ISSN: 2287-688X

Annals of
Plant Sciences

Volume 12, Issue 07 (2023) pp. 5895-5911

Research Article

Induced Mutagenesis for Enhancing Genetic Variability and Agronomic Performance in Sorghum Varieties for Burkina Faso

Minimassom Philippe Nikièma[1], **Djibril Yonli**[1], **Hamidou Y. A. Yanogo**[1,2], **Nofou Ouédraogo**[1], **Hamidou Traoré**[1], **Mahamadou Sawadogo**[2] **and Anupama J. Hingane**[3]

[1]*Institut de l'Environnement et de Recherches Agricoles, 04 BP 8645, Ouagadougou 04, Burkina Faso*

[2]*Training and Research Unit - Life and Earth Sciences, University Joseph Ki-Zerbo, Ouagadougou, 03 BP 7021, Burkina Faso*

[3]*Plant Breeding and Genetics Laboratory, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture Department of Nuclear Sciences and Applications (NAFA), International Atomic Energy Agency (IAEA), PO Box 100, 1400 Seibersdorf, Austria*

Abstract

Sorghum is one of the main cereals in terms of production and cultivated area in Burkina Faso. However, genetic variability in Sorghum varieties is low. The study aims to induce genetic variability in farmers' preferred sorghum varieties and select the novel desired traits. Seeds of two Sorghum varieties (Grinkan and Sariaso14) were irradiated with gamma rays at 200, 300, 400 and 500 Gy doses. The mutant populations were developed using the single seed descends method. A 2-years field assessment was conducted to assess the genetic variability among 403 advance generation Sorghum mutants. A significant difference between the doses was observed for leaf number plant^{-1} (NPL) ($P \leq 1\%$) and the plant height (PlHe) ($P \leq 5\%$) of Sariaso14 lines and only for the PlHe ($P \leq 1\%$) of Grinkan lines. All irradiation doses significantly increased the grain weight panicle^{-1} of Sariaso14 lines while they affected those of Grinkan lines. The genotypic coefficient of variation (GCV), the phenotypic coefficient of variation (PCV), the broad sense heritability (H^2) and the genetic gain (GG) were high for grain weight panicle^{-1} (GrWe). They were 90.82%, 92.84 %, 0.95 and 183%, respectively for Sariaso14 lines and 80.85%, 89%, 0.82 and 151.3% respectively for Grinkan lines demonstrating that the observed variations for this trait was mainly due to genetic factors. The clustering of the mutants showed that the mutagenesis allowed the selection of dwarf, early maturity and high grain weight mutants. Thus, the induced mutation has improved the agronomic performances of sorghum varieties.

Keywords: *Sorghum, mutation breeding, gamma rays, genetic variability.*

Introduction

Agricultural production and food security repeatedly face several challenges such as climate change and reduction of arable land. Meanwhile, the world's population is growing at an exponential rate, slightly more than 1% per year (United Nations projections, 2022). This growth leads to a sharp increase in food requirements (Ronald, 2014). Cereals are the basic component of the local diet in sub-Saharan Africa and more particularly in Burkina Faso. Ranked fifth in the world's cereals, sorghum is grown mainly in the semi-arid area of the tropics and sub-tropics (Mundia, *et al.,* 2019). Sorghum grains and flour are consumed in several dietary forms such as pasta, couscous, soft drinks, local beer among others (Dicko, *et al.,* 2006) and also used in poultry and livestock feeding (Trouche, *et al.,* 2010). As a food crop, sorghum was reported to have high nutritive

---

***Corresponding Author:**
Minimassom Philippe Nikièma;

DOI: http://dx.doi.org/10.21746/aps.2023.12.7.3

compounds so that it can be used for substituting rice (Soeranto, *et al.,* 2001). In Burkina Faso, sorghum is grown by more than 71% of farm households in all agro-ecological zones, from the South in the Sudanian climate to the North in the Sahelian climate, although its preferred cultivation zone is between 600 and 900 mm isohyets. Its growing covers about 45% of total cultivated land (Vom Brocke, *et al.*, 2010); making it the first most cultivated cereal. Sorghum therefore plays a significant role in the food self-sufficiency of the country's populations. However, its production and productivity are constrained by the use of low yielding cultivars, which are susceptible to some biotic and abiotic stresses. Sorghum yield is less than 1ton/ha in Africa (FAOSTAT, 2018) whereas it is about 2 tons/ha in USA (USDA, 2021). Based on field experiments, yields have exceeded 11 ton/ha, with above average yields ranging from 7-9 ton/ha in areas where moisture is not a constraint; showing that sorghum has a high production potential (Soeranto, *et al.,* 2001). However, the majority of Burkina's producers grow traditional varieties that are endowed with low yield. Only 15% of them grow improved varieties (Ouédraogo, 2015). Successful crop improvement in terms of yield and quality is dependent on the availability of genetic variation, especially in the primary gene pool within a crop species (Olasupo, *et al.,* 2016). Unfortunately, genetic variability in sorghum landraces in Burkina Faso is very low. Bhagasara, *et al.,* (2017) emphasized that genetic improvement for quantitative and qualitative traits depends on the nature and amount of variability present in the genetic stock and desirable traits having high heritability are more helpful for crop improvement through selection. Spontaneous mutations that may contribute to creating genetic variability within a plant species have a very low frequency of occurrence on the order of $1/10^6$ genes (Gressel and Levy, 2006). Induced mutagenesis is therefore used to accelerate mutations. Induced mutagenesis may create genetic diversity to improve desired traits in plant species (Ahluwalia, *et al.,* 2004) using chemical or physical mutagens. Among the radiation-based methods, gamma irradiation is known to be the most effective in inducing a wide range of mutations (Bado, *et al.*, 2015).

The use of mutagens allows the induction of desired traits that cannot be found in nature (Pathirana, 2011). Thus, induced mutations have great potential to provide new genetic improvements. Several varieties were developed through the use of mutagenic agents or by hybridization and released for their resistance to diseases, lodging and contribution to grain quality and yield improvement.

Beneficial mutations, such as high protein digestibility, brown midrib, dwarfism, early flowering, high lysine content have been induced in sorghum (Oria, *et al.,* 2000). According to IAEA database (http://mvgs.iaea.org), there are more than 3,400 officially released mutant varieties of 238 different species in more than 72 countries around the world that not only increase biodiversity but also provide new germplasms for plant breeding. Considering the need to further diversify the genetic base in sorghum, this study aimed to assess genetic variability generated by induced mutations in 'preferred and improved sorghum varieties with the prospect of improving their quantitative and qualitative agronomic traits.

Materials and Methods

Materials

The study site, Kouaré Environmental and Agricultural Research Station was described by Nikièma, *et al.,* (2020).

The study is focused on the mutant population developed from two Sorghum varieties, namely Sariaso14 and Grinkan. Sariaso14 was developed by the breeding program of "Institut de l'Environnement et de Recherches Agricoles (INERA)/Burkina Faso," while Grinkan was developed by "Institut d'Economie Rurale (IER)/Mali." Nikièma, (2021) described their agro-morphological traits, and seeds of both varieties were obtained from INERA. The choice of these two varieties was based on their tolerance to *Striga hermonthica* and their preference among farmers. The study aimed to mutate these varieties for enhancing their tolerance to *Striga hermonthica* and developing a sustainable Striga-resistance.

Methods

Generating of sorghum mutant populations

Sorghum seeds of Sariaso14 and Grinkan were irradiated with gamma rays (^{60}Co) at doses of 200, 300, 400, and 500 Gy (figure 1). These irradiations were performed at the Isotope and Radiation Technology Application Center, National Nuclear Energy Agency (BATAN), Jl. Cinere Pasar Jumat, Jakarta, Indonesia. Irradiated seeds (M1) and parent seeds were planted in an alpha-lattice design with 0.4 m between the plants and 0.8 m between rows of 1.6 m length, replicated three times. Panicles from the M1 population were self-pollinated before anthesis and individually harvested and M2 seeds were sown using the "single seed descend" method. The M2 families were successively advanced to M3 and M4 following the same process. Plants were selected and advanced from generation n to n+1 based on distinct phenotypic variations compared to the parents (Figure 1). Plant phenotypic traits were recorded on the three central plants from the row of each replication.

Experimental design and trial management

Evaluation of agro-morphological traits of sorghum M3/M4 lines was conducted in 2017 and in 2018 under rainfed conditions using an alpha-lattice experimental design with three replications. In 2017, 325 M4 mutant lines from Sariaso14 and 78 M3 mutant lines from Grinkan were compared to the parental varieties (Table 1). Following this experimentation, 165 M5 lines of Sariaso14 and 65 M4 lines of Grinkan, were selected in 2018 for their distinctive agro-morphological traits and compared to the parental varieties (Table 1) to estimate the trait selection values. The planting layout involved two blocks per replication, with each bloc consisting of 116 genotypes spaced 80 cm apart between the seedling rows and 40 cm apart between the plants. Each planting row contained 5 holes and the data were collected from the three middle holes, with replications separated by 1 m. The mineral fertilizers, NPK (12-24-12) and urea [(CO) 2NH2, 46% N] were applied 21 and 50 days after the sowing (DAS), respectively, while three hoe-weeding were carried out for weed controlling. The rainfall recorded during the sorghum growing season was 440.8 mm in 2017 and 525.6 mm in 2018.

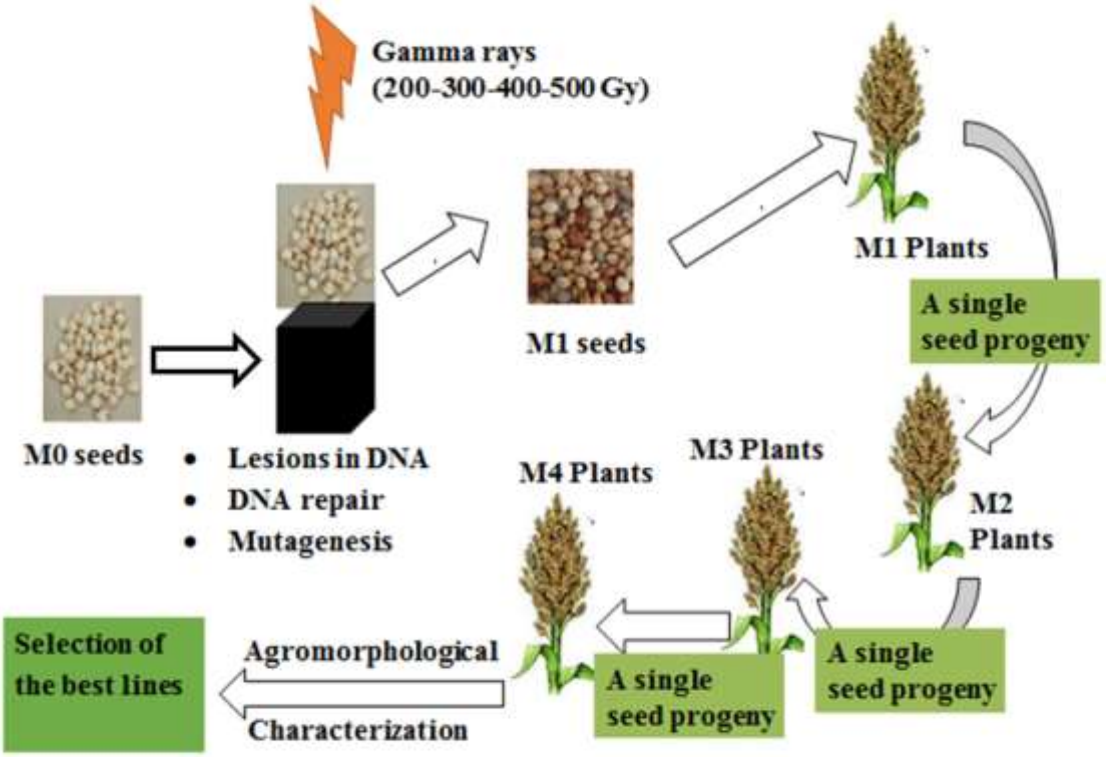

Figure 1: Stages of mutant population development

Table 1: Number of sorghum mutant lines screened for their agro-morphological traits at Kouaré Station, 2017-2018

Doses of gamma-ray irradiation						
Sorghum varieties	Mutant lines used	200 Gy	300 Gy	400 Gy	500 Gy	Total
Rainy season 2017						
Grinkan	Population M3	27	25	10	16	78
Sariaso14	Population M4	92	103	108	22	325
Total		119	128	118	38	403
Rainy season 2018						
Grinkan	Population M4	24	21	8	12	65
Sariaso14	Population M5	61	72	10	22	165
Total		85	93	18	34	230

Data Collection and Statistical Analysis

The measured parameters were described and summarized in table 2. Only quantitative variables of sorghum plants and panicles were collected in 2017.

The data recorded in 2017 were subjected to analysis of variance and estimation of different variability parameters. The analysis of variance (ANOVA) was calculated using Statistical Analysis System (SAS) software version 9.4. The Newman-Keuls test at the 1%, 5% and 10% threshold was performed. The Rx64.3.5.2 software was used to analyse the mutant lines screened in 2018 according to the potential traits of interest to be selected. So, the mutant lines were clustered according to their agronomic performances such as productivity, maturity duration and the height of the sorghum plants. The Statistical Tool for Agricultural Research (STAR) 2013 was used to calculate variance components.

Estimation of variance components

Genotypic variance (VG), Phenotypic variance (VP), Environmental variance (VE), Genotypic coefficient of variation (GCV), Phenotypic coefficient of variation (PCV), Environment coefficient of variation, Heritability (H^2) and Genetic gain (GG) were therefore calculated using data collected in 2018, as suggested by Burton and DeVane, (1953); Singh and Chaudhury, (1999).

$\mathrm{VG} = \frac{\mathrm{MSG-MSE}}{\mathrm{R}}$, where MSG = mean square of genotypes; MSE = mean square of error and R is the number of replications.

VP = VG+VE, where VG = genotypic variance, VE = MSE = mean square of error.

$\mathrm{GCV} = \frac{\sqrt{\mathrm{VG}}}{\mu} * 100$, where VG = Genotypic variance and μ= grand mean of a character.

$\mathrm{PCV} = \frac{\sqrt{\mathrm{VP}}}{\mu} * 100$, where VP = Phenotypic variance and μ = grand mean of a character.

$\mathrm{ECV} = \frac{\sqrt{\mathrm{VE}}}{\mu} * 100$, where VE = mean square of error, μ = grand mean of a character.

$H^2 = \frac{\mathrm{VG}}{\mathrm{VP}}$ where H^2= heritability in broad sense, VG = genotypic variance and VP = phenotypic variance.

$\mathrm{GG} = \frac{\mathrm{GA}*100}{\mu}$, where GA=K* $\sqrt{\mathrm{VP}}$ *H^2, K= selection differential at 5 per cent selection pressure i.e. 2.06; μ = grand mean of a character.

The magnitude of coefficient of variation was categorized as high (> 20%), moderate (10-20%) and low (< 10%) (Sahu, *et al.*, 2015; Abebe, *et al.*, 2017) while three heritability classes, i.e.: high ($H^2 > 0.5$), moderate ($0.2 < H^2 < 0.5$), low ($H^2 < 0.2$) were considered (Rahayu, *et al.*, 2018).

Table 2: Phenotypic variables recorded on Sorghum mutant lines

Variables	Methods/tools used	Observation period
Qualitative variables		
Leaves aspect (LeAs)	Visual observation of leaf shape	At flowering stage
Shape of the peduncles (ShPe)	Visual assessment of the curvature or non-curvature of the peduncle	At flowering stage
Stalks color (StCo)	Visual observation on absence, weak, moderate and strong presence of anthocyanin pigment	At flowering stage
Grains color (GrCo).	Visual observation of seed coat color	Post-harvest
Quantitative variables		
Chlorophyll content (ChCo1 and ChCo2)	Measured with a chlorophyll meter, SPAD 502 Plus	At flowering stage and maturity stage
Total number of leaves per plant (NPL)	Manual counting	At flowering stage
Plant height (PlHe)	Using a graduated wooden ruler	Seeds maturity stage
Panicles weight (PaWe) in g)	Using a precision scale with a maximum weight of 1 kg	Post-harvest
Diameter of peduncles (DiPe in cm)	Using a Vernier caliper	Post-harvest
Panicles filling rate (PaFiRa)	An estimation of the panicle filling rate on a 25% scale	Seeds maturity stage
Length of panicles (LePa)	With a ruler	Post-harvest
Grains weight per panicle (GrWe)	Using a precision scale with a maximum weight of 1 kg	Post-harvest
Leaves senescence (LeSe))	Calculated by dividing the number of dry leaves per plant by the total number of leaves on the plant	At the milky grain stage
Date of grains maturity (DaMa)	Counting the number of days between sowing and the physiological maturity of the grains	Between 105-115 JAS

Results

The results of the analysis of variance indicated that there were significant differences among all the mutant lines for most of the traits that were recorded indicating the creation of high genetic variability among them.

Genetic variation induced by gamma irradiation effect among sorghum mutant populations

ANOVA results showed that there was a significant difference between the irradiation doses for the leaf number plant^{-1} (P = 0.003) of Sariaso14 lines and on plant height of Sariaso14 (P = 0.02) and Grinkan lines (P = 0.005) (Table 3).

Table 3: Effect of gamma irradiation doses on three quantitative plant traits of Sariaso14 and Grinkan mutant lines in 2017

Doses of gamma-ray irradiation (Gy)						**Statistical tests**	
Variables	0	200	300	400	500	LSD	F
Sariaso14 mutant lines							
NPL	10	11.96	11.21	11.17	10.16	0.69	104.39 ***
ChCo	38,2	39.81	40.5	40.9	40.16	5.24	0.59
PlHe	137,33	162.1	147	165.23	144.02	19.55	24.78 **
Grinkan mutant lines							
NPL	12.33	10.86	10.8	11.22	11.8	2.03	1.49
ChCo	33.53	34.65	36.82	40	38.7	8.06	1.68
PlHe	107.67	105.66	115.41	115.83	137.5	17.9	13.32 ***

*NPL: Number of leaves at 105 and 110 DAS, ChCo: Chlorophyll content of the 3rd leaf under the panicle at 75 and 80 DAS, PlHe: Plant height at 105 and 110 DAS, LSD: Smallest Significant Difference between Means, F: Fisher's F, ***: significant difference (P≤1%), **: significant difference (P≤ 5%).*

The mutant lines generated from Sariaso14 seeds that were exposed to gamma ray doses of 200, 300, 400, and 500 Gy showed a decrease in panicle length and peduncle diameter when compared to the parental variety. (Figure 2). On the other hand, three irradiation doses 200, 300 and 400 Gy improved the panicle weight and panicle filling rate of mutant lines. The panicle filling rate was also improved by 63%, 55.7%, 59 and 55.3% with mutants generated from seeds irradiated at 200, 300, 400 and 500 Gy doses respectively (Figure 2).

Gamma irradiation led to a reducing effect on panicle length, panicle filling rate and weight of Grinkan-derived mutant lines (Figure 3). The average of panicle length was reduced from 21% to 29% while the average filling rate was less than that of parent by 11%-20%. The average weight of the parental variety panicle (60 g) was higher than those obtained with the mutant lines, ranged from 10.95 g to 30.45 g. The average peduncle diameter of mutant plants generated with seeds irradiated at 300 Gy (8.13 cm), 400 Gy (9.04 cm) and 500 Gy (7.88 cm) doses was higher than that of the parental variety (6.84 cm).

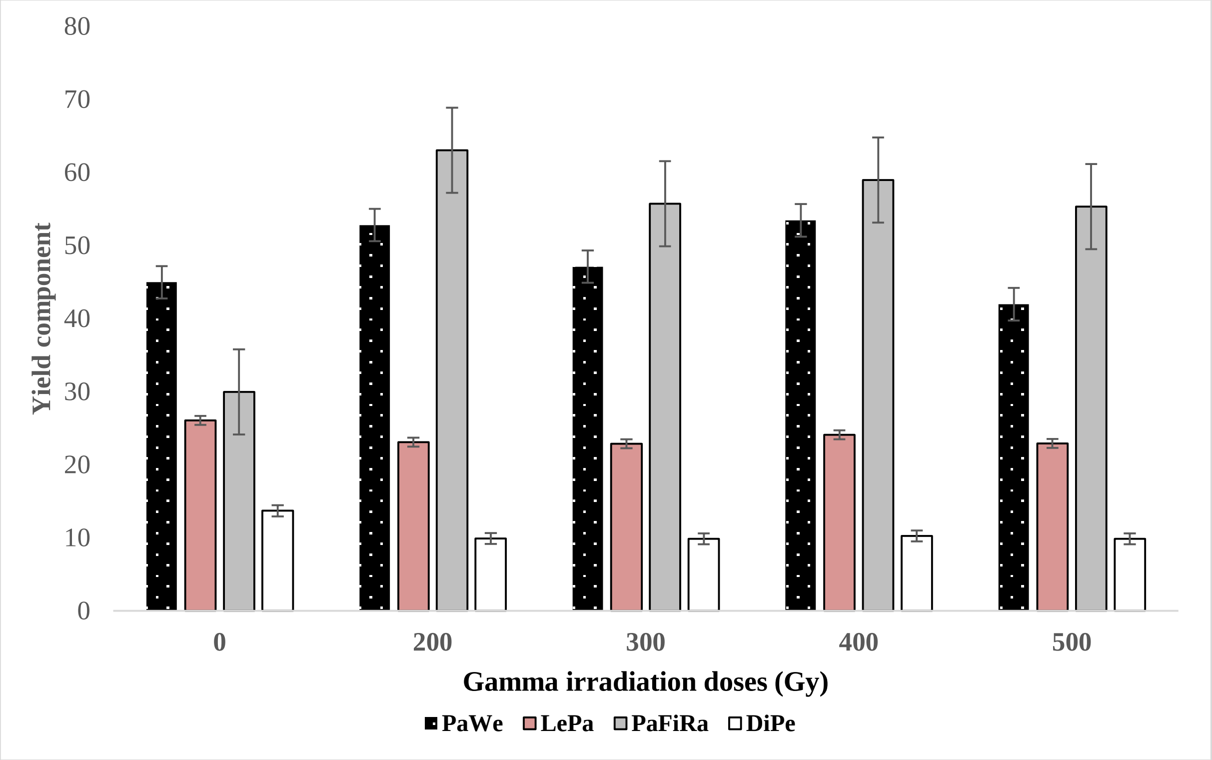

Figure 2: Effects of gamma irradiation on panicle traits of mutant lines developed from sorghum variety Sariaso14

PaWe: panicle weight; LePa: length of panicles ; PaFiRa: Panicules filling rate ; DiPe: diameter of pedoncles

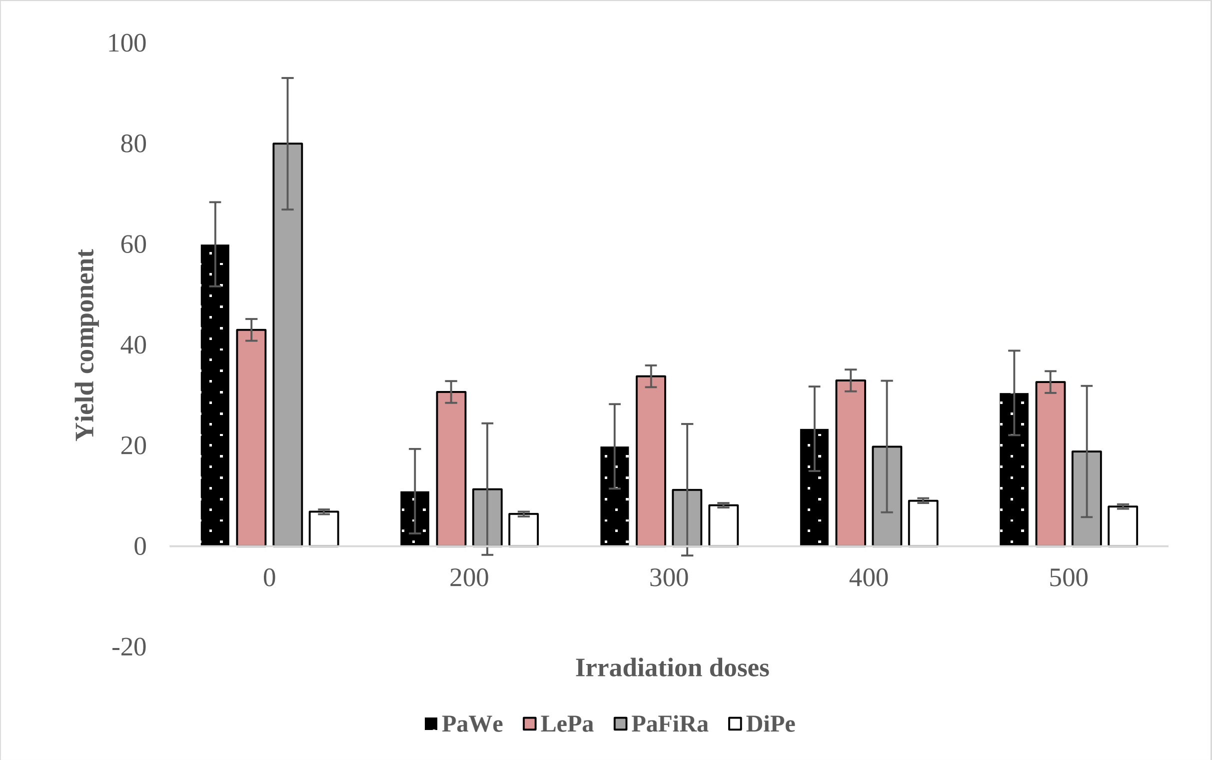

Figure 3: Effects of gamma irradiation on panicle traits of mutant lines developed from sorghum variety Grinkan.

PaWe: panicle weight; LePa: length of panicles ; PaFiRa: Panicules filling rate ; DiPe: diameter of pedoncles

Quantitative traits induced by gamma rays-mutation

ANOVA results showed very highly significant difference between sorghum mutant lines for number of plant leaves (P = 0.0005), chlorophyll content (P = 0.001), Plant height, panicle weight per line, panicle length per line, panicle filling per line and peduncle diameter (P<0.0001) with Sariaso14 mutant lines. Coefficients of variation were ranged from 12.14% to 47.62% (Table 4). Grinkan mutant lines also showed variability in agro-morphological characteristics. Significant differences were recorded between the mutant lines for number of leaves (P = 0.01), panicle length (P = 0.08), peduncle diameter (P= 0.03) and the other variables (P<0.0001). The coefficient of variation ranged from 18.44% to 90% (Table 5).

Table 4: Analysis of variance for quantitative traits of mutant lines developed from sorghum variety Sariaso14

Traits	Minimum	Maximum	Mean	LSD	F	CV%
NPL	3,67	14,5	10,87	2,20	3,40 ***	12,14
ChCo	18,53	58,8	40,23	16,72	1,97 ***	24,87
PlHe	55	229	151,98	62,3	2,23 ***	24,56
LePa	14,39	37,5	23,21	5,43	1,71***	14,35
PaFiRa	5	100	58,19	3,54	1,57***	47,62
PaWe	10	170	48,51	45,91	2,07 ***	47,62
DiPe	4,73	16,81	9,96	3,54	1,50 ***	21,74

*NPL: number of total leaves per line, ChCo; chlorophyll content, HtPl: height of plants at maturity, PaWe: panicle weight per line, LePa: panicle length per line, PaFiRa: panicle filling per line, and DiPe: peduncle diameter. CV: Coefficient of variation, LSD: Least significant difference between means, F: Fisher's F, ***: Very highly significant difference (P≤ 1%).*

Table 5: Analysis of variance for quantitative traits of mutant lines developed from sorghum variety Grinkan

Variables	Minimum	Maximum	Mean	LSD	F	CV%
NPL	4,5	16	11,07	4,45	1,67 **	21,95
ChCo	20,35	52,33	36,8	17,7	1,68	26,25
PlHe	52,5	201	116,9	39,5	3,72 ***	18,44
LePa	19,5	39	26,2	10,343	1,46 *	20,1
PaFiRa	709	100	21,76	38,49	2,95 ***	90
PaWe	2,83	135	28,5	32,18	4,20 ***	57,44
DiPe	4,14	13,02	8,92	4,3955	1,70 **	25,07

*NPL: number of total leaves per line, ChCo; chlorophyll content, HtPl: height of plants at maturity, PaWe: panicle weight per line, LePa: panicle length per line, PaFiRa: panicle filling per line, and DiPe: peduncle diameter. CV: Coefficient of variation, LSD: Least significant difference between means, F: Fisher's F, ***: Significant difference (P≤1%), **: Significant difference (P≤5%) and; *: significant difference (P≤10%).*

Qualitative traits induced by gamma rays-mutation

Qualitative traits of Sariaso14 and Grinkan varieties influenced by induced mutations are presented in tables 6 and 7. Trait variations in Sariaso14 mutant lines showed that 98.15% of mutant lines have normal leaves like those of the parental variety. However, novel characters such as curled leaves and erect leaves were detected with low frequencies. The percentage of green stems at flowering stage was 89.02 while 8.11% of the plants have low anthocyanin pigment on the stems and

2.87% of the plants have high anthocyanin pigment stems. The peduncle of 99.1% of mutant lines was erect while 0.3% of the peduncle was curved.

Changes in grain color were observed in 285 mutant lines (Figure 4) of which 17.9% have white grains and 7% have high anthocyanin pigment of grains.

Table 6: Occurrence frequencies of qualitative traits in Sariaso14 mutant lines

Phenotypes	Traits	Number of plants	Occurrence frequency of traits (%)
Leaf form	Normal	957	98.15
	Wrapped	12	1.23
	Erected	6	0.62
	Total	**975**	**100**
Stalk color	Green	868	89.02
	Low anthocyanin pigment	79	8.11
	High anthocyanin pigment	28	2.87
	Total	**975**	**100**
Peduncle form	Erected	966	99.08
	Semi-curved	6	0.62
	Curved	3	0.3
	Total	**975**	**100**
Color of grains	White	51	17.89
	White-dirty	30	10.53
	Low anthocyanin pigment	135	47.36
	Moderate anthocyanin pigment	49	17.2
	High anthocyanin pigment	20	7.02
	Total	**285**	**100**

Stem color and stalk shape of Grinkan mutant lines were similar to that of the parental variety. However, 2.56% of mutant lines had erect leaves that distinguished them from the parental variety and from that of other lines. Three grain colors were discriminated with Grinkan mutant lines. The grain color of 73.2% of mutant lines had white grain color similar to that of the parental grains while 23.2% had a dirty white color and 3.6% had an anthocyanin pigment (Table 7).

Table 7: Occurrence frequencies of qualitative traits in Grinkan mutant lines

Traits	Phenotype	Number of plants	Occurrence frequency of trait (%)
Leaf form	Normal	228	97.44
	Erect	6	2.56
	Total	**234**	**100**
Grain color	White	41	73.21
	White-dirty	13	23.22
	White-anthocyanated	2	3.57
	Total	**56**	**100**

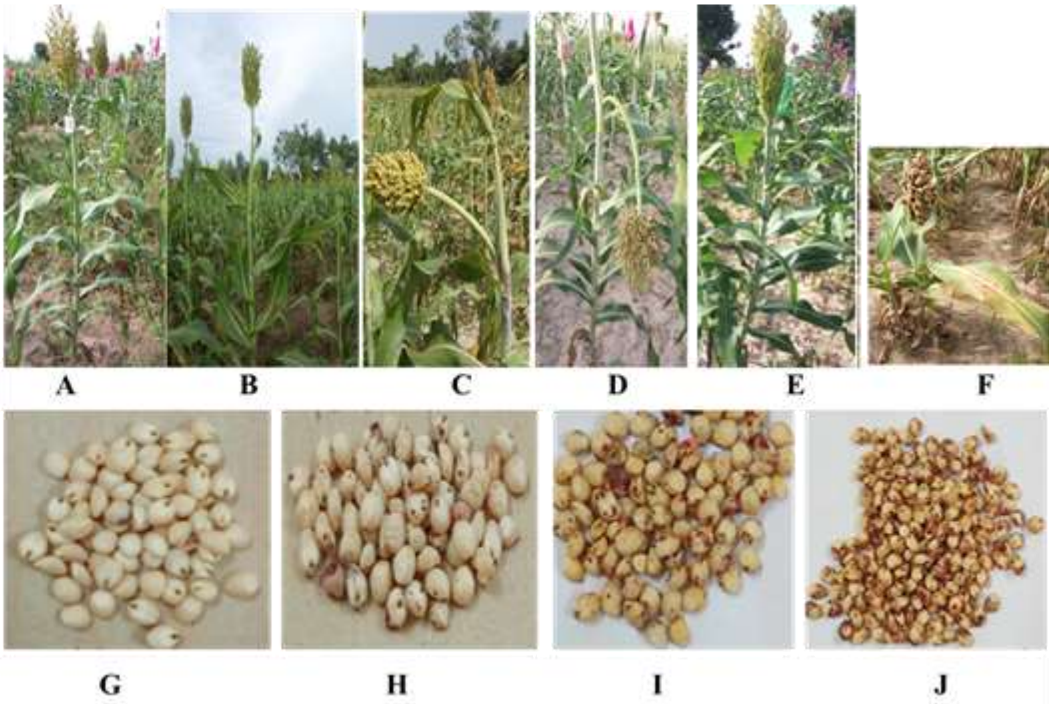

Figure 4: Qualitative traits induced by gamma-mutation in Sariaso14 and Grinkan sorghum varieties

A: Sariaso 14 parent (wild type) with normal leaves and peduncle; B: mutant line (Sa-290-P3-M4) with erect leaves; C: mutant line (Sa-585-P2-M4) with semi-curved peduncle; D: mutant line (Sa-7-P2-M4) with curved peduncle; E: Grinkan parent (wild type); F: Gk-209-M4 mutant with reduced size and early maturity; G: mutant line (Sa-75-P3-M4) with white kernels; H: Sariaso14 parent with low anthocyanin pigment of kernels; I: mutant line (Sa-273-P2-M4) with moderate anthocyanin pigment kernels; J: mutant line (Sa-91-P2-M4) with high anthocyanin pigment kernels.

Traits Selection Value of M4/M5 Sorghum Mutant Lines

Estimated genotypic variances (VG), phenotypic variances (VP), Genotypic Coefficients of Variation (GCV), Phenotypic Coefficients of Variation (PCV), Environment coefficient of variation (ECV), broad sense heritability and genetic gain of Sariaso14 and Grinkan mutant lines were depicted in tables 8 and 9. With regard to Sariaso14 mutant lines, the GCV estimates were ranged from 4.6% for days to maturity (DaMa) to 90.8% for grain weight panicle^{-1} (GrWe). The same trend was observed with the PCV whereas ECV estimates ranged from 3.6% for days to grains maturity to 27.8% for leaves senescence (LS). Both GCV and PCV were high for three traits (GrWe, LS and PlHe) while PCV and ECV were high for LS and chlorophyll contents (ChCo I and ChCo II). Only PCV was high for the total number of leaves plant^{-1}. The broad sense heritability and the genetic gain were low with ChCo I and ChCo II but very high for grain weight panicle^{-1}with 0.95 and 183% respectively while in the Grinkan mutant lines, there was a range of GCV estimates between 6.65% for days to grain maturity and 80.85% for grain weight per panicle. Both GCV and PCV estimates varied for these traits, with high GCV for GrWE, LS, and PlHe, and low PCV only for DaMa and ChCo I. Additionally, ECV estimates ranged from 2.85% for days to grain maturity to 45.14% for ChCo II, with high ECV for GrWe, LS, and ChCo II. The broad sense heritability was between 8% and 84%, with high heritability for GrWe, PlHe, and MaDa, moderate for TNL and ChCoI, and high GG for GrWe, TNL, LS, and PlHe (Table 8).

Table 8: Parameters of genetic variability in Sariaso14 and Grinkan mutant lines of Sorghum

Sariaso14 mutant lines									Grinkan mutant lines						
Traits	VG	VP	GCV	PCV	ECV	H^2	GG		VG	VP	GCV	PCV	ECV	H^2	GG
GrWe	5096.59	5325.79	90.82	92.84	19.26	0.95	183.03		1739.84	2108.09	80.85	89	37.19	0.82	151.30
TNL	3.63	7.6358	17.70	25.65	18.57	0.48	25.16		5.10	9.26	19.01	25.62	17.16	0.55	29.06
LS	278.28	548.91	28.22	39.63	27.83	0.50	41.39		148.71	365.14	21.64	33.91	26.11	0.40	28.45
PlHe	2439.88	2955.90	30.97	34.09	14.24	0.82	57.97		1216.07	1728.7	25.55	30.46	16.58	0.70	44.14
ChCo I	31.82	169.78	11.32	26.16	23.58	0.19	10.10		17.01	32.42	8.22	11.35	7.83	0.52	12.28
ChCo II	15.49	65.28	14.63	30.04	26.24	0.24	14.69		13.69	159.43	13.83	47.22	45.15	0.08	8.35
DaMa	24.35	39.3	4.65	5.90	3.64	0.62	7.53		54.80	64.88	6.65	7.23	2.85	0.84	12.59

GrWe: Grains weight per panicle; TNL: total number of leaves per plant; LS: leaves senescence, PlHe: Plants height, ChCo I: Chlorophyll content at flowering stage; ChCo II: Chlorophyll content at maturity stage; DaMa: Date of grains maturity; VG: genotypic variance; VP: phenotypic variance; GCV: genotypic coefficient of variation; PCV: phenotypic coefficient of variation; ECV: environmental coefficient of variation; H^2*: broad sense heritability and GG: genetic gain.*

Clustering of Mutant Lines by Hierarchical Ascendant Classification

Delayed leaf senescence, reduced plant height, reduced maturity cycle and high grain weight were highly sought-after traits in cereal breeding. A clustering was therefore carried out to highlight the difference in agronomic traits between the mutant lines and their parents. The mutant population of Sariaso14 was subdivided into three clusters constituted of 90, 24, and 52 genotypes, respectively. In cluster 1, the V-test values for plant height and grain weight per plant were negative, while in cluster 2, they were positive for plant height and chlorophyll content but negative for date-to-grain maturity. As for cluster 3, the V-test values were negative for plant height and chlorophyll content at the flowering stage, but positive for grain weight per plant (Table 9). The Grinkan mutant lines were classified into three clusters consisting of 15, 21, and 30 genotypes. In cluster 1, the test values were positive for leaf senescence and negative for chlorophyll content at the flowering stage, while in cluster 2, the test values were positive for leaf senescence, chlorophyll content at the flowering stage, plant height, and grain weight per plant, and negative for chlorophyll content at the maturity stage. In cluster 3, only chlorophyll content at the flowering and maturity stages had positive V-test values (Table 10).

Table 9: Test-values of variables of Sariaso14 mutant lines

	Cluster 1			**Cluster 2**			**Cluster 3**		
Variables	V-test	Cluster mean	Overall mean	V-test	Cluster mean	Overall mean	V-test	Cluster mean	Overall mean
PlHe	-5.22	148.44	159.45	10.70	219.06	159.45	-2.49	150.98	159.45
GrWe	-9.57	50.22	78.59				10.03	126.46	78.59
ChCo I				3.13	52.83	49.81	-2.07	48.59	49.81
DaMa				-2.20	104.89	106.19			

GrWe: Grains weight per panicle; PlHe: Plants height; ChCo I: Chlorophyll content at flowering stage; DaMa: Date of grains maturity.

Table 10: Test-values of variables of Grinkan mutant lines

	Cluster 1			**Cluster 2**			**Cluster 3**		
Variables	**V-test**	**Cluster mean**	**Overall mean**	**V-test**	**Cluster mean**	**Overall mean**	**V-test**	**Cluster mean**	**Overall mean**
LS	2.69	61.58	56.34	2.43	60.11	56.34	-4.54	51.07	56.34
ChCo I	-6.15	46.33	50.13	2.46	51.33	50.13	2.87	51.18	50.13
PlHe				4.97	155.75	136.47	-3.48	126.38	136.47
GrWe				3.65	67.98	51.58	-2.07	44.61	51.58
TNL				2.54	12.55	11.87	-2.10	11.45	11.87
ChCo II				-2.67	24.53	26.73	3.38	28.81	26.73

GrWe: Grains weight per panicle; LS: leaves senescence; PlHe: Plants height, ChCo I: Chlorophyll content at flowering stage; ChCo II: Chlorophyll content at maturity stage; TNL: Number of leaves per plant.

Discussion

Gamma irradiation doses higher than 200 Gy induced high plant height in the mutant lines of both sorghum varieties while the dose of 200 Gy induce dwarf plant in Grinkan mutants. These results revealed that gamma rays may significantly influence the height of plants generated from seeds irradiated with gamma rays. Sakin, (2002) and Umami, *et al.,* (2021) have indeed reported that gamma irradiation doses caused a significant increase in the height of wheat and sorghum plants, respectively. Gamma rays are part of ionizing radiations that interact with atoms or molecules to produce free radicals in cells (Jan, *et al.,* 2013) and their effect on the growth and morphology of plant species may be significant (De Micco, *et al.,* 2011; Piri, *et al.,* 2011; Iglesias-Andreu, *et al.,* 2012). The reducing effect of gamma irradiation (200 Gy dose) on plant height of Grinkan mutants was also observed by Ambli and Mullainathan, (2014) on millet plants consecutive to induced mutagenesis. The effect of reduction/increase in plant height would be due to the chromosomal abnormalities generated following a modification of the permeability of the cell wall or to morphological and physiological damage induced by gamma irradiation (Ziaei, *et al.,* 2016). Plant morphology and height can change in a positive or negative direction depending on the gamma irradiation dose. Gamma rays have an effect on growth hormone activity such as auxin which is responsible for plant growth. Campbell, *et al.,* (2004) explained that the effect of gamma irradiation excites cell membrane proteins to pump H+ ions to the cell wall. H+ ion activates the enzyme to break some of the hydrogen cross-links in the cellulose molecular chain. The plants then elongate due to the water which enters by osmosis (Campbell, *et al.,* 2004). Some mutant lines such as Gk206M5, Gk209M5, Sa104M6 and Sa137M6 showed dwarfism coupled with early grain maturity. Malek, *et al.,* (2012) emphasized that the reduction in plant height is coupled with an increase in grain yield. In addition, plant dwarfism due to the mutation may be combined with the early maturity of cereal grains (Olejinizac and Adamska, 1999), a highly desirable trait in cultivated plants. The induction of early maturity is one of the traits most frequently noted in induced mutation breeding experiments on many crops (Kharkwal, *et al.,* 2004). Reducing the height of sorghum plants is a desirable trait because of their ability to mitigate the lodging effect. The induced mutation enhanced chlorophyll synthesis in some mutant lines compared to the parental varieties. The high chlorophyll content is a useful trait for drought adaptation and grain filling. Spano, *et al.,* (2003) reported that high chlorophyll content in leaves is associated with the "Stay Green" phenotype and low leaf senescence. In sorghum, traits that may be associated with drought tolerance include higher leaf photosynthetic activity (Lawlor and Cornic, 2002). Mutant lines that exhibited high chlorophyll content during grain filling are therefore considered as "candidate" lines in selection for water deficit tolerance.

Gamma irradiation doses positively influenced some yield components of mutant lines created from the Sariaso14 variety. On the other hand, they reduced those of Grinkan mutant lines. Sakin and Yildirim, (2004) reported that the induced mutation significantly increases yield components in cereals. Shah, *et al.,* (2001), Khatri, *et al.,* (2005) and Rawat, *et al.,* (2019) showed that gamma-ray irradiation may induce high-yielding in mutants of several plant species. Based on these results, Singh and Datta, (2010) suggested the use of low doses of gamma irradiation to improve wheat plant vigor and yield. The improvement of yield components is therefore a consequence of the gamma-ray effect which caused biochemical changes in plant tissues or cells; the plant will then regulate cell division and elongation (Agarwal, *et al.,* 2008). However, a reduction effect in sorghum grain yield due to gamma irradiation was observed by Bebawi, (1984) while Khan, *et al.,* (2003) revealed a progressive decrease by 39.38% in the number of tillers plant^{-1} and by 1.93% in barley grain yield. Previous studies suggested that doses of gamma radiation up to 400 Gy have direct inhibitory effects on certain performance-related traits (Khan, *et al.,* 2003). But, the exact nature of these inhibitory effects on yield components is not well clarified and requires further studies. In Sahelian countries that are prone to climate change and the early cessation of rains, it is important to select mutants with early maturity and high productivity. The significant differences observed between the mutant lines for the measured traits indicate the existence of genetic variability between the mutant lines from the same variety. The high coefficients of variation suggest some possibilities for further crop breeding through selection and hybridization to improve desired traits. High variability within an individual trait indicates that there are opportunities for selection of this trait. On the other hand, low variability indicates that hybridization is the strategy to generate high-performance lines (Tiwari, *et al.,* 2011). Genotypic and phenotypic coefficients of variation were higher for grains weight per panicle, leaves senescence and plants height of Grinkan. and Sariaso14 mutants and suggested that the variation of these traits is due to genetic effect. In addition to these traits, the phenotypic coefficient of variation of leaves number, and chlorophyll content was high. These higher coefficients of variation revealed that the mutation induction created a large variability for these five quantitative traits. Satheeshkumar and Saravanan, (2012) found also similar results from the screening of rice varieties. Heritability was high for grain weight panicle^{-1}, the plant height and the delay to maturity and low to medium for the other traits of Sariaso14 mutants. Similarly, with Grinkan mutants, the heritability was high for all the parameters except the leaf senescence and the chlorophyll content at the maturity stage. The high broad sense heritability showed that the traits were improved by the induced mutagenesis. Genetic gain was very high for grain weight panicle^{-1} of the mutants of both varieties. High heritability coupled with high genetic gain for grain weight per panicle and plants height of Sariaso14 and Grinkan mutant lines resulted in additive gene effects and the selection for both traits may be effective. Low heritability coupled with low genetic for chlorophyll content indicated that this trait is highly influenced by environmental effects and the selection of mutants based on this trait would be ineffective.

The positive test values (V-tests) observed with some characters showed that the mean of these characters in the cluster is higher than the overall mean. On the other hand, negative V-tests indicate that the mean of the character in the cluster was less than the overall mean. The selection of Sariaso14 mutant lines that could have a good grain yield therefore belongs to cluster 3 and the dwarf mutants should be selected from cluster 1 while the early maturity plants should be selected from cluster 2.

In the context of mutants developed from Grinkan, it is recommended to prioritize the selection of high-grain yield mutants from cluster 2, while focusing on the identification of dwarf plants within cluster 3. Additionally, mutants exhibiting high chlorophyll content at the maturity stage should be targeted within cluster 3. Notably, cluster 2 comprises individual lines that exhibit a long maturity cycle compared to the average. Given the scarcity and early cessation of rainfall, the selection of lines with an extended growth cycle would not provide significant benefits to sorghum producers. Instead, it would be more advantageous to focus on traits such as grain weight and delayed leaf senescence, which contribute to productivity and enhance the tolerance of lines to cope with water deficits. These findings have implications for the strategic selection and breeding of sorghum mutant's varieties to optimise their yields and tolerance to water scarcity (Talwar, *et al.,* 2009).

Conclusion

This study successfully induced genetic variability in two preferred sorghum varieties, Grinkan and Sariaso14, through gamma-ray irradiation. The mutant populations exhibited significant variations in various agronomic traits compared to their respective parent lines. Notably, the irradiation doses had a significant impact on the leaf number and plant height of the mutant lines, with differing effects observed between the two varieties. The yield components of Sariaso14 mutants were significantly improved, while the effects on Grinkan mutants were more variable. High genetic coefficients of variation, heritability, and genetic gains were observed for grain weight per panicle in both mutant populations, indicating a strong genetic influence on this trait.

The clustering analysis revealed the successful selection of dwarf mutants, early maturity mutants, and high grain weight mutants among the induced population. These findings demonstrate that mutagenesis has the potential to enhance the agronomic performance of sorghum varieties by introducing desired traits. The increased genetic variability resulting from this study holds promise for addressing the low genetic diversity currently present in sorghum varieties in Burkina Faso. Ultimately, the development and adoption of improved sorghum varieties can contribute to enhancing productivity and resilience in sorghum farming systems.

Acknowledgement

The authors express their gratitude to the International Atomic Energy Agency (IAEA) for its multiform support for the conduct of this study. They thank the "Institut de l'Environnment et de Recherches Agricoles (INERA) for the facilities offered in the use of the environmental and agricultural research station of Kouaré.

References

1. Abebe, T., Sentayehu, A. and Leta, T. "Genetic Variability, Heritability and Genetic Advance for Yield and its Related Traits in Rainfed Lowland Rice (*Oryza sativa* L.) Genotypes at Fogera and Pawe, Ethiopia." *Adv Crop Sci Tech* 5.272 (2017):1-8.
2. Agarwal, R., Rane, S.S. and Jayashree, K. S. "Effects of ^{60}Co radiation on thylakoid membrane functions in *Anacystis nidulans.*" *Journal of Photochemistry and Photobiology B: Biology* 9.1(2008): 9-19.

3. Ahloowalia, B.S., M. Maluszynski. and K. Nichterlein. “Global impact of mutation derived varieties.” *Euphytica* 135 (2004): 187-204.
4. Ambli, K. and L. Mullainathan. “Induced physical and chemical studies in M1 generation of pearl millet (*Pennisetum typhoides*) (Burn.) Stapf.Var.co (cu)-9.” *International Journal of Recent Scientific Research* 5.10 (2014): 1806-1809.
5. Bado, S., Brian, P. F., Stephan, N., Abdelbagi, M. A., Pierre, J.L., Bradley, J. T. and Margit, L. “Plant Mutation Breeding: Current Progress and Future Assessment.” *Plant Breeding Reviews* 39 (2015): 23-88.
6. Bebawi, F.F. “Effect of gamma irradiation on *Sorghum bicolor*. *Striga hermonthica* relations.” *Environmental and Experimental Botany* 24 (1984): 123-129.
7. Bhagasara, V.K., Ranwah, B.R., Meena, B.I. and Rumana, K. “Estimation of GCV, PCV, Heritability and Genetic Gain for yield and its related components in Sorghum [*Sorghum bicolor* (L.) Moench].” *International Journal of Current Microbiology and Applied sciences* 6.5 (2017): 1015-1024.
8. Burton, G.W. and DeVane, E.H. “Estimating heritability in tall fescue (*Festuca arundinacea*) from replicated clonal material.” *Agronomy Journal* 45.10 (1953): 478-481.
9. Campbell, N.A., (Reece JB, Mitchell LG). Biologi, Ed. 5 jil. 3 [cd]/ Campbell Biology, Erlangga, Jakarta (2004).
10. De Micco, V., Carmen, A., Diana, P. and Marco, D. “Effects of sparsely and densely ionizing radiation on plants.” *Radiation and Environmental Biophysics* 50.1 (2011): 1-19.
11. Dicko, M.H., Harry, G., Alfred, S. T., Alphons, G.V. and Willem, J.V.B. “Sorghum grain as human food in Africa: relevance of content of starch and amylase activities.” *African Journal of Biotechnology* 5 (2006): 384-395.
12. FAOSTAT. Food and Agricultural Organization of the United Nation in http://www.fao.org (2018).
13. Gressel, J. and Avraham, A. L. “Agriculture: The selector of improbable mutations.” *Proceedings of the National Academy of Sciences* 103 (2006): 12215-12216.
14. Iglesias-Andreu, L.G., P. Octavio-Aguilar. and J. Bello-Bello. “Current importance and potential use of low doses of gamma radiation in forest species.” *Gamma radiation. Rijeka, Croatia: InTech Europe* (2012): 265-280.
15. Jan, S., Talat, P., Rehana, H. and Tariq, O.S. and M. Zafar. “Effects of presowing gamma irradiation on the photosynthetic pigments, sugar content and carbon gain of *Cullen corylifolium* (L.) Medik.” *Chilean Journal of Agricultural Research* 73.4 (2013): 345-350.
16. Khan, K., Muhammad, I.M., A. Azim., B. Ahmad., K. Fazli. and S. Hassan. “Effect of Gamma Irradiation on Yield and Yield Components of Barley (*Hordeum vulgare* L.).” *Pakistan Journal of Biological Sciences* 6 (2003): 1695-1697.
17. Kharkwal, M.C., Pandey, R.N. and Pawar, S.E. “Mutation breeding for crop improvement.” *In: Plant Breeding-Mendelian to Molecular Approaches, Jain HK, Kharkwal MC (eds), Narosa Publishing House, New Delhi, India* (2004): 601-645.
18. Khatri, A., Khan, I.A., Siddiqui, M.A., S. Raza. and Nizamani, G.S. “Evaluation of high yielding mutants of *Brassica Juncea* cv. S-9 developed through Gamma rays and EMS.” *Pakistan Journal of Botany* 37.2 (2005): 279-284.
19. Lawlor, D.W. and Cornic, G. “Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants.” *Plant Cell Environ* 25.2 (2002): 275-294.
20. Malek, L.A, Begum, H.A., M. Begum., Sattar, M.A., Ismail, M.R. and Rafii, M.Y. “Development of two high yielding mutant varieties of mustard [*Brassica juncea* (L.) Czern.] through gamma rays irradiation.” *Australian Journal of Crop Science* 6.5 (2012): 922-927.
21. Mundia, W.C., Silvia, S., Kofi, A. and Guangxing, W. “A regional Comparison of Factors Affecting Global Sorghum Production: The case of North America. Asia

and Africa's Sahel." *Sustainability* 11.7 (2019): 2135.

22. Nikièma, M.P, D. Yonli., Rabefiraisana, H.J., N. Ouédraogo., H. Traoré., Yanogo, H.Y.A., K. Dao., M. Sawadogo., L. Jankuloski., I. Ivan. and Ghanim A.M.A. "Induced Resistance to *Striga hermonthica* in Sorghum by Gamma Irradiation." *American Journal of Plant Sciences* 11.10 (2020): 1545-1561.
23. Nikièma, M.P. "Genetic improvement of Sorghum [*Sorghum bicolor* (L.) Moench] for resistance to *Striga hermonthica* (Del.) Benth and to water deficit by induced mutagenesis." *PhD thesis at the University of Ouagadougou* (2021): 166.
24. Oladosu, Y., Rafii, M.Y., Abdullah, N., Hussin, G., Ramli, A., Rahim, H.A., Miah, G. and Usman, M. "Principle and application of plant mutagenesis in crop improvement: A review." *Biotechnology & Biotechnological Equipment* 30 (2016): 1-16.
25. Olejinizac, J. and E. Adamska. "Achievement of mutation breeding of cereal and oilseed in Poland." *Proc 3rd Int Symp New Genetical Approaches to Crop Improvement-III, Nuclear Institute of Agriculture, Tandojam, Pakistan* (1999): 55-63.
26. Oria, M.P., Hamaker, B.R., Axtell, J.D. and Huang, C.P. "A highly digestible sorghum mutant cultivar exhibits a unique folded structure of endosperm protein bodies." *Proc. Natl. Acad. Sci* 97 (2000): 5065-5070.
27. Ouédraogo, N. "Genetic Improvement of Local *Sorghum* (*sorghum bicolor* L. Moench) varieties for drought tolerance." *Partial fulfilment of the requirements for the award of doctor of philosophy plant breeding degree. University of Ghana, Legon* (2015): 149.
28. Pathirana, R. "Plant mutation breeding in agriculture." CAB Reviews: *Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 6.32 (2011):1-20.
29. Piri, I., Mehdi, B., Abolfazl, T. and Mehdi, J. "The use of gamma irradiation in agriculture." *African Journal of Microbiology Research* 5.32 (2011): 5806-5811.
30. Rahayu, S., Suwarno, W.B., M. Ghulamahdi., Aswidinnoor, H. "Analysis of panicle morphology traits in F2 and reciprocal F2 populations of rice (*Oryza sativa* L.)." *SABRAO Journal of Breeding and Genetics* 50.1 (2018): 9-24.
31. Rawat, V.S., Singh, S.S., Wani, M.R. and A. Singh. "Potential of fractionated doses of gamma rays to stimulate growth and yield of *Amaranthus caudatus* in M1 (First filial generation) and M2 (Second filial generation) generation." *Forest Res Eng Int J* 3.3 (2019): 76-81.
32. Ronald, P.C. "Lab to farm: applying research on plant genetics and genomics to crop improvement." *PLoS Biol* 12.6 (2014): e1001878.
33. Sahu Ku, P., Deepak, S., Pooja, S., Satyapal, S., Chaudhary, P.R. and Sao, F.C. "Assessment of genetic parameters for various quantitative and qualitative traits in hybrid rice (*Oryza sativa* L.)." *International Journal of Tropical Agriculture* 30.1 (2015): 97-102.
34. Sakin, M.A and Ahmet, Y. "Induced mutations for yield and its components in durum wheat (*Triticum durum* Desf.)." *Food, Agriculture & Environment* 2.1 (2004): 285-290.
35. Sakin, M.A. "The use of induced micro mutation for quantitative characters after EMS and gamma ray treatments in durum wheat breeding." *Journal of Applied Sciences* 2.12 (2002): 1102-1107.
36. Satheeshkumar, P. and K. Saravanan. "Genetic variability, correlation and path analysis in rice (*Oryza Sativa* L.)." *International Journal of Current Research* 4 (2012): 082-085.
37. Shah, S.A., I. Ali. and K. Rahman. "Abasin 95 a new oilseed rape cultivar developed through induced mutations." *Mut. Breed. Newslett* 45 (2001): 3-4.
38. Singh, B. and Datta, P.S. "Gamma irradiation to improve plant vigour, grain development, and yield attributes of wheat." *Radiat Phys Chem* 79 (2010): 139-143.
39. Singh, R.K. and Chaudhary, B.D. "Biometrical Genetics Analysis." *Kalyani Publishers, New Delhi* (1999): 318.
40. Soeranto, H., Nakanishi, T.M. and Razzak, M.T. "Mutation Breeding in *Sorghum* in

Indonesia." *Radioisotopes Journal* 50 (2001): 169-175.

41. Spano, G., N. Di Fonzo., C. Perrotta., C. Platani., G. Ronga., Lawlor, D.W., Napier J.A., Shewry, P.R. "Physiological characterization of 'stay green' mutants in durum wheat." *J. Exp. Bot* 54 (2003): 1415-1420.
42. Talwar, H., Surwenshi, A. and N. Seetharama. "Use of SPAD chlorophyll meter to screen sorghum (*Sorghum bicolor*) lines for postflowering drought tolerance." *Indian Journal of Agricultural Sciences* 79.1 (2009): 35-39.
43. Tiwari, D.K., Praveen, P., Sachchidanand, T., Giri, S.P. and Dwivedi, J.L. "Studies on genetic variability for yield components in rice (*Oryza sativa* L.)." *International Journal of the Bioflux Society* 3.1 (2011): 76-81.
44. Trouche, G., Sansan, D., Grégoire, P., Adama, S., Ousmane, O. and D. Den Gosso. "Évaluation participative de nouvelles variétés de sorgho." *Sélection Participative. CIRAD, Montpellier* (2001): 36-55.
45. United Nations projections, 2022: World Population Growth Rate 1950-2022 in https://www.macrotrends.net/countries/WLD/world/population-growth-rate.
46. Umami, N., Maudi, N.D., Andriyani, A. and Bambang, S. "Gamma Radiation Effect on Growth, Production and Lignin Content of Sorghum sudanense at Different Harvest Ages." *Buletin Peternakan* 45.3 (2021): 183-188.
47. USDA (United States Department of Agriculture). "Crop Production 2021 Summary." (2021).
48. Vom Brocke, K., Gilles, T., Eva, W., Clarisse, P. B.K., Eric, G. and Jacques, C. "Participatory variety development for sorghum in Burkina Faso: Farmers' selection and farmers' criteria." *Field Crops Research* 119 (2010):183-194.
49. Ziaei, A., Gorji, A.M. and Davoud, H. "Efficiency of Gamma Ray to Induce Genetic Diversity in Potato." *Biosci., Biotech. Res. Asia* 13.4 (2016): 2107-2115.

Source of support: Nil;
Conflict of interest: The authors declare no conflict of interests.

Cite this article as:

Nikièma, M.P., Djibril, Y., Hamidou, Y.A.Y., Nofou, O., Hamidou, T., Mahamadou, S. and Anupama, J.H. "Induced Mutagenesis for Enhancing Genetic Variability and Agronomic Performance in Sorghum Varieties for Burkina Faso." *Annals of Plant Sciences*.12.07 (2023): pp. 5895-5911.