlled dose (Feng and Kim 2020). Various countries have conducted research on utilization of irradiation as an authorized method for pest control in wheat, dried legume seeds, and flour (Ahmad and Khan 2021).

Acceptability of Radiation in Food Industry

Customers have certain assumptions about food that has been irradiated. Nonetheless, studies have shown that eating food that has been radioactively irradiated is completely safe. On a national and international level, radiation-processed food's safety has been extensively studied. As declared by IAEA/FAO/WHO Joint Expert Committee, food items

exposed to ionizing radiation doses of up to 10 kGy are considered safe in terms of health and do not present any toxicological concerns. This conclusion stems from comprehensive research involving laboratory animals conducted across multiple countries (Liu and Zhao, 2019). The radiation doses necessary for treatment are notably below this upper threshold.

Additionally, the committee acknowledged that radiation is a physical process akin to heat treatment rather than an additive to food. When food is irradiated, it absorbs an appropriate amount of radiation energy from a radiation field. Importantly, the radioactive source used does not interact with the food in any manner. Gamma rays, X-rays, or electrons used in radiation processing do not make food radioactive.

Looking at various foods processing and preservation methods, radiation processing has the least adverse effect on the nutritional composition of food (McDonald and Wang, 2018).

Scientifically, radiation has minimal effects on micro and macronutrients such as protein minerals, carbohydrates, and fats. However, depending on the method of processing employed, the impact of radiation on vitamins varies. For example, vitamin B1 (thiamine) and vitamin C shows similar susceptibility to both radiation and heat processing. Food items rich in vitamins A, E, C, K, and B1 are less stable to ionizing radiation compared to those rich in riboflavin, niacin, and vitamin D (McDonald and Wang, 2018).

Factors, such as food type, radiation dosage, and packaging determine the impact of radiation on nutritional value. Foods exposed to doses up to 1 kilo-Gray shows minimal alterations in vitamin content. The International Atomic Energy Agency (IAEA), the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) in 2021 concluded that radiation does not induce specific nutritional concerns in food. It was also dismissed by the three joint bodies that consuming irradiated food could lead to chromosomal abnormalities.

There are regulatory authorizations in effect in several nations for irradiation processing of food products. However, only a small number of food items are really being produced using this technique in any of these nations (WHO 2020).

Approximately three quarters of food processed by irradiation techniques originates from China, the United States, and Ukraine. China stands out as the foremost nation in food irradiation. There is a global inclination towards expanding facilities for the radiation processing of food on commercial basis. China boasts nearly 200 facilities, including over forty (40) gamma irradiators with capacities surpassing 1000 kCi and around 100 exceeding 300 kCi. Additionally, China introduced 20 new irradiators during the period from 2006 to 2010 (Li and Zhang, 2020).

Empirical Studies on Food Irradiation

The empirical studies reviewed in this section were obtained through a systematic search of major academic databases including Google Scholar, ScienceDirect, SpringerLink, Web of Science, and Scopus. Relevant literature was identified using search keywords such as gamma irradiation, food irradiation, cowpea irradiation, legume irradiation, seed preservation, storage stability of legumes, and effects of gamma radiation on seed germination and nutritional composition. Priority was given to peer-reviewed journal articles, conference proceedings, and authoritative institutional publications related to irradiation technology and legume preservation. Studies were selected based on their relevance to gamma irradiation effects on storage stability,

nutritional composition, pest control, and germination characteristics of cowpea and other legumes.

Irradiation of Different Food Items

The effect of applying gamma radiation on the Storability and Sensory acceptability of Sudanese Sorghum was studied by Raga *et al.* (2023). An effort was made to increase the sorghum grains' shelf life (storage stability) by giving doses of 10 and 30 kGy to the grains using a gamma radiation source (Co-60) as a means of preservation. A control sample and irradiated sorghum grains were kept at room temperature (30 +/- 5°C) and relative humidity of 30 +/- 5%. During storage, the physical characteristics of the traditional Sudanese cuisine (Aceda) including insects' presence and cracked kernels were monitored. Insect density in the 10KGy irradiated grains was only one insect per kilogram, while the control sample (non-irradiated grains) had 140 insects per kilogram. The flavour, texture, and taste of the sorghum porridge made from the non-irradiated control grain declined, and the sorghum porridge made from the irradiated grain showed a decrease in these attributes. Additionally, the sorghum grain did not retain its flavour well while it was being stored, even with a 10 kGy dose.

An overview of irradiation and its benefits for foods derived from plants was conducted by Ana (2022). According to the International Atomic Energy Agency (IAEA), 33 nations are utilizing the method commercially, and over 50 countries have sanctioned the application of irradiation for approximately 50 distinct food varieties. Despite decades of usage to sterilize food and fulfil international quarantine regulations, health concerns remain about consuming irradiated food. This affordable method retains irradiated food's organoleptic properties, improving bioactivity and nutritional value. The primary focus of this study is to examine the impacts of applying radiation to plant-based foods. When used correctly, irradiation can be a useful tool for getting rid of or decreasing insect and microbial infestations and the food-borne illnesses they cause. This increases the safety of a lot of foods and prolongs their shelf life.

Recent technological advancement in gamma irradiation was reviewed by (Sawera *et al.*, 2022) highlighting improvements in precision and efficiency, which enhance the application of this technology in food preservation.

Nguyen and Kim (2021) look into regulatory consideration for gamma irradiation in food processing; This research discussed regulatory considerations emphasizing that gamma irradiation is widely accepted under various international food safety standards, further supporting its use as a preservation method. Mila *et al.* (2020) also surveyed consumer acceptance of irradiated food and found high levels of acceptance, especially when consumers were informed about the safety and benefits of the irradiation process.

International Studies on Irradiation of Legumes

Kumar *et al.* (2018) conducted controlled experiments on cowpea seed lots to determine how low doses of gamma irradiation (50–250 Gy) influence seed longevity under ambient storage. They used accelerated ageing tests and standard germination procedures to estimate storability and vigour indices. Results showed that 50–150 Gy produced an initial stimulatory effect on seed enzyme systems (α -amylase, peroxidase), which correlated with higher early germination and improved vigour index after three months of storage compared with controls. Seeds treated at 200–250 Gy showed slight declines in both germination and seedling dry weight values, indicating the threshold where beneficial hermetic

effects reverse. Importantly, proximate composition (protein, fat, carbohydrate) remained statistically unchanged across treatments, supporting the idea that low doses can enhance storage performance and early vigour without compromising nutritional quality. The study used multiple Nigerian cowpea cultivars, revealing genotype-dependent responses: some landraces-maintained vigour longer after low-dose treatment than improved varieties, underlining the need to tailor dose recommendations by cultivar when optimising for seed banks and farmers storing seed for planting.

In addition, international studies have demonstrated that irradiation can influence seed germination and physiological performance. Marcu *et al.* (2013) reported that gamma irradiation alters enzymatic activity and hormonal balance in seeds, which may either enhance or suppress germination depending on dose and genotype. These findings emphasize the importance of dose optimization tailored to specific legume species and varieties.

Several international studies have focused on dose-response relationships in legumes. For instance, Osman and Al-Bachir (2012) investigated gamma irradiation effects on legumes' hydration and cooking behaviours, including cowpea analogues like chickpea and lentil. Their study demonstrated that irradiation at 300–900 Gy significantly reduced cooking time, attributed to partial breakdown of cellulose and pectin structures, leading to improved water absorption and faster softening during cooking. Additionally, the authors observed no significant reduction in crude protein or crude fat contents across all treatment groups, indicating preservation of major proximate components. For cowpea, which is prized for its nutritional integrity, these findings provide empirical support that gamma irradiation can enhance processing quality while preserving nutritional value. Moreover, the improved hydration capacity could benefit storage studies by reducing the impact of seed hardening, a common storage-related deterioration. The relevance to the thesis lies in demonstrating that gamma irradiation can simultaneously improve post-harvest and culinary qualities when doses are optimally chosen. Studies by Darfour *et al.* (2012) further showed that proximate components such as protein, fat, ash, and carbohydrate in legumes are largely unaffected by irradiation, although slight changes in moisture content and functional properties may occur.

Farkas and Mohácsi-Farkas (2011) reviewed empirical studies on gamma irradiation effects across legumes, including cowpea, soybean and lentils, focusing on nutrient preservation. They observed a consistent trend across multiple studies showing that irradiation below 1 kGy does not cause significant degradation of proteins, essential amino acids or lipids. Minor changes were observed in heat-labile vitamins but these were within acceptable nutritional limits. Importantly, gamma irradiation enhanced storage safety by reducing microbial contamination and detoxifying certain antinutritional factors such as trypsin inhibitors and phytic acid. These trends validate the rationale for using gamma irradiation in cowpea, where proximate composition stability is a major concern. The review emphasises that dose determines nutritional outcomes, and staying within low-moderate ranges (100–800 Gy) can maintain cowpea nutritional quality while substantially improving shelf life.

Such evidence directly supports the thesis objective of identifying dose ranges that optimize both pest control and nutritional preservation.

Rodriguez and Silva (2010) provided empirical microscopy and biochemical analyses of cowpea seed tissues before and after gamma irradiation. Using doses up to 500 Gy, they documented subcellular changes in aleurone layers and embryo membranes, including increased membrane lipid peroxidation at doses above 300 Gy (measured by MDA assays) and modest increases in antioxidant enzyme activities (catalase, superoxide dismutase) at low doses. These biophysical alterations helped explain observed effects: low doses can stimulate repair and antioxidant responses (hormesis), whereas higher doses induce membrane damage that reduces viability and germination. The study links biochemical markers (electrolyte leakage, MDA) to practical outcomes (germination decline, reduced seedling vigour) and suggests using such markers as part of a protocol to screen optimal doses for specific seed lots. For thesis work, these mechanistic insights support using physiological assays alongside germination and proximate analyses when determining optimal gamma doses for cowpea.

From a postharvest and food quality perspective, irradiation has also been examined as a preservation technique. Farkas (2006) reported that gamma irradiation effectively reduces insect infestation and microbial load in stored legumes, thereby extending shelf life without significant deterioration of macronutrients when applied within internationally recommended dose limits. Similar findings were reported by Singh and Kole (2005) in mung bean, where gamma irradiation induced significant variability in flowering time, seed size, and yield-related traits.

In 2003, Al-Kaisey *et al.* showed that proximate components such as protein, fat, ash, and carbohydrate in legumes are largely unaffected by irradiation, although slight changes in moisture content and functional properties may occur.

As far back as 1995, Diehl had reported that gamma irradiation effectively reduces insect infestation and microbial load in stored legumes, thereby extending shelf life without significant deterioration of macronutrients when applied within internationally recommended dose limits.

Overall, international literature confirms that gamma irradiation is a versatile tool for mutation induction, storage preservation, and quality management in legumes. However, outcomes are highly dependent on irradiation dose, genetic background, and evaluation parameters.

The international literatures studied reveal that gamma irradiation has been for purposes such as mutation induction, storage preservation, pest control, nutritional quality and obtaining physiological responses. As can be seen in Table 2.2, the effects are determined by both irradiation dose and genetic background. In several studies, lower or moderate doses produced beneficial or stimulatory responses, while higher doses were more likely to cause reduced germination or other adverse effects. The differences which exist among these species and genotypes suggest that irradiation doses require careful optimization according to the intended purpose rather than applying a single dose across various legumes (Marcu *et al.*, 2013; Diallo *et al.*, 2025; Horn *et al.*, 2016; Atchaya *et al.*, 2023).

Table 2: Summary of International Gamma-Irradiation Studies on Legumes

Country	Study	Legume / material	Gamma dose	Major finding
Romania	Marcu <i>et al.</i> (2013)	Maize (<i>Zea mays</i>)	0.1–1 kGy	Gamma irradiation affected seed germination, growth and pigment content, with responses varying with dose. The study also detected radiation-induced free radicals using ESR analysis.
Senegal	Diallo <i>et al.</i> (2025)	Bambey 21, Me51-M4-39M9, Ndout violet pods	0–400 Gy	LD ₅₀ and phenotypic responses varied among genotypes. Lower doses stimulated germination speed and some traits, whereas higher doses produced stronger mutations and reductions in several quantitative traits.
Sudan	Osman <i>et al.</i> (2012)	Faba bean (<i>Vicia faba</i>)	300–900 Gy	Irradiation reduced cooking time and improved water absorption, while major nutritional components such as protein and fat were largely maintained.
Ghana	Darfour <i>et al.</i> (2012)	Cowpea (<i>Vigna unguiculata</i>) flour	0.25–1.5 kGy	Irradiation generally maintained proximate composition but produced changes in some functional and pasting properties of cowpea flour.
Namibia	Horn <i>et al.</i> (2016)	Nakare (IT81D-985), Shindimba (IT89KD-245-1), Bira (IT87D-453-2)	0–600 Gy, genotype-dependent	Gamma irradiation generated substantial genetic variability. Stable mutants differing in flowering, maturity, flower/seed colour and grain yield were selected through M ₂ –M ₆ generations.
Ghana	Ocloo <i>et al.</i> (2012)	Cowpea (<i>Vigna unguiculata</i>)	0.25–1.5 kGy	Irradiation did not produce significant changes in the measured physical and sensory characteristics of the cowpea cultivars.
Iraq	Al-Kaisey <i>et al.</i> (2003)	Broad bean (<i>Vicia faba</i>)	2.5–10 kGy	Gamma irradiation reduced several antinutritional factors, including trypsin inhibitor activity and oligosaccharides, with effects generally increasing with dose.
Hungary / international review	Farkas & Mohácsi-Farkas (2011)	Legumes and other foods	<1 kGy discussed	The review indicated that appropriate irradiation doses can preserve major nutritional components while providing preservation and microbial/insect-control benefits.
India	Atchaya <i>et al.</i> (2023)	Paiyur-1	0–400 Gy	50 and 100 Gy produced superior germination; 50 Gy also showed favourable shoot/root growth and plant height, demonstrating dose-dependent physiological responses.
Germany / international review	Diehl (1995)	Food/legume products	Various	The review described irradiation as a preservation technology capable of reducing insects and microorganisms while maintaining nutritional quality within appropriate dose limits.

Studies on Cowpea Irradiation in Nigeria

The summary of some studies carried out on cowpea in Nigeria has been presented in Table 3. These empirical studies on cowpea (*Vigna unguiculata* (L.) Walp.) irradiation has primarily focused on radiosensitivity, seed germination, seedling performance, and morphological variation, with relatively fewer studies addressing nutritional quality and storage stability.

Recently, Akaagerger and Tsavnannde (2024) investigated the effect of gamma irradiation on the nutritional quality and shelf life of cowpea seeds produced in Benue State, Nigeria. Their findings showed that irradiation at doses between 200 and 500 Gray did not significantly alter major proximate components such as protein, fat, ash, crude fibre, and carbohydrate, although moisture content differed significantly. Importantly, irradiated seeds experienced significantly lower weight loss during storage compared to non-irradiated controls, suggesting improved resistance to storage pests.

Atchaya *et al.* (2023) examined gamma irradiation effects on vegetable cowpea growth parameters across doses from 50 to 400 Gy. Germination percentage was higher at lower irradiation doses (50–100 Gy), indicating selective enhancement of early physiological processes. Shoot and root lengths, plant height, and seed vigour also varied with dose, suggesting dose-dependent vegetative responses. Although primarily focused on growth rather than storage, the study's determination of lethal dose (LD₅₀) and response curves underscores the need for dose calibration for desired agronomic outcomes. Data from such germination/growth responses can inform optimal doses for maximizing germination potential while maintaining seed quality within storage optimization frameworks.

Jayashri *et al.* (2022) explored the impact of multiple gamma irradiation doses (100–500 Gy) on the storage life and germination performance of grain cowpea. All dose treatments were effective in controlling insect infestation and

preventing weight loss compared to non-irradiated controls, demonstrating gamma irradiation's role in enhancing storage stability. Notably, 200 Gy achieved the highest germination percentage (84.33%) and enhanced seedling vigour parameters such as speed of germination, shoot length, and dry weight. Lower doses also improved root length and vigour indices, indicating a potential threshold where irradiation stimulates physiological processes. Conversely, higher doses above 200 Gy showed progressive decreases in morphological parameters, emphasizing the importance of optimizing the irradiation dose to avoid detrimental effects. These findings underscore the balance needed between sufficient pest control and preservation of germination potential for cowpea storage management.

Gnankambary *et al.* (2019) evaluated the radiosensitivity of three cowpea genotypes—KVx396-4-5-2D, Moussa Local and Komsaré—across doses ranging from 0 to 300 Gy. Their germination results demonstrated a clear dose-dependent decline, with germination sharply reduced beyond 150 Gy and completely inhibited at 300 Gy. The authors further showed that survival percentages and seedling vigour indices (shoot length, root length, seedling dry weight) followed similar trends, establishing that gamma irradiation can induce measurable physiological stress when doses exceed varietal tolerance. This research is useful for understanding the upper limits of gamma irradiation in cowpea intended for storage, especially when maintaining germination potential is important for farmers who store seeds for subsequent planting. The study importantly highlights genotype-specific variability, indicating that Nigerian cowpea varieties may require tailored irradiation limits to optimize both storage stability and germination capability. Such dose-response patterns align with the thesis objective of determining an “optimal” dose window that minimizes deterioration while preserving seed viability.

Mensah *et al.* (2017) investigated how gamma doses between 50 and 400 Gy influence biochemical attributes in cowpea

and pigeon pea seeds. Their results demonstrated that low doses (50–150 Gy) produced mild stimulatory effects, including slight increases in soluble protein, enzymatic activity (amylase and peroxidase) and improved germination energy, suggesting hormesis. However, doses above 300 Gy caused declines in enzymatic activity and membrane integrity, visible through increased electrolyte leakage. Although proximate composition remained relatively stable up to 200 Gy, higher doses created measurable physiological stress. These findings have direct implications for optimizing gamma irradiation doses in cowpea: low doses may enhance certain quality attributes while high doses may degrade physiological functionality, particularly germination. This reinforces the thesis framework that the “optimal dose” emerges from balancing desirable storage improvements with avoidance of biochemical stress that could compromise seed viability or nutrient retention.

Eze *et al.* (2016) performed community-level trials in South-eastern Nigeria, combining farmer-scale storage (jute sacks, polypropylene bags, and hermetic silos) with gamma-irradiated cowpea seeds at doses of 0, 150, and 350 Gy. Over an eight-month storage period they measured weight loss, insect damage, germination at the end of storage, and farmer acceptance. Results showed that 150 Gy-treated seeds stored in hermetic silos produced the best outcomes—minimal weight loss (<3%), low insect perforation, and germination rates above 80% after storage. Conversely, 350 Gy suppressed insect damage most effectively but reduced germination to levels unacceptable for planting (below 60%). Farmer surveys indicated willingness to adopt irradiation at the 150 Gy level when paired with hermetic storage because it preserved both food grain and planting seed quality. The study provides practical, field-tested evidence that supports thesis goals: optimisation requires matching dose to intended end-use (consumption vs. planting) and storage system—realities often missed in lab trials.

Siddiqui *et al.* (2015) assessed the impact of 100–600 Gy gamma irradiations on moisture content, storage stability and seed microbial load. Their findings showed that moisture content decreased progressively with dose, leading to improved storability and reduced fungal growth. Since cowpea exhibits similar seed coat permeability and biochemical behaviour, these results are empirically relevant for understanding how gamma irradiation may influence water activity in Nigerian cowpea. Lower moisture enhances resistance to spoilage microbes and enzymatic degradation, therefore contributing to longer storage longevity. Additionally, the study reported no significant changes in crude protein and fat content up to 400 Gy, indicating proximate composition stability at low–moderate doses. The study strengthens the thesis rationale by providing evidence that gamma irradiation serves as a multifaceted preservation tool—lowering moisture activity, suppressing microbial load and enhancing storage resilience without harmful nutrient loss at optimal doses.

Djoukeng *et al.* (2014) assessed the proximate composition of cowpea seeds subjected to gamma irradiation (100, 300 and 500 Gy) and then stored for six months under ambient tropical conditions. The investigators performed monthly proximate analyses (AOAC, 2012) and sensory acceptability tests. Across all doses tested, crude protein content showed no significant decline, and crude fibre and ash values fluctuated within analytical error margins; however, a modest reduction in extractable lipids was observed at 500 Gy after six months. Microbial counts (yeast and mould) were significantly lower in irradiated lots, particularly at 300 and 500 Gy, which translated to better organoleptic stability over time. The

authors concluded that 300 Gy offered the best compromise—substantial pest and microbial suppression with minimal proximate alteration—making it a strong candidate for optimisation when the objective includes both storage stability and maintaining nutritional value. The study’s empirical design and repeated measures strengthen its recommendations for Nigerian cowpea storage programmes. Adebawale and Adeoye (2013) investigated how gamma irradiation influences antinutritional factors (phytate, tannins, trypsin inhibitors) in cowpea seeds. Using doses between 100 and 1000 Gy, they found that even low doses (200–400 Gy) significantly reduced trypsin inhibitor activity and phytate levels, improving *in vitro* protein digestibility. Tannin content was less sensitive to irradiation and showed significant reduction only at the highest dose ranges (>600 Gy). Notably, proximate macronutrient contents remained stable across the lower dose range, indicating that nutrient preservation and antinutrient reduction can be decoupled—an important consideration for optimisation. The authors concluded that a moderate dose around 300–400 Gy would be advantageous for improving nutritional quality (via antinutrient reduction) without compromising proximate composition or seed viability, making this range attractive when the goal is to maximize nutritional outcomes from stored cowpea destined for human consumption rather than planting.

Tresina *et al.* (2011) assessed gamma irradiation effects on physicochemical and proximate parameters of *Vigna unguiculata* subsp. *unguiculata* at varying doses (2–25 kGy). While this study used higher doses than typical storage studies, results showed moisture content decreased significantly with increasing dose, suggesting dose-dependent effects on water dynamics. Crude protein increased, whereas crude lipid, crude fibre, and ash contents decreased in a dose-dependent manner, highlighting trade-offs in nutritional components at high doses. Such proximate composition changes are vital when considering irradiation for nutritional quality preservation in addition to pest control. These broad dose studies offer comparative insights relevant when selecting lower doses for storage stability without compromising key nutritional aspects.

Abu (2009) evaluated gamma-irradiated cowpea seeds for colour, cooking quality, and pasting characteristics. High doses caused significant colour changes and altered cooking time due to starch and pectic substance degradation, indicating that gamma irradiation can affect functional quality beyond storage stability. Changes in nutrient leaching and textural attributes occurred in a dose-dependent manner, demonstrating that while gamma irradiation can improve certain processing traits, careful dose control is essential to preserve desirable physicochemical properties for nutritional and consumer acceptance.

One of the early Nigerian studies by Obisesan and Amujoyegbe (1997) examined the effects of gamma irradiation on seedling performance of selected cowpea varieties. Their results showed a progressive decline in germination percentage, seedling height, and leaf development with increasing irradiation dose, confirming varietal differences in radiosensitivity.

Subsequent research expanded into mutation breeding. Studies involving cowpea varieties such as K VX396-4-5-2D and local landraces reported that gamma irradiation induced both qualitative and quantitative variations, including changes in flower colour, pod characteristics, seed coat colour, and growth parameters. These studies also estimated lethal dose fifty (LD₅₀) values based on germination and seedling survival, indicating that optimal mutation induction

doses vary across genotypes due to differences in seed size, coat thickness, and physiological status.

Other Nigerian academic works, including postgraduate theses, have reported that gamma irradiation induces variability in growth, flowering, and yield-related traits of cowpea under local agro-ecological conditions. However, these studies were often limited to early mutant generations (M₁–M₄) and focused largely on phenotypic evaluation without molecular validation.

Collectively, Nigerian studies confirm that gamma irradiation affects cowpea germination, growth, and storage behaviour in a dose- and genotype-dependent manner, and that it holds promise for crop improvement and postharvest management. Table 4 shows a cross-section of storage and seed performance of cowpeas when irradiated with Gamma rays.

Critical Discussion of Empirical Studies

Dose – Dependent Effects of Gamma Radiation

When combined together, the studies reviewed reveal a broadly dose-dependent reaction of cowpea to gamma irradiation even though there still exists an inconsistency in the dose associated with beneficial or detrimental effects that are observable. Kumar *et al.* reported stimulatory responses within 50–150 Gy, whereas Gnankambary *et al.* observed a marked decline in germination beyond 150 Gy. Jayashri *et al.*, however, reported a peak germination at 200 Gy under their experimental storage conditions. These findings vis-à-vis their variability suggest that the observed response to irradiation may not be interpreted to stem from absorbed dose alone but may also depend on other factors such as the genotype, experimental conditions, seed condition and endpoint evaluated.

Table 3: Nigerian Studies on Gamma-Irradiated Cowpea

Author	Variety / genotype	Dose	Trait improved / major response
Akaagerger & Tsavnande (2024)	NR	200–500 Gy	Lower weight loss during storage; major proximate components were maintained.
Atchaya <i>et al.</i> (2023)	Vegetable cowpea	50–400 Gy	Higher germination at 50–100 Gy; favourable changes in shoot/root length, plant height and seed vigour.
Jayashri <i>et al.</i> (2022)	Grain cowpea	100–500 Gy	200 Gy produced the highest germination (84.33%) and improved seedling vigour; lower doses also improved root length and vigour indices.
Gnankambary <i>et al.</i> (2019)	KVx396-4-5-2D, Moussa Local, Komsaré	0–300 Gy	No improvement at higher doses; germination, survival and seedling vigour declined beyond 150 Gy.
Mensah <i>et al.</i> (2017)	Cowpea and pigeon pea seeds	50–400 Gy	50–150 Gy produced mild stimulatory effects, including increased enzymatic activity and improved germination energy.
Eze <i>et al.</i> (2016)	NR	0, 150, 350 Gy	150 Gy combined with hermetic storage produced >80% germination and <3% weight loss after storage.
Siddiqui <i>et al.</i> (2015)	NR	100–600 Gy	Reduced moisture and fungal growth; improved storability while protein and fat remained stable up to 400 Gy.
Djoukeng <i>et al.</i> (2014)	NR	100, 300, 500 Gy	300 Gy provided the reported compromise between pest/microbial suppression and preservation of proximate composition during storage.

NR = Not reported in the relevant section of the article.

Table 4: Gamma Irradiation, Storage and Seed Performance

Study	Dose	Storage duration	Bruchid / pest control	Germination
Kumar <i>et al.</i> (2018)	50–250 Gy	3 months	NR	50–150 Gy associated with higher early germination; 200–250 Gy showed slight declines.
Akaagerger & Tsavnande (2024)	200–500 Gy	NR	Lower weight loss during storage, suggesting improved resistance to storage pests.	NR
Jayashri <i>et al.</i> (2022)	100–500 Gy	NR	All irradiation doses controlled insect infestation and prevented weight loss relative to controls.	200 Gy: 84.33%, highest reported germination; higher doses progressively reduced morphological performance.
Eze <i>et al.</i> (2016)	0, 150, 350 Gy	8 months	150 Gy + hermetic storage: low insect perforation; 350 Gy suppressed insect damage most effectively.	150 Gy: >80%; 350 Gy: <60%.
Djoukeng <i>et al.</i> (2014)	100, 300, 500 Gy	6 months	300 and 500 Gy significantly reduced yeast/mould counts; article describes 300 Gy as providing substantial pest/microbial suppression.	NR
Gnankambary <i>et al.</i> (2019)	0–300 Gy	NR	NR	Germination sharply reduced beyond 150 Gy and was completely inhibited at 300 Gy.

Genotype-Dependent Radiosensitivity

A review of the studies indicates that cowpea's radiosensitivity shows a variation vis-à-vis genetic backgrounds thereby buttressing the established fact that irradiation dose alone may be insufficient for predicting the expected biological response. Gnankambary *et al.* (2019), for example, evaluated three cowpea genotypes and found that germination and seedling survival declined markedly at doses above 150 Gy, while the estimated LD₅₀ varied among genotypes. This variation was attributed by the authors to differences in individual seed characteristics and quality (Gnankambary *et al.*, 2019).

It is important to note that this observation is consistent with the genotype-dependent responses reported by Kumar *et al.* (2018), where irradiation of samples resulted into either stimulatory or inhibitory effects depending on which material is being studied. To further buttress this, Ramolekwa *et al.* (2024), observed variation in physiological, physicochemical and yield characteristics among M4 cowpea mutant lines derived from 300 – 500 Gy irradiation (Kumar *et al.*, 2018; Ramolekwa *et al.*, 2024).

When critically studied together, these findings suggest that there may be no single irradiation dose that can be assumed to yield an equivalent response across cowpea all genotypes. Consequently, dose optimization being used for mutation

breeding and/or seed preservation should put into cognisance the genetic background of the cowpea together with the specific feature being targeted.

Irradiation Dose versus Storage/Pest Control

A further review into the studies suggests that increasing irradiation dose does not necessarily yield a proportionate enhancement in storage protection. Eze *et al.* (2016) reported that while 150 Gy yielded a desirable balance between insect control, storage stability and germination, 350 Gy yielded stronger suppression to insect while but reducing germination to an unacceptable level. At this point, a trade-off might just be the result between effective pest control and preservation of seed viability.

Furthermore, a similar pattern was reported by Jayashri *et al.* (2022), where irradiation was effective against pulse beetle infestation, while 200 Gy produced the highest germination (84.33%) and higher doses were associated with progressive reductions in germination and morphological performance. These findings suggest that the dose providing the strongest pest-control effect may not necessarily be the most suitable dose when the irradiated cowpea is intended for subsequent planting.

When taken together, the reviewed evidence indicates that irradiation for cowpea storage should be evaluated as a balance between pest suppression and preservation of seed viability for future use. Therefore, dose selection should consider both the required level of storage protection and the minimum acceptable germination performance rather than relying on pest – control efficacy alone.

Limitations of Existing Empirical Studies and Research Gap

Despite the contributions of both international and Nigerian studies, several critical limitations and research gaps remain evident. Existing studies have widely examined gamma irradiation of cowpea using diverse separate parameters which includes: mutation breeding, postharvest preservation, nutritional quality, and germination or seed viability. This has resulted in an integrated understanding vis-à-vis how irradiation dose impacts these interconnected particularly for cowpea cultivated under Nigerian agro-ecological conditions. A more comprehensive approach is therefore required in order to identify the irradiation conditions which are able to simultaneously control storage pests, preserve nutritional quality while maintaining seed viability and accounting for genotype-dependent responses.

First, most Nigerian studies emphasize morphological and early growth traits, such as germination percentage, seedling vigour, plant height, and leaf characteristics. There is limited integration of nutritional quality assessment, particularly detailed proximate composition, micronutrients, and antinutritional factors, which are crucial given cowpea's role in human nutrition.

Second, storage stability and preservation studies are insufficiently comprehensive. While some research has examined short-term shelf life or weight loss, there is a lack of systematic evaluation of long-term storage performance, seed viability retention, moisture dynamics, and combined effects of irradiation on pest control and germination potential during storage.

Third, dose optimization has not been holistically addressed. Existing studies often determine LD₅₀ values based solely on germination or seedling survival, without integrating multiple quality indicators such as storage stability, nutritional integrity, and germination potential. This limits the practical

applicability of findings for recommending optimal irradiation doses.

Fourth, molecular and cytogenetic analyses are largely absent in Nigerian cowpea irradiation studies. Most conclusions are drawn from phenotypic observations, leaving the genetic basis, mutation stability, and heritability of induced traits insufficiently understood.

Fifth, many studies utilize a narrow germplasm base and single-environment evaluations, thereby limiting understanding of genotype × environment (G × E) interactions and the stability of irradiation-induced traits across different Nigerian agricultural ecologies.

Consequently, there is a clear research gap in integrated studies that optimize gamma irradiation dose for cowpea by simultaneously evaluating storage stability, proximate composition, preservation efficiency, and germination potential under Nigerian conditions. Addressing this gap will contribute to both mutation breeding and postharvest management, providing scientifically grounded recommendations for the use of gamma irradiation in cowpea improvement and storage.

Future Perspectives

Alternative Irradiation Technologies

Future studies can examine alternative such as electron-beam and X-ray irradiation and/or complements to the conventional use of gamma irradiation. While beams are able to provide high dose rates, shallow depth of penetration and no requirement for the use of radioactive sources, X-ray irradiation systems are machine-based and can be switched off when not in use. This presents X-ray systems as a worthy alternative when safety concerns are paramount.

Combined and Optimized Irradiation Approaches

A combination of two or more approaches could also suffice. Irradiation with established storage methods to determine whether improved pest control and preservation can be achieved without compromising seed viability. This would be particularly relevant to the central dose-optimization problem identified in this study, where storage stability, nutritional quality and germination need to be considered together.

Omics and Advanced Biological Characterization

Furthermore, studies could take the use of transcriptomic, metabolomic and related omics approaches in order to clarify the biological pathways via which irradiation of plant products produces dose- and genotype-dependent responses. This may help to open up the field beyond phenotypic measurements towards a better understanding of the mechanisms underlying observed changes.

AI-Assisted Breeding and Dose Optimization

Artificial-intelligence approaches may eventually find usage in the integration of irradiation dose, genotype, germination, storage, nutritional and environmental data to support the ultimate prediction of suitable irradiation conditions.

CONCLUSION

Cowpea remains one of Nigeria's most important food and income-generating legumes, yet the sustainability of its production is persistently undermined by post-harvest losses of up to 16%, driven largely by insect infestation and the limitations of conventional, pesticide-dependent storage practices. This review has shown that gamma irradiation offers a well-established, non-thermal route to addressing this problem, with a dual value proposition: it can disinfest stored grain and extend shelf life without inducing radioactivity or,

at appropriately controlled doses, generate the genetic variability required for mutation breeding and varietal improvement. The literature reviewed confirms that the biological effects of gamma radiation on cowpea and related legumes are strongly dose-dependent and genotype-dependent, mediated through water radiolysis, reactive-oxygen-species generation, DNA damage and repair, and downstream biochemical and physiological responses. International studies have generated valuable dose–response benchmarks, while Nigerian studies have begun to characterize local cultivar responses, particularly for germination, seedling vigour, and early growth traits. Looking ahead, the future perspectives outlined in this review including complementary irradiation technologies such as electron-beam and X-ray processing, combined irradiation storage protocols, omics-based mechanistic studies, and artificial-intelligence-assisted dose optimization offer a realistic and progressive roadmap for closing existing research gaps. Realizing this roadmap will require coordinated investment and collaboration among research institutions, regulatory bodies, and agricultural extension services in Nigeria. Ultimately, an optimized and well-characterized gamma irradiation protocol for Nigerian cowpea holds strong potential to reduce postharvest losses, support climate-resilient mutation breeding, and strengthen national food security, while offering a safer, more sustainable alternative to conventional chemical-based preservation methods.

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