

Effects of low-dose gamma radiation on quality and storability of groundnut (*Arachis hypogaea* L.) seeds

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Abstract

Shelled and unshelled groundnut seeds (*cv. Chinese*) subjected to low doses of gamma irradiation (0,1,2,3,4 and 5 Gy) and stored under ambient conditions were evaluated using eight tri-weekly intervals over a five-month storage period for seed quality and storability. The experimental design adopted was a Completely Randomized Design (CRD) with each of the twelve treatments replicated three times. Data comprising Physiological, Sanitary and Genetic seed qualities collected included moisture content, germination percentage, germination speed and peak, root and shoot lengths, seedling vigour, percentage emergence, days to 50% flowering, leaf and petiole colours, Statistically significant differences between irradiated shelled and unshelled seeds and their controls were observed for root and shoot lengths as well as speed of germination. Unshelled seeds recorded significantly ($p \leq 0.05$) lower seed moisture content with higher values for percentage germination, speed and peak of germination. Pathogen infectivity however rose significantly ($p \leq 0.05$) from 22% to 79.9% over the storage period. Days to seedling emergence, petiole and leaf colour as components of genetic seed quality were not affected significantly by irradiation despite the seed form with both shelled and unshelled having similar seed germinations despite irradiation dose. A dose range of 2–4 Gy was observed to have had slight stimulatory effect on seed germination and seedling vigour of both seed forms. Further investigations using 2–4 Gy radiation doses are recommended.

1.0 Introduction

Groundnut (*Arachis hypogaea* L.), an annual plant of the family *Fabaceae*, is a significant crop in the West African subregion, cultivated for its food, fodder, and industrial uses. Many constraints, both biotic and abiotic, plague groundnut production in West Africa. These constraints include erratic rainfall in the subregion, lack of seeds of high quality, pests and diseases, low inputs for cultivation, post-harvest challenges such as time and method of harvesting, and proper storage techniques [1,2]. Constraints such as pests and diseases, and the storage environment, are very important, as they are major determinants of the quality of groundnut seeds needed for both cultivation and consumption [3,4].

Groundnut, being an oilseed, is reported to store poorly with a rapid deterioration rate when compared to other crops [5]. Tian *et al.* [6] described deterioration of seeds as an irreversible and inevitable process due to a phenomenon known as ageing, leading to loss of vigour and viability. Factors such as temperature and relative humidity of the storage environment [7], genetics [8], presence of microflora and insects [9], mechanical damage [10,11], and seed maturity [8] are reported to influence seed deterioration. The loss of seed viability in groundnut is also reported to be rapid, resulting in over 50% loss within a four to five-month period. Begum *et al.* [12] and Ranga *et al.* [13] attributed loss or decrease in viability in groundnut to the invasion of storage pests, poor initial seed quality, and unfavourable storage conditions. Species of fungal genera like *Aspergillus*, *Fusarium*, *Alternaria*, *Curvalaria*, and *Macrophorma* have been reported to cause discolouration, progressive death of plant cells and tissues, loss of viability, and the synthesis of mycotoxins, especially in seeds with high oil content [14]. Also, insect pests such as groundnut bruchids cause various degrees of damage, such as shrivelling, discolouration, holes, contamination with webbing and frass, which render the seeds unfit for use [13]. The combined factors significantly reduce the quality of groundnut seed.

Seed quality is a concept that comprises physical, physiological, genetic, and health components of agricultural seeds. These components are mostly manifested in terms of seed viability and vigour of the resulting plants. Knowledge of storage potentials of seeds is highly important in preventing quality reduction. Poor storage can cause a reduction in germination capacity, shrivelling, discolouration, shrinking, seed necrosis, rotting, and toxification (aflatoxin production) of the seeds, thereby rendering the seeds unfit for cultivation or consumption [14, 13]. To extend the shelf life, groundnut seeds are normally stored unshelled, as shelled seeds are known to quickly lose viability [15]. Some studies [16,17] have proposed the pre-treatment of seeds with fungicides and insecticides before storage to prevent pest infestation, which is another major cause of seed deterioration. While several methods, including hermetic packaging and storing on racks at ambient temperatures, use of vacuum sealing, storage at low temperatures, and use of traditional methods, including storage in wood ash or even sand, have been reported [18, 19,20, 21,22]. Most of these methods have been ineffective in extending

groundnut seed viability above 20 months of storage. Losses of between 50–94% viability in groundnut seeds stored for up to six months have been confirmed by Santos et al. [23]. Furthermore, the reduction in groundnut seed germination rate, loss in amount of essential biochemicals, and other deteriorating physiological changes are caused by storage pests and unfavourable storage conditions [12].

The use of irradiation as a method of seed preservation, while available in Ghana, has often not been explored. Irradiation is a procedure that involves exposing materials to ionising radiation, such as X-rays, gamma rays, and electron beams [24]. Irradiation is widely utilised in various fields such as food processing, medicine, industrial chemistry, and agriculture. Irradiation has been reported to inhibit the activities of organisms that cause food spoilage. It is also effective in prolonging the mean life of crops by creating changes in biological processes related to post-harvest processes, such as fruit ripening, root and tuber sprouting, and aging [25,26]. Gamma rays are the most utilised form of irradiation, due to their high energy and penetrating power [27]. Gamma radiation has been used in mutation breeding of crops by affecting plant growth and development and bringing about alterations in biological processes in cells and tissues [28, 29]. The effect of gamma radiation on biological entities is shown to be a result of interactions between gamma rays and cellular molecules, such as water, to form free radicals [27]. Ashraf *et al.* [30] reported that these radicals possess the ability to alter constituents of plant cells and consequently influence the biological processes of plants. Gamma irradiation has also been used for seed preservation and as a seed primer [31, 32, 33]. However, the effect of gamma irradiation on plants is reported to vary depending on the species, varieties, range of doses, dose rate, and matrix of irradiated matter [31,34, 35]. The method, though quite eco-friendly and climatically favourable, is not fully exploited but may hold the potential to enhance commercial storage of quality groundnut seed for supply to smallholder groundnut farmers. The use of low doses of gamma radiation has the potential to enhance the quality of groundnut seeds before storage with minimum effect on quality, thereby helping to maintain and prolong groundnut seeds in storage.

This study assesses changes in seed quality parameters of groundnut, subjected to selected low doses of radiation under ambient conditions for five months. Specifically, the study assesses the radiation dose rate(s) that provides optimum protection while maintaining viability to acceptable standards, the effect of gamma radiation on physiological and sanitary quality of shelled and unshelled groundnut seeds during ambient storage, and the impact of the irradiation doses on the genetic qualities (emergence percentage, days to emergence, days to 50% flowering, leaf and petiole colour) of groundnut varieties.

2.0 Materials and Methods

2.1. Site and Crop Varieties

The study was conducted at the National Seed Testing Laboratory of the Ghana Seed Inspection Division, Plant Protection and Regulatory Services Directorate of the Ministry of Food and Agriculture, Pokuase, Accra-Ghana from December 2018 to May 2019. Foundation seed of *Arachis hypogaea* cv. Chinese used for the study produced by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was obtained from the Savannah Agricultural Research Institute (CSIR - SARI), Ghana. The variety is commercially available and commonly used by farmers in the cultivation of the crop. It is not a genetically modified cultivar. Two seed forms, shelled and unshelled, were sourced for the study. The seeds were packed in hermetic bags (700 mm gauge) weighing 100 grams and 150 grams for shelled and unshelled groundnut seeds, respectively. The variety selected is quite popular in Ghana, due to its relatively early maturing trait (100 days), medium oil content (35%), and wide adaptability to various ecological zones.

2.2. Gamma radiation

Irradiation of seeds was carried out at the Radiation Technology Centre of the Biotechnology and Nuclear Agriculture Research Institute (BNARI), Ghana Atomic Energy Commission (GAEC), Kwabenya, Accra. The seeds were exposed to selected doses of gamma radiation (Table 1) with a Co⁶⁰ source, a dose rate of 70 Gyhr⁻¹ and 71 Gyhr⁻¹ for shelled and

unshelled seeds, respectively. These dose rates were determined after a preliminary test using ethanol-chlorobenzene (ECB) as a dosimeter. The materials were placed on an adjustable metallic stool of height 70 cm from the ground and at a distance of 150 cm from the ground, bearing the source to achieve a low absorbed dose application for the samples. Three packs each of shelled and unshelled (shelled packs weighing 100 g and unshelled packs weighing 150 g) groundnuts were placed manually in the irradiation room, with the source in its shielded position in the storage room. The packs were rotated on their axis while they were irradiated to improve dose uniformity and reduce variation within the packs. After completion of irradiation, the source was moved to its shielded position, and the irradiated packs were replaced with a new batch for the next irradiation. The process continued until all the packs were treated.

Table 1 Details of the gamma irradiation of the seeds			
Code	Irradiation dose (Gy)	Exposure time (Min)	
		Shelled (S)	Unshelled (US)
D0	0	0	0
D1	1	1	0.85
D2	2	2	1.70
D3	3	3	2.55
D4	4	4	3.40
D5	5	5	4.25
<i>D=dose</i>			

Radiation doses of 0, 1, 2, 3, 4, and 5 Gy were used for the experiment. These doses were selected because of their beneficial and non-deleterious effects on selected seed quality parameters [31,36, 37]. The 0 Gy dose, which was the control, served as a reference point for comparison with the treated seeds. The exposure time was used to achieve the target irradiation doses as stated above.

2.3. Laboratory evaluation

Observations on seed quality were recorded shortly after irradiation and served as the reference point. Observations at 3 weekly intervals on storability characteristics of seeds were taken for five months based on the parameters listed below:

2.3.1. Germination test and seedling performances

Germination tests were conducted with 50 seeds in four replicates using the between paper (BT) method at 25 °C and 90% relative humidity [38]. Counting and evaluation were carried out on the 10th day after planting. Seeds were evaluated and graded as normal, abnormal, and dead. The number of normal seeds that germinated was counted in the four replications, and the % germination was evaluated based on the ratio between normal seeds and abnormal seeds, and then expressed as a percentage.

The speed of germination was calculated based on the formula provided by Maguire [39] after daily germination counts during the first 10 days after planting.

Speed of Germination = $\Sigma (n/t)$ (Eq. 1)

Where n = Number of newly germinated seeds at time ‘t’

t = Days from sowing

The peak value of germination was determined as recommended by Czabator [40] :

$$\text{Peak Value} = \frac{\text{Cumulative number of seeds newly germinated on each day}}{\text{Number of days elapsed since initial imbibition}} \text{ (Eq. 2)}$$

Ten (10) seedlings were randomly selected from each replication on the 10th day after sowing and used to determine seedling and root length. Lengths of the shoot were measured from the collar region (between the hypocotyl and radicle) to the tip of the apical bud, while the length of the root was measured from the collar region to the tip of the primary root.

Vigour Index was deduced from germination percentages and seedling length, as suggested by Abdul-Baki and Anderson [41], where:

$$\text{Vigour Index, I} = \text{Germination percentage (\%)} \times \text{Seedling length (cm)} \text{ (Eq. 3)}$$

2.3.2 Pathogen infectivity (%)

Incidence of pathogen infection was calculated based on the number of infected seeds observed at three-weekly intervals throughout the storage period. Detection of pathogenic infection was determined using Agar plating. Seed samples were superficially sterilized in 4% bleach (Sodium hypochlorite) solution for 30 s. Excess bleach on the seeds was rinsed off using sterilised distilled water. The seeds were dried on sterile blotter paper and placed on 9 mm sterile potato dextrose agar (PDA) plates that were amended with chloramphenicol antibiotic. Four seeds were placed in each petri dish containing PDA in three replicates per replicate of radiation doses. The plates were thereafter incubated at room temperature (25–28 °C) for seven days. The small number of seeds used was due to the fairly large size of the kernels, so as to maintain a fair distance between them when identifying fungal colonies that have infected the kernels. All fungal growths were identified with the aid of the Illustrated Genera of Imperfect Fungi manual [42], and their frequencies of occurrence were determined accordingly [43].

Pathogen infectivity percentages were computed for each sample using the formula below;

$$\text{Pathogen infectivity (\%)} = \left(\frac{\text{Number of infected seeds}}{\text{Total number of seeds used}} \right) \times 100 \text{ (Eq. 4)}$$

2.3.3. Moisture Content (%)

Moisture content (MC) of seed samples was determined using a WAGTECH PROJECTS AG62-100 programmable seed moisture analyser. About 100 grams of the seeds were poured into the moisture analyzer to measure their moisture content. The measurement was repeated in triplicate to determine the moisture content of the seeds as affected by the treatments.

2.4. Field Evaluation

The treated seeds were planted out in rows of 10 hills of three seeds each in a 60 cm × 30 cm planting pattern. This was done to ascertain the distinctiveness, uniformity, and stability (DUS) of the groundnut variety after the laboratory evaluation. The hills were later thinned to two stands per hill. The evaluation measured the underlisted morphological characteristics of the variety using the controls as checks. These were as follows:

Within 7 days, visual observations were carried out on the number of days it took seedlings from respective treatments to emerge after germination.

Within two weeks (14 days) after planting, the number of seedlings emerging from the plot was counted and compared. The number of seedlings that emerged after planting was counted over the number of seeds planted and then expressed as a percentage.

More so, the number of days for 50% flower appearance was also evaluated

At 60–70 days after planting, leaf colour, shape, and petiole colour were assessed using visual pictures as checks.

2.5 Statistical analysis

The data generated were subjected to Analysis of Variance (ANOVA) to test the significant difference among the treatments using GenStat (12th edition). After the normality test, germination percentage was arcsine transformed, while moisture content was square-root transformed before the test of significance among the treatments. The means were back-transformed for presentations. Means were separated using Least Significant Difference (LSD) at a probability level of 0.05. The relationships between the radiation dose and percentage germination, seedling length, vigour index, and percentage infectivity were studied using both linear and quadratic regression models. In the model, the parameters served as the dependent variables while the radiation dose was used as the independent variable.

3.0 Results

3.1. Laboratory evaluation - Seed quality parameters immediately after gamma irradiation

Seed quality tests 24 h after irradiation showed no significant effect of the treatments on each of the seed quality parameters measured, except for significantly higher moisture content ($p < 0.05$) in unshelled seeds ($6.86 \pm 0.05\%$, means are $\pm$ s.e, $\%CV = 1.0$) than in shelled seeds ($6.56\% \pm 0.05\%$, means are $\pm$ s.e, $\%CV = 1.0$).

3.2. Laboratory evaluation - Effect of Gamma radiation doses on germination

Germination percentages were significantly ($p < 0.05$) higher during storage in irradiated seeds than in non-irradiated seeds (Table 2). The highest germination percentage (88%) was observed in seeds treated with 2 and 4 Gy of radiation, which were significantly different from seeds treated with 0 and 5 Gy (84 and 86% respectively). The remaining doses (1 and 3 Gy) were not statistically different ($p \geq 0.05$) from 2, 4, and 5 Gy. A non-significant and positively correlated non-linear relationship ($R^2 = 0.84$; $p = 0.059$) was identified between germination percentage and radiation dose (Fig. 1).

Table 2
Influence of radiation doses on percentages, speed, and peak value of germination

Doses (Gy)	Germination percentages (%)	Peak value of germination	Speed of germination (No. days ⁻¹)
0	84	17.620	7.325
1	87	17.994	7.596
2	88	18.027	7.708
3	87	18.004	7.617
4	88	18.065	7.744
5	86	17.815	7.642
Mean	87	17.920	7.605
LSD _(0.05)	0.031	0.238	0.176
S.e.d	0.016	0.120	0.089
CV %	6.300	3.300	5.800

Peak of germination was significantly ($p < 0.05$) higher in irradiated seeds than in controls. The highest values (18.027 and 18.065, respectively) observed in seeds treated with 2 and 4 Gy of gamma rays were significantly different from 0 and 5 Gy (17.620 and 17.815, respectively). The doses 1 and 3 Gy were not statistically different ($p \geq 0.05$) from 2 and 4 Gy.

The speed of germination was significantly ($p < 0.05$) higher in seeds treated with gamma radiation than in the control. The fastest speed of germination was observed in seeds treated with 2 and 4 Gy (7.708 and 7.744, respectively), which were significantly different ($p < 0.05$) from the control and the 5 Gy (7.325 and 7.642, respectively).

3.3. Laboratory evaluation - Effect of gamma radiation on seedlings

Root length was significantly lower ($p < 0.05$) in seeds irradiated with 5 Gy than in seeds treated with 2 Gy (Table 3) in both forms. The lowest root length values were seen on seeds exposed with 1,3, and 4 Gy in both forms and were similar with the control (un-radiated).

Table 3
Influence of radiation dose on vigour and seedling parameters

Dose (Gy)	Root length (cm)	Shoot length(cm)	Seedling length(cm)	Vigour Index
0	14.03	5.27	17.55	1473
1	13.94	5.97	19.90	1736
2	14.64	6.27	20.91	1851
3	14.08	5.99	20.29	1762
4	14.12	6.12	20.40	1794
5	13.75	5.95	19.58	1689
Mean	14.09	5.93	19.88	1718
LSD _(0.05)	0.77	0.34	1.288	123
S.e.d	0.39	0.17	0.65	62.60
CV (%)	13.80	14.20	16.20	17.80

Shoot length was significantly lower ($p < 0.05$) in the control than in seeds irradiated (Table 4), however, among the different dose, no significant differences ($p \geq 0.05$) existed. A positive non-linear correlation existed ($R^2 = 0.89$; $p = 0.03$) between seedling length and radiation dose (Fig. 1).

Seedling vigour index was significantly higher ($p < 0.05$) in irradiated seeds than in controls. Among the dose, seeds treated with 2 Gy performed significantly better than the 5 Gy dose. However, the 2 Gy dose was not significantly different ($p \geq 0.05$) from seeds irradiated with 1, 3, and 4 Gy in both forms. Furthermore, the relationship between vigour index and radiation dose was positive and non-linear c ($R^2 = 0.87$; $p = 0.0045$).

3.4. Laboratory evaluation - Effect of seed forms (shelled and unshelled) on germination and seedlings' performance

Germination percentages, speed of germination, peak of germination, seedling length, and vigour were all significantly ($p < 0.05$) higher in unshelled than shelled groundnut forms (Table 4.). Moisture content was significantly lower ($p < 0.05$) in unshelled seeds than in shelled groundnut seeds.

Table 4
Influence of groundnut forms on germination parameters, Seedling length, vigour, and moisture content

Forms	Germination percent. (%)	Peak of germination	Speed of germination	Seedling length (cm)	Vigour Index	Moisture content (%)
Shelled	85	17.50	7.18	19.38	1650	6.70
Unshelled	88	18.34	7.98	20.16	1785	6.60
Mean	87	17.92	7.58	19.77	1718	6.65
LSD _(0.05)	0.018	0.14	0.100	0.740	71.300	0.003
S.e.d	0.009	0.069	0.050	0.380	36.100	0.001
CV%	6.300	3.300	5.800	16.200	17.800	0.700

3.5. Laboratory evaluation - Effect of irradiation doses by seed forms on root and shoot length of seedlings

Irradiation doses by forms of groundnut had a significant ($p < 0.05$) effect on root length (Table 5). Irradiated seeds produced lengthier roots than the controls (non-radiated) of both forms (shelled and unshelled). The unshelled seeds from 2 Gy exposure performed better than the controls but similar with seeds treated with 2, 3, and 4 Gy for shelled and 1,4 and 5 Gy for unshelled forms.

Table 5
Influence of doses and forms on root and shoot length of groundnut seedlings

Doses (Gy)	Root length (cm)		Shoot length (cm)		Speed of Germination	
	Shelled	Unshelled	Shelled	Unshelled	Shelled	Unshelled
0	11.38	13.20	4.88	5.66	6.98	7.67
1	13.82	14.05	5.92	6.02	7.26	7.93
2	14.22	15.06	6.09	6.46	7.34	8.08
3	14.45	13.70	6.08	5.91	7.03	8.21
4	14.48	14.07	6.21	6.03	7.30	8.19
5	13.97	14.09	5.99	5.90	7.15	7.82
Mean	13.72	14.03	5.86	5.99	7.17	7.98
LSD _(0.05)	1.09	1.09	0.48	0.48	0.25	0.25
S.e.d	0.55	0.55	0.24	0.24	0.13	0.13
CV (%)	13.80	13.80	14.20	14.20	5.80	5.80

Shoot lengths were significantly higher ($p < 0.05$) in irradiated seeds than in controls of both forms. The lowest shoot length value was observed in non-irradiated shelled seeds, while the highest value was observed in unshelled seeds treated with 2 Gy. The performance of shoot length from the 2 Gy seeds was, however, not statistically different ($p \geq 0.05$) from seeds treated with 2, 3,4, and 5 Gy for shelled and then, 1 and 4 Gy for unshelled seeds.

3.6. Laboratory evaluation - Effect of storage period on seedling length, vigour, moisture, and seed health

Storage period showed a significant effect ($p < 0.05$) on seedling length, vigour index, moisture content and pathogen infectivity during laboratory analysis (Table 6). Seedlings length and vigour index peaked at week 6 and 9 and declined at week 21.

Table 6
Influence of storage period on seedling parameters, vigour, moisture, and seed health

Storage Period (weeks)	Seedling length (cm)	Vigour Index	Moisture content (%)	Pathogen infectivity (%)
0	20.64	1901	6.71	22.20
3	18.09	1606	6.62	29.20
6	24.17	2153	6.59	47.20
9	23.21	1930	6.48	54.20
12	20.00	1725	6.63	68.10
15	19.12	1601	6.54	69.40
18	17.67	1563	6.9	77.80
21	15.29	1258	6.93	79.90
Mean	19.77	1717	6.68	56.00
LSD _(0.05)	1.49	142.50	0.005	15.72
S.e.d	0.75	72.20	0.003	7.97
CV (%)	16.20	17.80	0.700	60.40

Moisture content was significantly higher ($p < 0.05$) at the 18th and 21st week than at other storage periods. The lowest values observed at the 3rd, 6th, 9th, 12th, and 15th weeks were significantly different ($p < 0.05$) from week 0 and other periods of storage. Moisture content reduced from week 0 up to week 9, rose and fell again from week 12 to 15 and continued falling till the end of the storage period.

Pathogen infectivity was lowest at the start of the storage period but increased to the maximum at the end of the storage period. Fungal species such as *Aspergillus flavus*, *A. niger*, *A. versicolor*, and *A. ochraceous* were identified during the tests and were predominantly higher than other species such as *Botrydiploia theobromae*, *Rhizopus spp*, and *Penicillium spp*.

3.7. Field evaluation

Days to germination of groundnut seeds planted in an open field were similar for both seed forms and doses (Table 7). However, field emergence percentages for the doses and groundnut forms were quite different.

Table 7
Emergence percentages and days to emergence of irradiated forms of groundnut seeds

Doses (Gy)	Days to germination		Field emergence (%)		Days to 50% flowering	
	Shelled	Unshelled	Shelled	Unshelled	Shelled	Unshelled
0	4	4	96	96	26	26
1	4	4	96	93	26	26
2	4	4	96	100	27	26
3	4	4	100	96	26	27
4	4	4	96	100	26	26
5	4	4	96	100	26	26
Mean	4	4	96	97	26	26
LSD _(0.05)	0.51	0.51	0.01	0.01	0.81	0.81
S.e.d	0.22	0.22	0.49	0.49	0.54	0.54
CV (%)	10.15	10.15	0.88	0.88	3.63	3.63

A 100% emergence was observed in 3 Gy for shelled seeds and 2, 4, and 5 Gy for unshelled. Days to 50% flowering were between 26 and 27 and was similar among the seed forms and the radiation dose. Morphological evaluation of the plants grown from the irradiated seeds was similar under the different radiation dose (Fig. 2).

The parameters (leaf shape, colour, and petiole colour) assessed were quite similar and, hence, were not discussed further.

4.0 Discussion

4.1 Laboratory evaluation - Seed quality analysis immediately after irradiation

Moisture content was significantly higher in unshelled seeds (6.86%) than in shelled seeds (6.56%) immediately after exposure. The observation is similar to the findings of Rao *et al.* [44], who reported lower moisture content of 5.6% for shelled and 5.9% for unshelled seeds in two groundnut varieties before storage. The lower moisture content observed in shelled groundnut seeds could be due to loss of moisture through direct exposure of kernels to environmental factors prevalent at the time of the year.

Seed forms and irradiation doses had significant effects on the speed of germination. Shelled seeds treated with doses of 2 and 4 Gy and unshelled seeds of 3 and 4 Gy gave the highest speed of germination and were significantly different from the lowest group, including control, 2 Gy in unshelled seeds, and 3 and 5 Gy in shelled seeds. Similarly, Singh & Singh [45] and Kani *et al.* [46], reported that the speed of germination of rice was stimulated by low irradiation doses. This was attributed to a phenomenon termed "*Hormesis*," according to Korystov & Narimanov [47] and Jalal *et al.* [48], who both described it as an incitement of beneficial effects by low radiation doses on plants.

4.2. Laboratory evaluation - Effect of Irradiation doses on physiological and seedling parameters studied

Germination parameters served as indices of the performance of the seed lot under field conditions. Germination percentages were significantly higher during storage in irradiated seeds than in controls. Ahuja *et al.* [31] reported a 10–25% increase in germination percentages at low doses in irradiated groundnut seeds, while Hussein *et al.* [49] also reported a

34% and 26% increase in germination in sunflower seeds at 5 and 40 Gy, respectively, but with a subsequent decrease as the dose intensity increased. The slight decrease in germination at 5 Gy when compared with the other doses in the present study may be attributed to the detrimental effects of increased radiation doses. Ahuja *et al.* [31] reported a decrease of 15% in germination percentages as doses approached 5 Gy in groundnut seeds. The non-linear relationship between radiation dose and germination implies inhibitory effects at higher radiation doses. Inhibitory impacts of high gamma doses on germination have been proposed to include reasons such as alterations in processes involving cell and tissue structures, severance and dissolution of seed membranes, and formation of free radicals leading to metabolic abnormalities in germinating seeds [50,51,52]. These effects are proportional to the dose concentration [53].

Parameters such as speed and peak value of germination determine the efficiency of a seed lot in terms of time taken to complete the total process of germination. Peak of germination and speed of germination were significantly higher in irradiated seeds than in non-irradiated seeds, and in low dose (such as 2 Gy) than in high dose (such as 5 Gy). Similarly, Wiendl *et al.* [54] irradiated tomato seeds with low radiation doses (25 – 15 Gy with a 25 Gy interval and 150–200 Gy with a 50 Gy interval) and reported a stimulatory effect on germination parameters for the doses closer to the control (0 Gy) but a gradual decrease in the parameters as doses increased.

The stimulatory and inhibitory effects of low and high doses, respectively, have been explained by various authors in different crops [33,51,55,56]. The invigorating effects of low radiation doses on physiological parameters could be ascribed to their impacts on the absorption of oxygen and activities of dehydrogenases through the provision of energy to the developing embryo and the entire metabolic process. The authors attributed the inhibiting effect of high radiation doses to a significant loss of electrolytes as a result of increased membrane permeability [57]. Gamma irradiation has also been reported to bring about oxidative trauma, leading to the formation of reactive oxygen species, which interact with biomolecules, including amino acids, lipids, RNA, and DNA, resulting in disruptions of cell metabolic processes [58, 59], though these are dependent on the intensity of exposure [60].

Variations in root and shoot length at the different radiation doses in the present study were also observed by Ilyas and Naz [61] in turmeric and Marcu *et al* [62] in lettuce. High radiation dose normally causes inhibition of root growth, but low doses may occasionally stimulate growth, as observed in 2 Gy and 5 Gy in this study. Root length was significantly lower in seeds irradiated with 5 Gy than in seeds treated with 2 Gy. At higher doses, the radiation damages DNA synthesis to cause physiological changes that inhibit the growth of the plant. This is also seen in the seedling vigour index, which tends to be higher under low irradiation dose than in control and in high radiation dose. Yadav *et al.* [63], showed an improvement in seedling length and vigour of maize at low doses (< 0.2kGy) of gamma rays, but decrease of the traits beyond the stated dose. These observations are supported by a significant ($p < 0.05$) positive non-linear correlation coefficient for seedling length ($R^2 = 0.89$) and for vigour index ($R^2 = 0.87$). The stimulatory effect of low-dose gamma rays on the growth of seedlings may be ascribed to their action in inducing hormonal activities or mechanisms to tolerate environmental stress [36,64], while higher doses can cause membrane disruption and hormonal imbalances.

4.3. Laboratory evaluation - Effect of groundnut forms on physiological parameters studied

Percentage, speed, and peak value of germination, seedling length, and vigour were all significantly higher in unshelled than shelled groundnut forms during the storage period. These observations are similar to the findings of Sujatha *et al.* [5], who reported that seeds stored as pods (unshelled) recorded significantly higher seed germination and seedling vigour Index (50.88% & 842, respectively) over kernel (44.05% & 770, respectively) stored under ambient conditions for twelve months. Moisture content was significantly lower in unshelled seeds than in shelled groundnut seeds. The low moisture content could be attributed to the presence of the pods, which help to reduce moisture absorption. The superior performance of unshelled seeds to shelled seeds could be attributed to the fact that the pods provide a sort of protection to the seeds against deteriorating factors (high humidity, pests, mechanical damage, etc.) while shelled seeds may get damaged during shelling, which hastens the deterioration of seeds and also makes kernels susceptible to other biotic and abiotic attack [5].

4.4. Laboratory evaluation - Interactive effect of doses and forms on physiological parameters studied

The interactive effect between doses and forms of groundnut on root and shoot lengths was significantly higher in irradiated seeds than in controls of both forms. Root lengths of shelled seeds irradiated with 3 Gy and unshelled seeds treated with 5 Gy were significantly different from the controls of both forms. Shoot lengths of shelled seeds irradiated with 2 Gy and unshelled seeds treated with 3 Gy were significantly different from both forms of non-irradiated seeds. These observations were similar to the findings of Charbaji & Nabulsi [65] and El-Rahman et al. [66], who reported effects of different levels of radiation doses on shoot and root lengths of different forms of grapevine (*Vitis vinifera* L.) and Mungbean (*Vigna radiata* (L.) Wilczek). The speed of germination was significantly higher in the irradiated seeds than in the control due to the influence of the interaction between doses and forms of groundnut. The highest values were recorded in shelled seeds irradiated with 2 Gy and unshelled seeds treated with 3 Gy, and were significantly different from non-irradiated seeds of both forms. The difference in the dose that impacted the high speed of germination in the forms of groundnut seeds could be attributed to the presence or lack of shell in the forms, as seeds stored in the pod had a higher irradiation dose rate compared to shelled seeds. The differential response of the different forms to radiation dose has been explained as one of the factors that influence the effect of irradiation on plant growth and development [67].

4.5. Laboratory evaluation - Effect of storage period on seedling length, vigour, moisture content, and pathogen infectivity

The decreasing trends in the means of seedling length and vigour as storage period increases in this study were noted by Vasudevan *et al.* [68], who identified a progressive reduction in seedling length and seed vigour as storage period increases, irrespective of the treatments in their study, and they attributed this to deterioration due to ageing. Mangena [69] and Abadia et al. [70] also reported a fast decline in vigour for soybean and maize seeds with increasing length of storage at room temperature. Vieira et al. [71] and Asiedu et al. [72] further indicated that loss of vigour was more rapid than loss of viability when seeds are stored, and they attributed the loss of vigour during storage to seed membrane deterioration due to high moisture content and leakage of electrolytes. Moisture content was significantly higher at the 18th and 21st week than at other storage periods. The fluctuating pattern observed in the moisture content of the seeds during storage could be attributed to the changes in relative humidity of the environment due to changes in the seasonal pattern from dry harmattan to rainy season during the storage period [22, 73].

Pathogen infectivity was significantly lower at 0 week than at the end of the storage period. This phenomenon is similar to the findings of Vasudevan *et al.* [68], also, in groundnut seeds stored for ten months. As the storage period increases, pathogen infectivity also increases, hence a reduction in the quality of groundnut seeds. The increase in seed pathogen infectivity during storage in the present study could be due to latent infestation or infection brought from the field or in the process of handling the seeds, which were then brought to the fore as a result of an increase in relative humidity of the environment or fluctuation in seed moisture content.

4.6. Field evaluation

The results from the field showed slight superiority of doses 2 to 4 Gy over the remaining doses (i.e., 0, 1, and 5 Gy) as well as unshelled seed over shelled, which was similar to results obtained in the laboratory studies, as also reported by Kumari [74]. Days to germination, days to 50% flowering, and the morphological characters of the resulting plants were quite similar for all the irradiation doses and seed forms. These results indicate that low radiation doses in both groundnut forms had no impact on the plant morphology, as it was probably too low for any significant changes to occur within the seed.

5.0. Conclusion

Groundnut seeds generally lose viability and other related seed quality characteristics in storage as a result of several biotic and abiotic factors. This study elucidated the effect of low gamma radiation doses on the biotic and abiotic factors that

influence the storability of groundnut seeds and overall quality, including physiological, sanitary, and genetic seed quality of the groundnut variety used in this study. Findings from the study suggest that irradiation doses between 2–4 Gy have a positive effect on groundnut germination percentage, speed, and peak of germination, seedling vigour, and other seedling physiological characteristics through the storage period. On the effect of radiation doses on seed forms, a dose range of 2–4 Gy had a positive effect on both seed forms for physiological characters such as germination percentage, speed, and peak value of germination, moisture content, and seedling parameters during storage, with unshelled seeds slightly outperforming and storing better than shelled seeds. However, the radiation doses used in the study did not improve the sanitary quality of groundnut seeds, irrespective of the form in which they are stored, as the doses were far too low to have an impact on pathogens. The doses used in the study had no significant effect on the genetic quality of the seed; hence, there was no change in the plant form compared to the non-irradiated samples. There was a relative decline in germination and seedling parameters, moisture content, and sanitary quality across the storage period, irrespective of the dose and forms, with shelled seeds declining more than seeds in pod (unshelled). Further studies could be conducted to ascertain the impact of different irradiation doses, especially on unshelled groundnuts in storage.

Declarations

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Author contributions

CAA: Conceptualization, Supervision, writing of original manuscript, review, and editing; **KOM:** Thesis writing, Methodology, Data curation, and analysis; **EOM:** writing of original manuscript, formal analysis, review, and editing; **FCKO:** Supervision, writing of original manuscript, review, and editing.

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Data Availability

Data will be made available upon request

Declarations of Interest

The authors declare no conflict of interest.

Consent to publish

Not applicable

Consent to Participate

Not applicable

Ethical Declaration

Not applicable

This study did not require ethical approval as it exclusively involved samples of healthy groundnut seeds, and did not involve human or animal subjects. The handling of groundnut seeds and plants in this study complied with institutional

principles and national guidelines (Plants and Fertilizer Act 2010).

Permission to collect the plant/plant parts:

Not applicable.

The groundnut variety cv. Chinese used in the study was a catalogued commercially available groundnut variety produced by the Savanna Agricultural Research Institute. The variety is not a genetically modified variety and is commonly cultivated by farmers in Ghana. The seed material was procured from the Institute directly for the experimental processes. Details of seed handling protocols for the experiments are described in the methodology.

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Figures

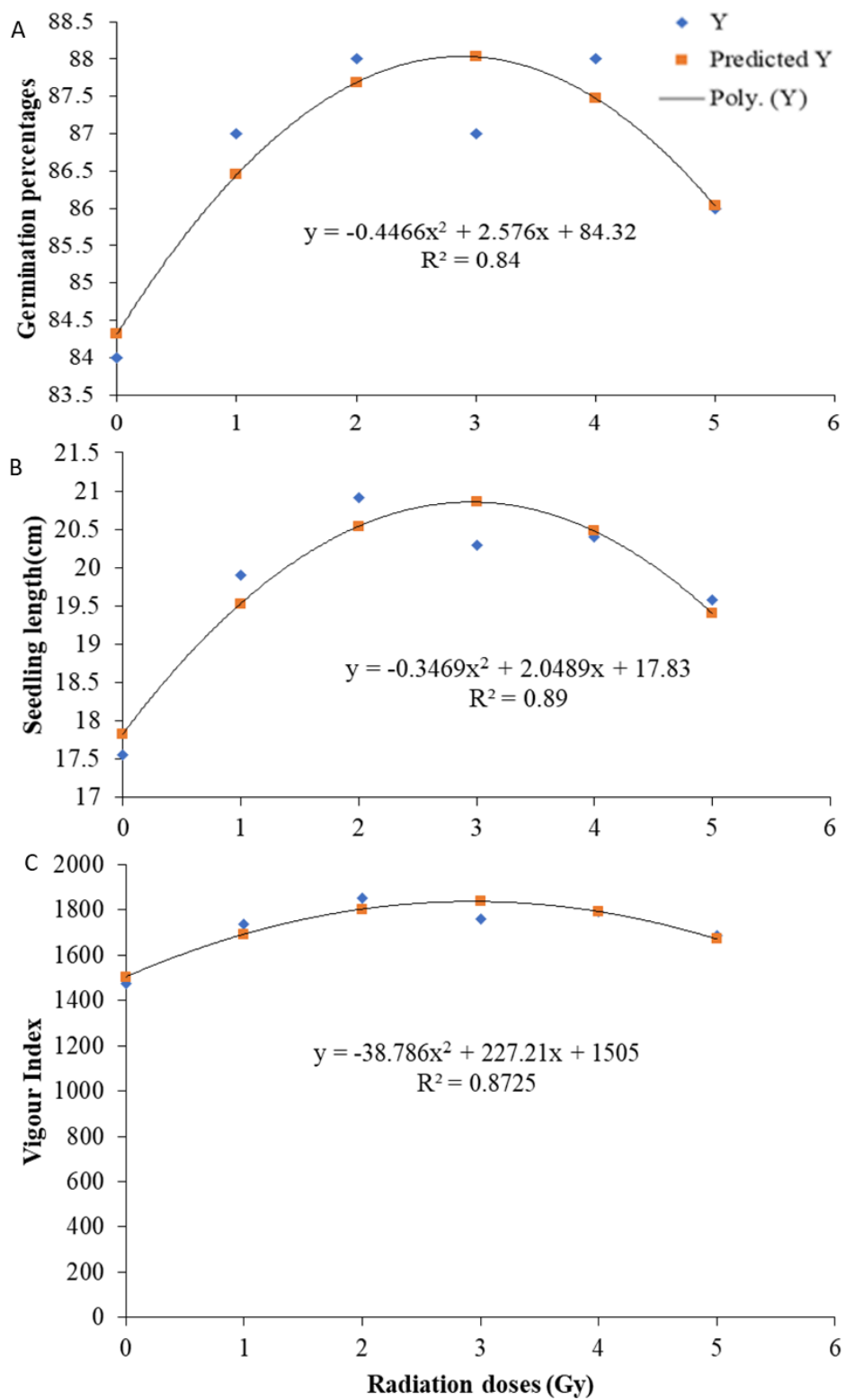


Figure 1

Relationship between radiation doses and germination percentages, seedling length, and vigour index

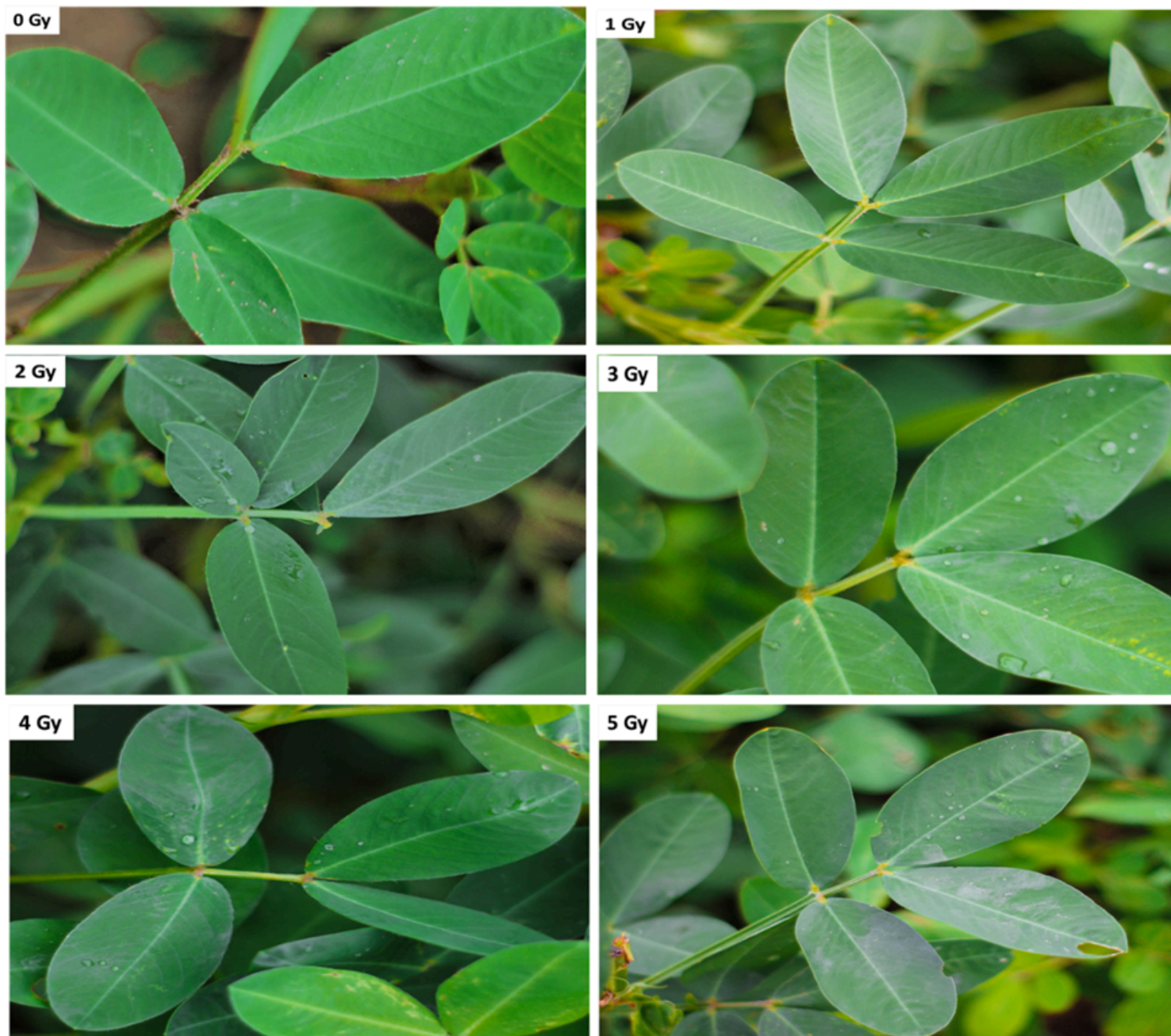


Figure 2

Leaf and petiole colour of groundnut cv. Chinese plants after seeds were exposed to different levels of irradiation (0 – 5 Gy)

The parameters (leaf shape, colour, and petiole colour) assessed were quite similar and, hence, were not discussed further.