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The Role of Gamma Radiation on the Productivity of Sesame Plants and Potassium Efficiency under Different Rates of Potassium Fertilization

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SEED irradiation is considered one of nuclear techniques used purpose for improving plant growth and enhancing fertilizer use efficiency. Thus, the present study aims at evaluating the response of sesame plants exposed to different doses of gamma radiation, i.e. 0, 50, 100, and 200 Gy, to different K rates (0, 57, 76 and 95 kg K ha^{-1}) and impact of interaction on crop yield, K recovery (KR), and efficiency (KUE). Therefore, a field experiment was conducted on sandy soil during the summer season of 2021 under drip irrigation system. The experiment was set up using a random complete block design. The results indicated that the high rate of K fertilization (95 kg ha^{-1}) with a proper dose of gamma irradiation (100 Gy) significantly increased the dry yield and K uptake of different sesame organs. Furthermore, the KR of seed yield significantly increased under 50, 100 Gy for gamma irradiation, while KUE was significantly increased under 50 Gy for gamma irradiation with a high K rate. On the other hand, a high gamma dose reflected a negative effect on yield, K uptake, recovery, and efficiency of sesame plant organs with K fertilization. These results implied that the gamma radiation may increase K uptake and efficiency and thus increase the productivity of sesame plants. It seems that plants exposed to irradiation become more efficient in absorbing K from soil comparing to the non-irradiated plants.

Keywords: Gamma Irradiation, K Recovery, K Use Efficiency, K Uptake, Sesame.

1. Introduction

One of the most significant oil crops is sesame (*Sesamum indicum* L.). Due to the edible seeds high nutritional content, it is grown in practically all tropical and subtropical nations of Africa and Asia **(Kouighat *et al.,* 2022)**. Because sesame seeds are eaten directly, sesame is regarded in Egypt as a food crop rather than an oilseed crop. It is evident that the growth in sesame farming over the past ten years, particularly on recently reclaimed sandy soils, primarily responsible for the rise in sesame production **(El-Hamidi, and Zaher, 2018)**.

One of the most efficient ways to increase plant production, yield components, and chemical composition is to irradiate seeds before to cultivation **(Rahimi and Bahrani, 2011)**. This process may increase the uptake carriers of plants to take up more nutrients and increase in growth **(Abbas et al., 2020)**. Radiation-induced morphological, structural, and/or functional modifications in plants physiology are influenced by the amount and length of time they are exposed to gamma rays **(Jan *et al.,* 2012)**. Seed irradiation may reduce the requirments of chemical fertilizers with no toxic substances accumulating or injurious radiation in the food chain **(Helmy 2015)**.

One of the most important macronutrients for plant growth and reproduction is potassium **(Xu *et al.,* 2020; Tolba et al., 2021; Khalil et al., 2023)**. Its became the third after N and P **(Morgan and Connolly, 2013)**. Its ions stimulate a number of enzymes, particularly those involved in respiration, photosynthesis, starch synthesis, and protein synthesis **(Wang *et al.,* 2013)**. Additionally, the daily fluctuations in leaf orientation or the opening and closing of stomata guard cells are affected by potassium concentration **(Oosterhuis *et al.,* 2014).** Previously, **Bin-Zakaria, (2009)** mentioned that original K was found in different forms ether available or those held in unavailable ones. Numerous enzymatic processes involved in different physiological impacts on plant development are depend on potassium **(Hasanuzzaman *et al.* 2018).** Adding potassium at the stage of flowering and maturity leads to an increase in yield **(El-Shafei et al 2023)**

Therefore, this trial aims to recognize the most proper gamma irradiation dose and potassium rate

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that achieved the enhancement of sesame yield production and in the time improved the acquisition and efficiency of potassium nutrient.

2. Materials and Methods

A field Experiment was carried out at the farm of Nuclear Research Center (NRC), Egyptian Atomic Energy Authority (EAEA), Abou-Zaabal, Egypt (30°17'08"N, 31°23'44"E) during 2021 summer season under drip irrigation system. The soil was classified as sand with 96.0 % sand, 4.0 % silt and 0.0 % clay; pH 7.2; EC 2.04 dS m^{-1}; soil organic matter (SOM) 0.03 g kg^{-1}; Total N, P, K, Fe, Mn, Zn and Cu 0.5, 2.0, 0.2, 5.8, 0.5, 1.4 and 1.4 g kg^{-1}, respectively; available N, P, K, Fe, Mn, Zn and Cu 3.0, 0.1, 8.0, 2.2, 0.01, 0.09 and 0.18 mg kg^{-1}, respectively. Extractants for available nutrients were KCl (N) and NH_4HCO_3-DTPA (P, K, Fe, Mn, Zn and Cu) and estimated according to **Carter and Gregorich (2008)**.

Experimental treatments were randomized complete block design (RCBD) in the field including two factors and replicated three times; Factor K*:* Potassium fertilizer was added in potassium sulphate form with four rates, i.e. untreated control (K_0), 57 (K_{57}), 76 (K_{76}) and 95 (K_{95}) kg K ha^{-1}. Factor R: Gamma irradiation: seeds were exposed to three gamma doses in addition to the untreated control as follows, Un-irradiated (R_0), 50 Gy (R_{50}), 100 Gy (R_{100}) and 200 Gy (R_{200}) using ^{60}Co Gamma source at Cyclotron project, NRC, EAEA. Seeds were irradiated in a ^{60} Co Gamma Irradiation Unit (Russian, CM-20 at 0.823 kGy h^{-1}, at NRC, EAEA), just before cultivation. Seeds of Sesame cv. Shandaweel-3 was provided by Oil Crop Department, Field Crops Research Institute, Agriculture Research Center, Giza, Egypt.

The plot area was about 10 m^2 (0.628 × 16 m). Seeds were sown on May 27th 2021 and harvested on July 18th 2021 (84-day season). All plots received N (71.4 kg N ha^{-1} as ammonium sulphate), 31 kg P ha^{-1} as calcium super phosphate and micronutrients as recommended. N was applied in three equal splits after 2, 4 and 6 weeks of sowing and P was added at the soil preparation process before cultivation. Also, a foliar spray was done in two equal splits after 3 and 6 weeks of sowing at a rate of 1200 L ha^{-1} of 1300 mg L^{-1} for each of Fe, Mn, Zn and Cu as chelates.

3.1- Soil and plant analyses

Surface soil (0-30 cm) was collected from the experimental site and transferred to the laboratory in polyethylene bags. Soil samples were dried at room temperature, crushed, and passed through a 2 mm sieve. Particle size distribution was determined using pipette method, and soil texture was applicate on the international triangle of soil texture **(Moeys, 2016)**. The soil pH was estimated in 1:2.5 soil: water suspension (w/v) ratio using pH meter and electrical conductivity (EC) was measured in soil paste extract by EC meter. Meanwhile, the wet oxidation method was used to calculate SOM content. Whereas, Total N (Kjeldahl model K-375), P (spectrophotometer GENWAY Model 6405), K (flame photometer JENWAY Model PFP7), Fe, Mn, Zn and Cu (atomic absorption Model Buck 210) were estimated in digested soil with 1 g soil, 10 mL H_2SO_4 and H_2O_2 **(Lu et al., 2017 and Lu et al. 2014)**.

For total K content in plant, in brief, dried plant samples were weighed about 0.2 g then digested overnight in H_2SO_4 (10 mL) at 180°C for 60 minutes then added H_2O_2 until the clear silver color, and then cooled, sample volume were adjusted to 50 mL with deionized water. The digested solution was made up of water to a constant volume and filtered, and total K concentration was estimated by flame photometer model Jenway PFP7 (**Estefan et al., 2013)**.

3.2- Data analyses and processing

Fertilizer K recovery (FKR %): K is the amount of K derived from fertilizer to plant (kg ha^{-1}) divided by the amount of fertilizer added to the soil (kg ha^{-1}) expressed as a percentage. This percentage was estimated using the following equation:

$$\text{K recovery (KR\%)} = \frac{\text{K uptake of fertilized treatment} - \text{K uptake of unfertilized treatment}}{\text{Rate of applied K fertilizer}} \times 100$$

Fertilizer K use efficiency (KUE) is determined according to the following equation expressing the efficiency as the amount of excess yield (kg ha^{-1}) obtained as a result of fertilizer application rate (kg ha^{-1}) (**Dobermann, 2007),** and expressed as kilograms of grains per kg applied K.

$$\text{KU}E = \frac{\text{Yield of fertilized treatment} - \text{yield of unfertilized treatment}}{\text{Rate of applied K}}$$

3.3- Statistical analysis:

All experimental data were subjected to ANOVA analysis and Dunken’s test to compere between treatments using SPSS program software version 20 **(Ates et al., 2019)**. All Figures were drawn using OriginPro program software version 2023.

4- Results and Discussion:

4.1- Effect of K levels and gamma ray doses on plant growth:

The main effect of K fertilization rates (Table 1) on the dry matter yield of roots, stalks, leaves and the seed yield of sesame followed a pattern of $K_{95}>K_{76}>K_{57}>K_0$. However, the main effect of gamma radiation shows a pattern of

$R_{100}>R_{50}>R_0>R_{200}$ in case of roots, leaves and seeds whereas in case of stalks it has the pattern of $R_{100}>R_{50}>R_{200}>R_0$. This indicates that the increase of irradiation doses up to 100 Gy led to increase dry matter yield of roots, leaves and seeds over those treated with 200 Gy or the untreated control.

Table 1: Main effects of both of potassium fertilization rates and gamma irradiation doses on dry matter yields (Mg ha^{-1}) of sesame plant parts.

		Sesame plant Part			
		Roots	Stalks	Leaves	Seeds
K Rate (K) kg ha^{-1}	K_0	1.50 ± 0.01d	6.17 ± 0.01d	1.88 ± 0.04d	0.81 ± 0.01d
	K_{57}	1.67 ± 0.01c	7.59 ± 0.01c	2.35 ± 0.04c	1.22 ± 0.01c
	K_{76}	2.53 ± 0.01b	9.67 ± 0.01b	3.11 ± 0.04b	1.57 ± 0.01b
	K_{95}	3.30 ± 0.01a	12.30 ± 0.01a	4.79 ± 0.04a	2.40 ± 0.01a
Irradiation Dose (R) Gy	R_0	2.07 ± 0.01c	8.14 ± 0.01d	2.59 ± 0.04c	1.34 ± 0.01c
	R_{50}	2.39 ± 0.01b	9.05 ± 0.01b	3.07 ± 0.04b	1.56 ± 0.01b
	R_{100}	2.68 ± 0.01a	10.13 ± 0.01a	3.90 ± 0.04a	1.92 ± 0.01a
	R_{200}	1.87 ± 0.01d	8.39 ± 0.01c	2.57 ± 0.04c	1.19 ± 0.01d

Notes: R_0, R_{50}, R_{100} and R_{200} are 0, 50, 100 and 200 Gy, respectively; K_0, K_{57}, K_{76} and K_{95} are 0, 57, 76 and 95 kg K ha^{-1}, respectively. Values in the same column followed by the same letter are not significantly different at $p \leq 0.05$.

Interaction between fertilization rates and irradiation doses (Fig. 1), indicated significant increases in roots, stalks, leaves and seeds dry matter yield with increasing potassium fertilization rates under all gamma irradiation doses. Likewise, dry mass of stalks, root, leaves and seed yield of irradiated plants tended to increase with upgrading gamma dose to 100 Gy; thereafter significant reductions were occurred. This was true under all potassium fertilization rates. These increments in dry matter yields may be attributed to the stimulation effect of 100 Gy gamma dose **(Moussa, 2018)**. Gamma rays are used for improving growth and quality of plants, for their high mutation frequency and they can interact with atoms and molecules. Thus, producing free radicals in cells affect the morphology, anatomy, biochemistry and physiology of the plants **(Chahal and Gosal, 2002)**. Potassium is vital for plant growth and physiology and has a regulatory function in protein synthesis, carbohydrate metabolism, and enzyme activity **Johnson *et al.*, 2022)**. **Ravichandran and Jayakumar (2018)** indicated that different doses of gamma rays can be made positive effectively utilized to create variability for various quantitative traits of the crop. Increasing the radiation dose more than 100 Gy may destruct many physiological and biochemical functions within plants; hence these plants suffered considerably and their growth were negatively affected **(Farid et al., 2021)**.

4.2- Effect of K fertilization levels and gamma ray doses on K uptake:

The main effect of K fertilization (Table 2) on K uptake by all sesame plant parts shows a pattern of $K_{95}>K_{76}>K_{57}>K_0$ indicating that the grown plants need more K to well grow up. The main effect of gamma radiation on roots, leaves and seeds showed a pattern of $R_{100}>R_{50}>R_0>R_{200}$, while the corresponding effect on stalks showed a pattern of $R_{100}>R_{50}>R_{200}>R_0$.

Table 2: Main effects of both of K fertilization rates and gamma irradiation doses on K uptake (kg ha^{-1}) by sesame plant parts

		Sesame plant parts			
		Roots	Stalks	Leaves	Seeds
K Rate (K)	K_0	9.598±0.12d	36.962±0.38d	16.210±0.45d	2.827±0.07d
	K_{57}	12.914±0.12c	53.279±0.38c	22.428±0.45c	6.426±0.07c
	K_{76}	21.324±0.12b	85.320±0.38b	32.074±0.45b	9.983±0.07b
	K_{95}	30.473±0.12a	116.891±0.38a	52.331±0.45a	23.385±0.07a
Irradiation Dose (R)	R_0	16.696±0.12c	64.533±0.38c	25.718±0.45c	9.138±0.07c
	R_{50}	20.180±0.12b	76.323±0.38b	31.323±0.45b	11.157±0.07b
	R_{100}	23.178±0.12a	89.005±0.38a	40.983±0.45a	14.325±0.07a
	R_{200}	14.254±0.12d	62.592±0.38d	25.018±0.45c	8.001±0.07d

See Table 1-foot notes. Values in the same column followed by the same letter are not significantly different at $p \leq 0.05$.

K uptake is related to the dry matter yield, making it follow the same gradient in the highest K uptake by sesame plant parts (Fig. 2). The highest K uptake by roots, stalks, leaves and seeds was achieved by $K_{95}R_{100}$. Increasing gamma irradiation dose more than 100 Gy in combination with all K rates led to decrease the K uptake by roots, stalks, leaves and seeds. This demonstrates that 100 Gy irradiation dose was the most positively effective one among all other doses. Similarly, K uptake tended to increase with increasing K fertilizer rate. This was true under all gamma irradiation doses. The lowest K uptake by roots and seeds were given by K_0R_{200}, while the lowest K uptake by stalks was resulted by the untreated treatment. K increased plants ability to withstand abiotic stress; however, the precise molecular mechanisms underlying these defences are still being studied. **Farag and El-Khawaga (2013)** and **Singh *et al.* (2013)** reported that gamma irradiation at low levels has a stimulatory effect.

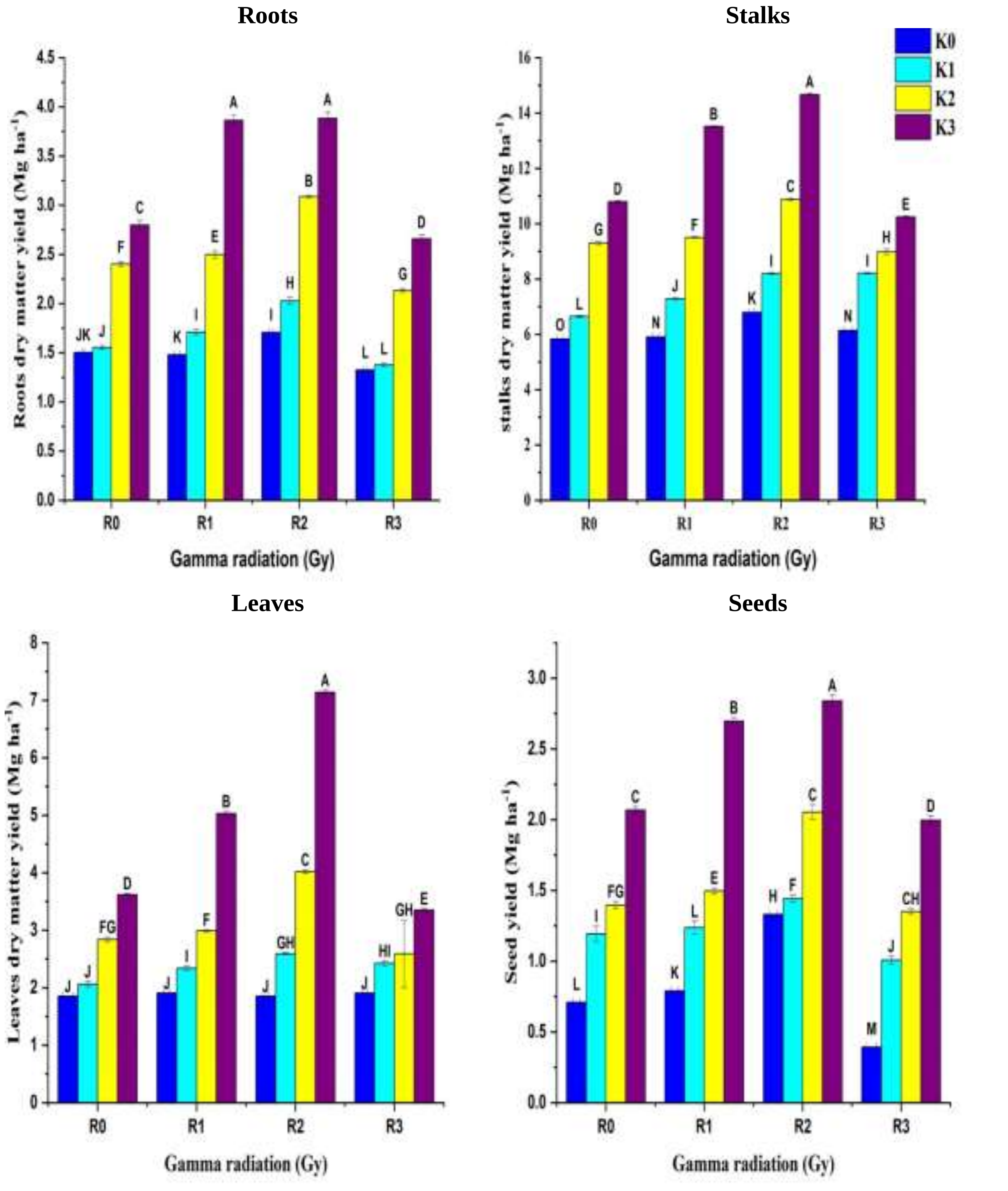


Fig. 1: Dry matter yield (Mg ha^{-1}) of sesame plant parts as affected by K fertilization rates and gamma ray doses. See Table 1-foot notes. Similar letters show that there are no significant differences between treatments.

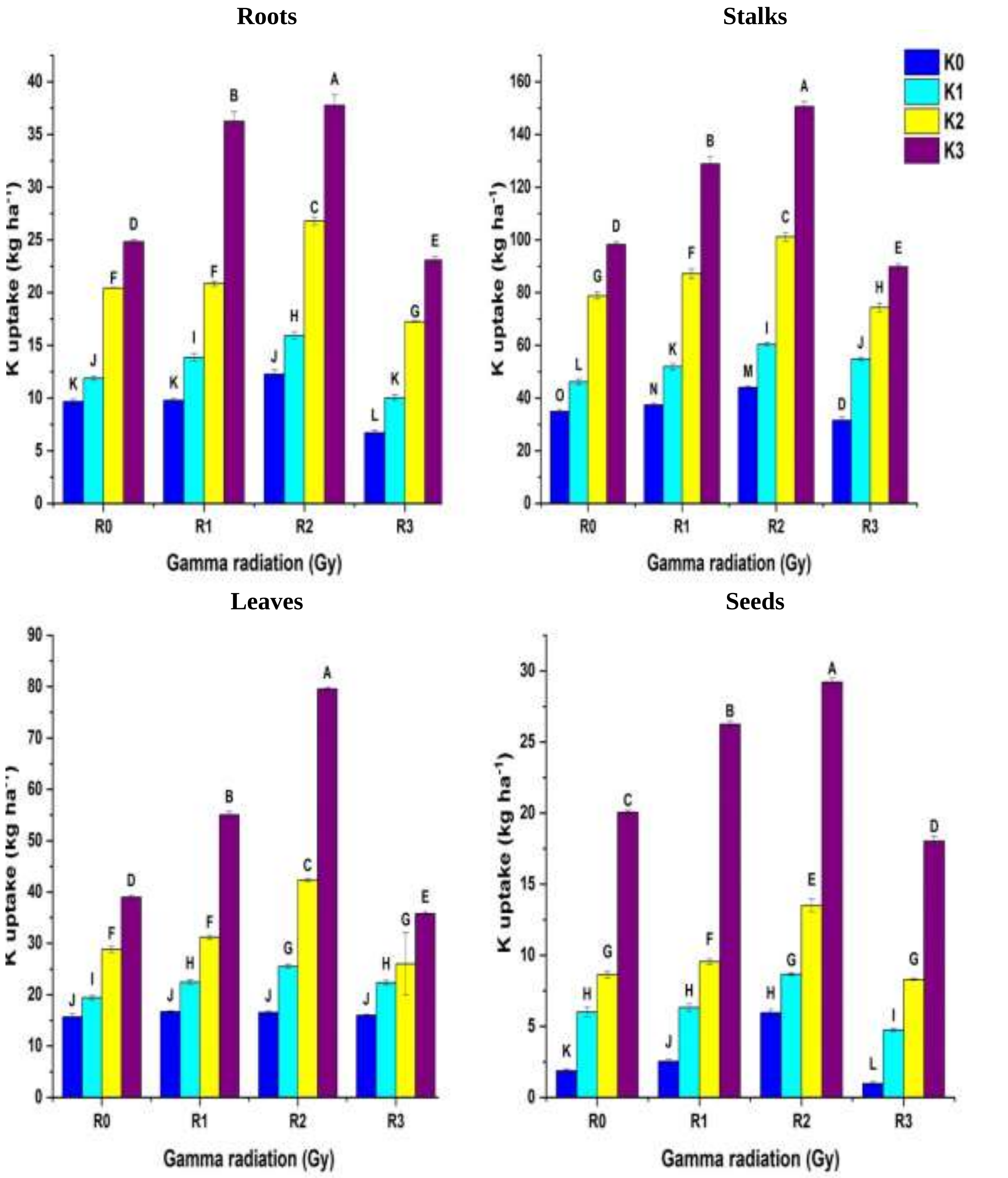


Fig. 2: Potassium uptake (kg ha^{-1}) by sesame plant parts as affected by K fertilization rates and gamma ray doses. See Table 1-foot notes. Similar letters show that there are no significant differences between treatments.

4.3- Effect of K fertilization levels and gamma ray doses on K Recovery (KR):

K fertilization main effect gave the following KR pattern for all sesame plant parts (K_{95}>K_{76}>K_{57}) (Table 3) and agree with the interaction effect. Gamma irradiation main effect showed that all doses of radiation gave a positive effect on KR by sesame plant parts, except seeds, comparing to the un-irradiated control. In this respect, seeds exposed to 50 Gy gave the highest KR. K fertilization increased KR following the sequence of K_{95}>K_{76}>K_{57}. Gamma irradiation also raised the values of KR by sesame plant parts (except for seeds) comparing to the un-irradiated control.

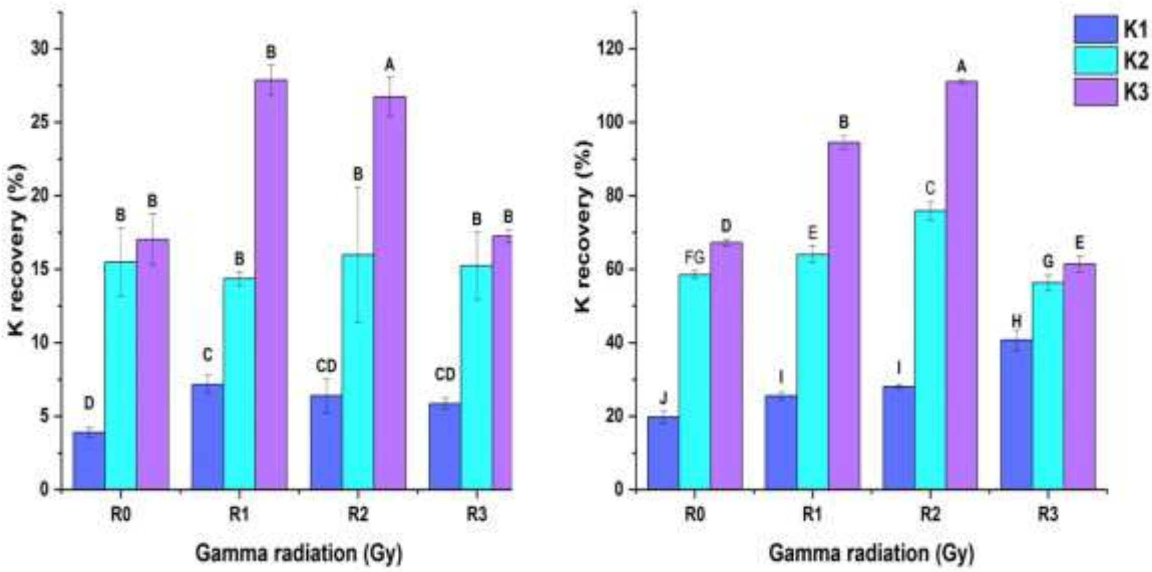
Table 3: Main effects of both of K fertilization rates and gamma irradiation doses on fertilizer K recovery (%) of sesame plant parts.

		Sesame plant parts			
		Roots	Stalks	Leaves	Seeds
K Rate (K) kg ha^{-1}	K_0	5.82±0.53c	28.51±0.52c	10.91±1.12c	6.32±1.13c
	K_{57}	15.26±0.53b	63.63±0.52b	21.86±1.12b	8.11±1.13b
	K_{76}	22.21±0.53a	83.51±0.52a	38.55±1.12a	21.64±1.13a
	K_{95}	12.12±0.61b	48.46±0.60d	16.13±1.29c	11.76±1.46b
Irradiation Dose (R) Gy	R_0	16.45±0.61a	61.31±0.60b	22.14±1.29b	13.61±1.46a
	R_{50}	16.37±0.61a	71.64±0.60a	40.40±1.29a	11.31±1.46c
	R_{100}	12.77±0.61b	52.78±0.60c	16.43±1.29c	11.40±1.46b
	R_{200}	5.82±0.53c	28.51±0.52c	10.91±1.12c	6.32±1.13c

See Table 1-foot notes. Values in the same column followed by the same letter are not significantly different at $p \leq 0.05$.

Data illustrated by Fig. (3), indicated that plants treated with 95 kg K ha^{-1} and exposed to 100 Gy dose exhibited the highest KR values among the other treatments. On the other hand, the lowest values of KR by roots, stalks and leaves were detected for the non-irradiated plants fertilized by 57 kg K ha^{-1}. Likewise, the lowest KR by seeds was detected in plants received 76 kg K ha^{-1} and irradiated with 100 Gy dose. Generally, K recovered by all plant parts tended to increase with increasing gamma dose up to 100 Gy, thereafter it decreased considerably. Also, fertilizer K recovery values increased with increasing the rate of applied K fertilizer under all gamma irradiation doses. Seeds exposed to 50 Gy produced the highest KR. In this regard, a range of quantitative aspects of the crop can be effectively made variable by using different gamma ray dosages. Potassium is necessary for the growth and physiology of plants and regulates the synthesis of proteins, the metabolism of glucose, and the activity of enzymes **(Ravichandran and Jayakumar 2018**; **Johnson et al 2022)**. Therefore, increasing KUE can significantly reduce K deficiency status and the potentially harmful effects of fertilizer N **(Congreves et al 2021)**. Variable recovery efficiency and agronomic efficiency of K in rice crops are widely mentioned by many researchers throughout the world **(Tan et al 2012).**

Roots **Stalks**



Leaves **Seeds**

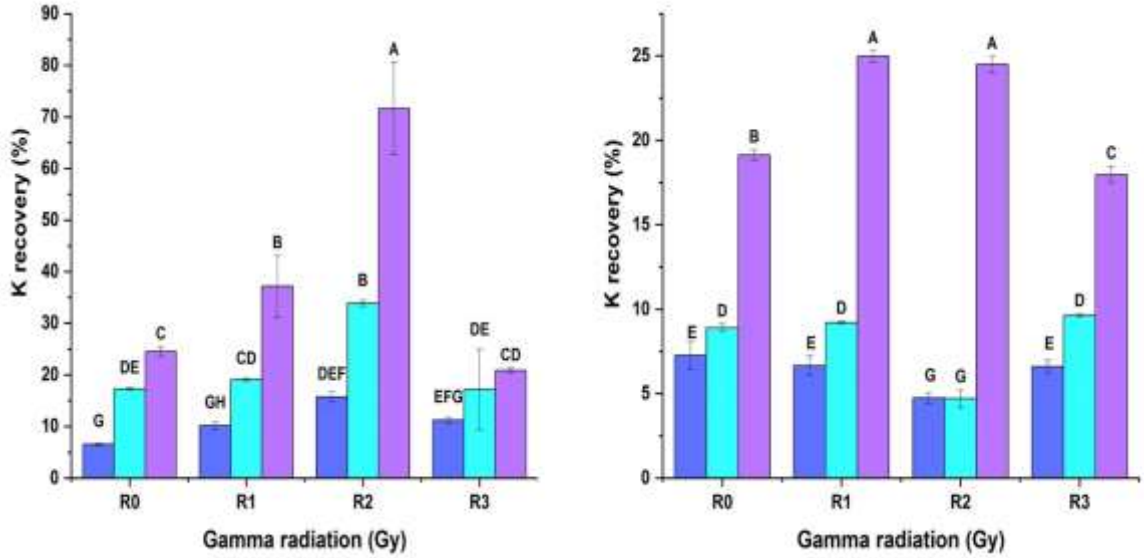


Fig 3: Fertilizer K recovery (%) of sesame plant parts as affected by K fertilization rates and gamma ray doses. See Table 1-foot notes. Similar letters show that there are no significant differences between treatments.

4.4- Effect of K fertilization levels and gamma ray doses on Fertilizer K Use Efficiency (KUE)

Main effect of K fertilization (Table 4) was as follows K_{95}>K_{76}>K_{57} with an average increase of 324 and 489% over R_0K_0 (roots), 85 and 160% (stalks), 95 and 268% (leaves) and 56 and 159% (seeds) for K_{76} and K_{95}, respectively indicating most positive effect in KUE being caused by high K rate followed by the medium K rate. The main effect of gamma irradiation was R_{100}>R_{50}>R_{200}>R_0, and this indicates that increasing seed irradiation up to 100 Gy could be useful; afterwards, negative impacts could be noticed.

Table 4: Main effects of both of potassium fertilization rates and gamma irradiation doses on fertilizer K use efficiency (kg kg^{-1}) by sesame plant parts

		Sesame plant parts			
		Roots	Stalks	Leaves	Seeds
K Rate (K) kg ha^{-1}	K_0	3.25±0.27^c	24.81±0.18^c	8.30±0.66^c	6.49±0.41^c
	K_{57}	13.77±0.27^b	45.99±0.18^b	16.17±0.66^b	10.11±0.41^b
	K_{76}	19.13±0.27^a	64.57±0.18^a	30.57±0.66^a	16.78±0.41^a
	K_{95}	8.79±0.31^c	37.36±0.21^d	11.73±0.77^c	9.56±0.47^b
Irradiation Dose (R) Gy	R_0	14.18±0.31^b	50.47±0.21^b	18.20±0.77^b	12.40±0.47^a
	R_{50}	16.71±0.31^a	53.74±0.21^a	32.21±0.77^a	9.14±0.47^b
	R_{100}	8.51±0.31^c	38.92±0.21^c	11.26±0.77^c	13.41±0.47^a
	R_{200}	3.25±0.27^c	24.81±0.18^c	8.30±0.66^c	6.49±0.41^c

See Table 1-foot notes. Values in the same column followed by the same letter are not significantly different at $p \leq 0.05$.

The highest calculated KUE (Fig. 4) by roots, stalks and leaves were induced by $K_{95}R_{100}$ while the highest KUE by seeds was found for $K_{95}R_{50}$ treatment. Efficient use of K by either seeds or stalks were the lowest at $K_{57}R_{100}$. In the same way, the lowest KUE values by roots and leaves were found owing to the application of $K_{57}R_0$. Generally, KUE values increased in all sesame plant parts with increasing the rate of ap plied K (K_{95}>K_{76}>K_{57}). Gamma irradiation also raised KUE values by sesame plant parts up to 50 Gy; thereafter, decreased. Interactions between these two factors were also positively affected KUE by sesame plant parts. In order to support the rising demand of food production from the agricultural land, the current focus is to increase KUE **(Srivastava et al 2019)**. K utilization efficiency (KUtE) is the ability of a plant to utilize acquired K from the soil to produce yield. Interestingly, the traits regulating K uptake efficiency (KUpE) and KUtE have been identified at whole plant level. Factors regulating KUpE are high root uptake capacity, early root vigour, high root-to-shoot ratios, high root length densities, proliferation of roots throughout the soil volume, high transpiration rates and exudation of organic compounds that are responsible for more non-exchangeable soil K. In a similar manner, KUtE is dependent on various factors such as effective K distribution within the plant, tolerance of the plant to low K concentrations, maintenance of optimal K concentrations in metabolically active cellular compartments, replacement of K in its non-specific roles, redistribution of K from senescent to younger tissues as well as maintenance of water relations and photosynthesis and a high harvest index **(White 2013; Srivastava et al 2019)**.

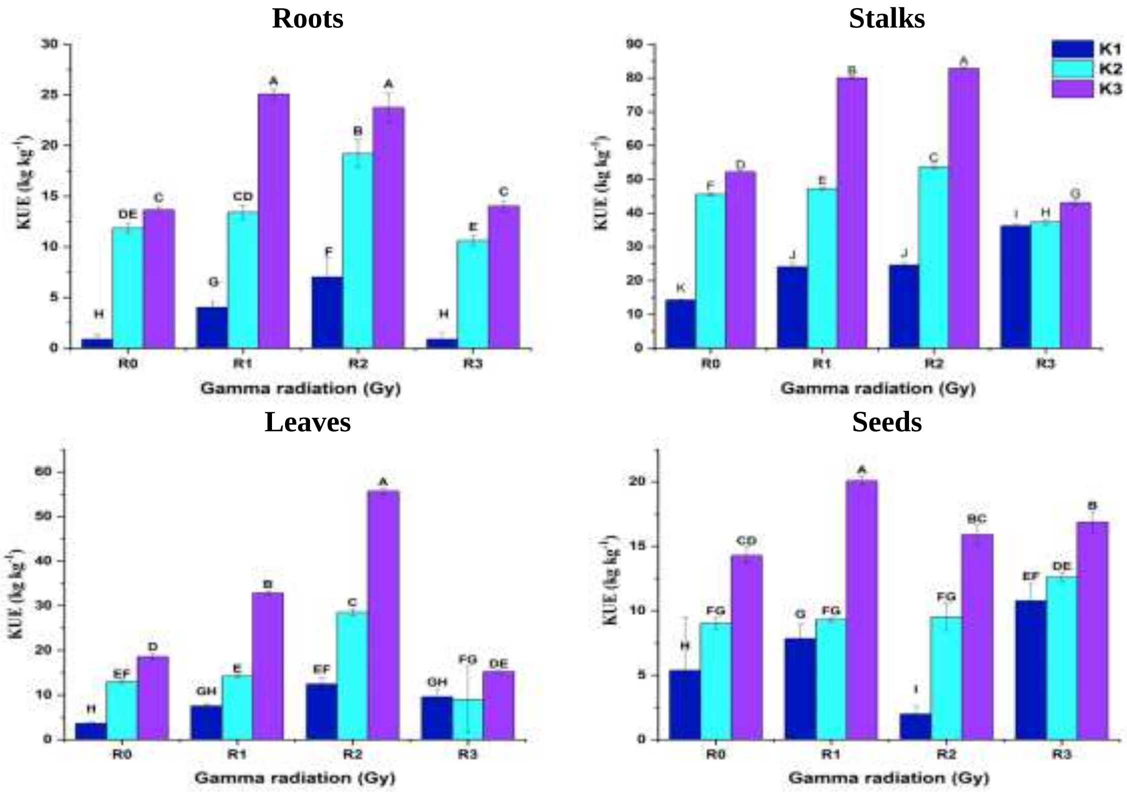


Fig. 4: Fertilizer K use efficiency (KUE) (kg kg^{-1}) of sesame plant parts as affected by K fertilization rates and gamma ray doses. See Table 1-foot notes. Similar letters show that there are no significant differences between treatments

5- Conclusion

Our results revealed that the treatment receiving both of high rate of potassium fertilization (95 kg ha^{-1}) and a medium dose of gamma irradiation (100 Gy) showed the highest dry matter yield, K uptake, KR, and KUE which suggested that the K efficiency enhanced when seeds treated by gamma radiation. Whilst the high dose of gamma rays may cause a negative effect in yield, uptake, KR, and KUE by sesame plant parts with/or without interaction with K fertilization. Our findings implied that the proper dose of gamma rays for sesame plants may increase the K uptake and its recovery by plant organs.

6- Author Contributions

Conceptualization, authors; methodology, formal analysis, resources and writing original draft preparation, all authors; writing review and editing

7-Funding

This research received no external funding.

8- Conflicts of Interest

The authors declare no conflict of interest

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