FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 13, July, 2026, pp 122 – 130
DOI: https://doi.org/10.33003/fjs-2026-1013-5731

Effects of Sodium Azide (NaN_3) on Germination and Yield Parameters of Sweet Pepper (*Capsicum annuum*), Cabbage (*Brassica oleracea*), and Sweet Potato (*Ipomoea batatas*)

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ABSTRACT
This research examined the impact of varying concentrations of sodium azide (NaN_3) at 0.5, 1.0, and 1.5 mM on the germination, growth, and yield of sweet pepper, cabbage, and sweet potato. The study was carried out in a screen house utilising a completely randomised pot design with three replications, where treated seeds and vine cuttings were evaluated over a period of eight weeks. The results from ANOVA indicated highly significant differences specific to each species ($p < 0.001$) across all measured parameters, with the type of crop having the most substantial effect on plant height ($F = 793.447$), root length ($F = 2045.677$), and biomass. Additionally, sodium azide concentration had a significant impact on root length ($F = 23.754$, $p < 0.001$) and exhibited near-significant effects on biomass ($p = 0.085–0.100$), suggesting physiological responses that are dependent on the dosage. The germination rate was not significantly affected ($p = 0.322$), indicating that the concentrations applied were below the levels that would inhibit germination. The results illustrate that sodium azide can induce noticeable phenotypic variation with distinct species-specific responses. These findings endorse sodium azide as a potent mutagenic agent for fostering genetic diversity in crop enhancement initiatives.

Received: 23 Jul. 2026
Accepted: 30 Jul. 2026
Published: 11 Aug. 2026

Keywords: Sodium Azide, *Capsicum annuum*, *Brassica oleracea*, *Ipomoea batatas*, Germination, Yield Parameters

INTRODUCTION

One of the substances that is commonly employed as a mutagenesis agent in the field of crop breeding is sodium azide (NaN_3). Its potential advantages in creating genetic variety, which would allow for the improvement of agricultural quality, are the reason for its adoption. The effects of sodium azide as a mutagen originate from its potential to impact DNA, which makes it feasible to see changes in terms of plant shape, yield, or response to stress conditions (Naaz *et al.,* 2023). Sodium azide being a mutagen works together with cell elements taking part in DNA replication and mitosis, which ensures the observation of diverse changes in the appearance of the exposed plants (Türkoğlu *et al.,* 2023). At the moment, however, it is not known how exactly sodium azide affects such plants as sweet pepper (*Capsicum annum*), cabbage (*Brassica oleracea*), or sweet potato (*Ipomoea batatas*). Sodium azide being a mutagenic substance allows influencing some of the cell processes such as enzyme activity inhibition, which leads to the improvement of germination rate or even crop yields (Wahid *et al.,* 2021). In the field of agronomy and plant science, it becomes essential to gain knowledge of the effects of sodium azide on those plants which are economically very important, including sweet peppers (*Capsicum annum*), cabbage (*Brassica oleracea*), and sweet potatoes (*Ipomoea batatas*), (Lalusin *et al.,* 2025). Sweet peppers are known for their high content of antioxidants, and cabbage is known due to its high iron content. Sweet potatoes are another important food source which contains a lot of carbohydrates. Hence, the effects of sodium azide can be studied on these plants in terms of their germination and yield patterns (Eldengawy *et al.,* 2020).

According to (Halewood *et al.,* 2018), the fundamental building blocks and foundations of plant growth and development serve as a platform for collecting raw materials employed in the genetic enhancement of commercially viable crops. Numerous enhanced varieties with greater commercial significance were produced using mutagenesis-based procedures, which also aided in the study of genetics and plant development processes (Penna *et al*., 2015). One of the benefits of mutational breeding is the chance to enhance one or two traits while maintaining the rest of the genotype. Mutation breeding represents great potential and is a helpful complementary technique for the genetic improvement of crops. It has been demonstrated that it is feasible to induce variability for various desired traits using mutations and that it is effective for genetic improvement programs (Bado *et al.*, 2015). Major crop species reproduced by seeds, including wheat, rice, barley, cotton, peanuts, and cowpeas, have been improved through the application of induced mutations. To increase the number of mutations, a variety of mutagens are employed, including chemical and ionising radiation (Oladosu *et al.*, 2016). Living things usually undergo mutations as a result of chemical mutagens. Many medications have both positive and negative effects. Many chemicals have clastogenic properties and affect plants because of the presence of radicals generated by reactive oxygen species (Freinbichler *et al.*, 2011). The shape and yield of the chemomutagens differ greatly from those of their nonmutated counterparts. Numerous studies have examined the effectiveness of different mutagens in various crops, but their conclusions vary greatly depending on the species in question and, occasionally, on the variations within a species. According to certain findings (Wani, 2016), chemically induced mutation is more effective than physically induced mutation, although other reports (Kumawat *et al.,* 2016) contradict this. Numerous studies attest to the role chemomutagens play in enhancing genetic variety in higher plants, which is a crucial component of quality breeding material in both sexually and clonally propagated crops (Ceballos *et al.,* 2015). Plant breeders have long been interested in genetic variety, which can occur spontaneously through mutations caused by physical, biological, or chemical causes. Breeders will be able to isolate, identify, and clone the genes involved in creating crops with higher yield and quality with the aid of mutants. One of the most potent chemical mutagens for agricultural plants is sodium azide (lhan *et al*., 2023).

It was shown to affect plant physiology by reducing tobacco callus's cyanide-resistant respiration (Zidenga *et al*., 2012). In several species, including plants and mammals, this substance is highly mutagenic (rajam *et al.,* 2012). It is highly mutagenic in a variety of species, and several screens are used to detect its mutagenicity. In other species, such as Drosophila (Buacheen *et al.,* 2023) and Arabidopsis (Bowman *et al.,* 2012), it is not mutagenic and only slightly mutagenic (Sanjuán *et al.,* 2008). The metabolism of the organic metabolite produced by the azide compound's breakdown is how the mutagenesis activity operates (Mistry *et al.,* 2022).

A study indicated that this metabolite enters the cell nucleus where it binds with the DNA and causes point mutations. Several studies have been performed on barley plants and bacteria in order to understand the mutagenic mechanism in recent times (Liu *et al.,* 2015). The mutagen is effective in plants as a strong mutagen and interferes with the metabolic functions of various parts of the plant (Xu *et al.,* 2011). Based on empirical evidence, mutagens like sodium azide might boost crop productivity through accelerated growth rate or through the development of beneficial phenotypic features Vita and Taranto, 2019). In addition, there is already existing research indicating that exposure to sodium azide can affect the pattern of germination either by increasing germination rates or inhibiting them through delaying seed formation at high cytotoxic doses Pour, (Tosun *et al*., 2023). This research project intends to investigate the impacts of sodium azide on the germination and yield of sweet potato, cabbage, and sweet pepper crops (Adeoti *et al.,* 2021).

MATERIALS AND METHODS

Sample Collection

Seeds of sweet pepper (*Capsicum annuum*), cabbage (*Brassica oleracea*), and vine cuttings of sweet potato (*Ipomoea batatas*) were sourced from a certified agricultural supplier to guarantee genetic integrity and viability (Hintum *et al.,* 2020). Before planting, these materials were brought to the herbarium unit of the Biological Sciences Department at Umaru Musa Yaradua University Katsina for authentication and viability assessment. The assigned voucher specimens were numbered UMYUH2289, UMYUH71, and UMYUH1396, respectively.

Viable Test Procedure

For testing the viability of seeds, the sink and float technique was used, which had to be done for at least three hours to obtain the correct result. After this, surface sterilization was performed by placing seeds in a 5% solution of sodium hypochlorite (NaOCl) for 10-15 minutes to eliminate the chances of seed-borne diseases (Kumar *et al.,* 2015).

Study Area

The experiment was carried out at the National Biotechnology Development Agency (NABDA). The region has a warm subtropical climate, receiving an average annual rainfall of approximately 700–800 mm. During the dry season, the mean monthly temperature is about 30 °C, while humidity levels peak in August and September and are lowest in February and March (Agbo *et al.,* 2021). The experimental site was a screen house with an insect-controlled environment, maintaining a temperature range of 27–35 °C and a relative humidity of 65% (Ntombela *et al.,* 2024). Sandy loam soil was collected, sun-dried, and sieved through a 2 mm mesh. Quantities of 10 kg and 40 kg of the soil were weighed and poured into 16 pots of two different sizes.

Study Design

Different concentrations of sodium azide (0.5 mM, 1.0 mM, and 1.5 mM) were prepared using distilled water. Sweet pepper and cabbage seeds were soaked in these mutagenic solutions for about 2 to 4 hours based on the preliminary trials aimed at determining optimal exposure time for effective mutagenesis without compromising seed viability. Control seeds were soaked in distilled water under identical conditions for comparison (Yousof *et al.,* 2010).

Table 1: Factorial Experimental Design of Sodium Azide (NaN_3) Treatment Concentrations (0.0, 0.5, 1.0, and 1.5 mM) Across the three Evaluated Crop Species

Crop Type	Treatment 1 (Low)	Treatment 2 (Med)	Treatment 3 (High)	Control
Sweet Potato	0.5 mM NaN_3	1.0 mM NaN_3	1.5 mM NaN_3	0.0 mM (Distilled Water)
Cabbage	0.5 mM NaN_3	1.0 mM NaN_3	1.5 mM NaN_3	0.0 mM (Distilled Water)
Sweet Pepper	0.5 mM NaN_3	1.0 mM NaN_3	1.5 mM NaN_3	0.0 mM (Distilled Water)

The experiment was conducted using a pot design (PD) as outlined by (Graber et al. 2010), focusing on a single treatment factor, the mutagenic agent sodium azide. The concentrations were set at three levels: 0.5 mM, 1.0 mM, and 1.5 mM, alongside a control group consisting of 100% water. An initial in vitro pilot study was performed to evaluate the impact of the mutagen on crop germination.

Germination and Growth Evaluation

Treated and control seeds were placed in the pots containing different quantity of soil (for the cabbage and sweet pepper, 10 kg of the soil was used, while 40kg for the sweet potato) and under controlled conditions for germination testing. Germination was observed and recorded biweekly till they all germinates. The germination percentage rate was calculated using

Germination Percentage (%) = (Number of germinated seeds / Total number of seeds sown) × 100 as described by ISTA (2015) and (Beck *et al.,* 2009).

Treated and control seeds were placed in sterile Petri dishes lined with moist filter paper to conduct germination tests under controlled conditions. Germination was monitored weekly for a duration of 14 days, and the germination percentage was determined using the method adopted by (ISTA, 2015). These observations are essential for evaluating the physiological and morphological impacts of sodium azide on the initial stages of plant development. Following germination, uniform seedlings were transferred into 16 pots of appropriate sizes, filled with sterilized loamy soil. For cabbage and sweet pepper, each pot contained 10 kg of soil, while 40 kg of soil was utilized per pot for sweet potato, with the plants being kept under screen house conditions. Growth parameters, including seedling height, leaf area, root length, and total biomass, were assessed biweekly over a period of eight weeks (Kharkwal and Shu, 2009).

Yield Analysis

During the complete vegetative growth phase, the plants were assessed for key yield-related metrics. These metrics included plant height, root development, fresh and dry biomass, and fruit size, along with crop-specific traits such as the number of fruits (for sweet pepper), leaf count (for cabbage), and tuber weight (for sweet potato). These indicators are crucial for evaluating the physiological performance and productivity of the crops that underwent sodium azide treatment, as supported by Wani *et al.* (2011).

Data Analysis

All statistical analyses were conducted utilizing the Statistical Package for the Social Sciences (SPSS), version 25.0. The normality of the data distribution was assessed through the Shapiro–Wilk test. Following this, the gathered data underwent analysis of variance (ANOVA) to identify significant differences between the treated and control groups. This methodology effectively quantified the mutagenic effects of varying sodium azide concentrations on crop yield, aligning with techniques employed in earlier mutagenesis research (Kharkwal and Shu, 2009).

RESULTS AND DISCUSSION

Result

The two-way ANOVA analysis indicated that neither the concentration of Sodium Azide ($F = 1.439$, $p = 0.322$) nor the type of crop ($F = 2.268$, $p = 0.185$) significantly influenced the measured parameter ($p > 0.05$). The majority of the observed variation was attributed to random experimental error, suggesting a consistent response across the different treatments. Consequently, the null hypothesis was upheld.

Table 2: Two-Way Analysis of Variance (ANOVA) Summary for Germination Rate (%) of Sweet Pepper, Cabbage, and Sweet Potato Under Varying Sodium Azide (NaN_3) Concentration

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	4.917	3	1.639	1.439	0.322
Crop Type	5.167	2	2.583	2.268	0.185
Residual (Error)	6.833	6	1.139	-	-

The two-way ANOVA analysis revealed that the type of crop significantly influenced plant height at the two-week mark ($F = 175.286$, $p < 0.001$). In contrast, the concentration of Sodium Azide did not exhibit a significant effect ($F = 1.327$, $p = 0.350$). The minimal residual variance suggests a high level of experimental precision, indicating that early plant height is predominantly influenced by species variations rather than the mutagen treatment. Although Fig 1 shows that sweet potato had a higher average seedling height (M = 5.85cm, group a) compared to sweet pepper (M = 3.20cm, group b) and cabbage (M = 2.95 cm, group b) after 2 weeks from the experiment ($p < 0.001$), no significant difference was found between sweet pepper and cabbage ($p > 0.05$).

Table 3: Impact of Sodium Azide (NaN_3) Concentration and Crop Species on Seedling Height (cm) Measured Two Weeks After Treatment

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	0.163	3	0.054	1.327	0.350
Crop Type	14.315	2	7.158	175.286	< 0.001
Residual (Error)	0.245	6	0.041	-	-

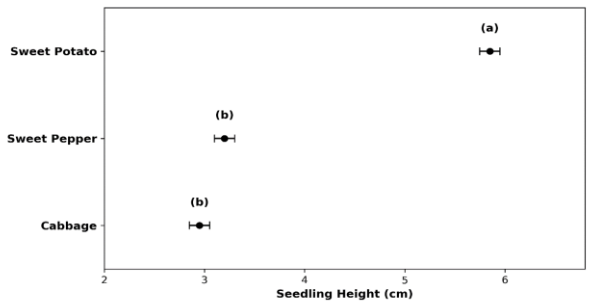

Figure 1: Pairwise Comparisons of 2-Week Seedling Height (cm) Across Crop Species Following Sodium Azide (NaN_3) Exposure

The findings indicated that the type of crop had a significant impact on the number of leaves after a two-week period ($F = 21.00$, $p = 0.002$), whereas the concentration of Sodium Azide did not show a significant effect ($F = 1.00$, $p = 0.455$). This suggests that the production of leaves was mainly determined by the type of crop rather than the concentration of the treatment. However, it was observed through Fig. 2 that the mean number of leaves in sweet potato was significantly more (M = 4.65, group a) than the number of leaves in cabbage (M = 2.00, group b; $p < 0.05$). The mean number of leaves in sweet pepper (M = 3.25, group ab) was intermediate between sweet potato and cabbage.

Table 4: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Leaf Count at 2 Weeks Post-Planting

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	1.000	3	0.333	1.000	0.455
Crop Type	14.000	2	7.000	21.000	0.002
Residual (Error)	2.000	6	0.333	-	-

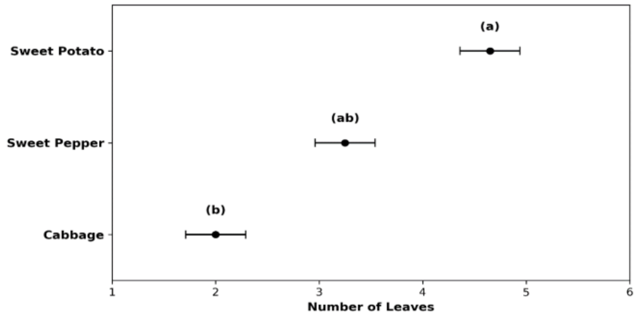

Figure 2: Pairwise Comparisons of 2-Week Leaf Count Across Crop Species Following Sodium Azide (NaN_3) Exposure

It is clear from table 5 that the concentration of Sodium Azide as well as the crop type has played a significant role in determining the number of leaves at the end of four weeks. The concentration has exerted a moderate impact ($F=5.333$, $p=0.040$), while the crop type showed a greater impact ($F=57.000$, $p<0.001$). Thus, it can be stated that the production of leaves is mainly affected by the crop type. But, from Fig 3 it is clear that leaf multiplication depended significantly on crop type and not chemical mutagenesis. The crop types which recorded the highest number of mean leaf count were; sweet potato with a mean of (M=8.00), sweet pepper with a mean of (M=5.75) and cabbage with a mean of (M=4.25). This is an indication of distinct morphological differences among the various species ($p < 0.05$). On the other hand, the concentration of sodium azide (NaN_3) did not show any statistically significant effect on leaf count ($p > 0.05$).

Table 5: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Leaf Count at 4 Weeks Post-Planting

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	4.000	3	1.333	5.333	0.040
Crop Type	28.500	2	14.250	57.000	<0.001
Residual (Error)	1.500	6	0.250	-	-

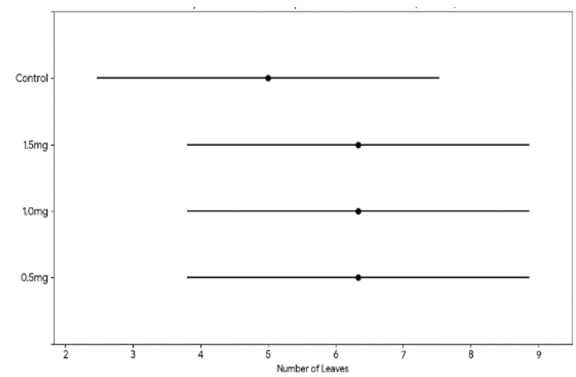

Figure 3: Tukey HSD Post-Hoc Pairwise Comparisons of Mean Leaf Count Across Concentrations (%) at 4 Weeks Post-Treatment

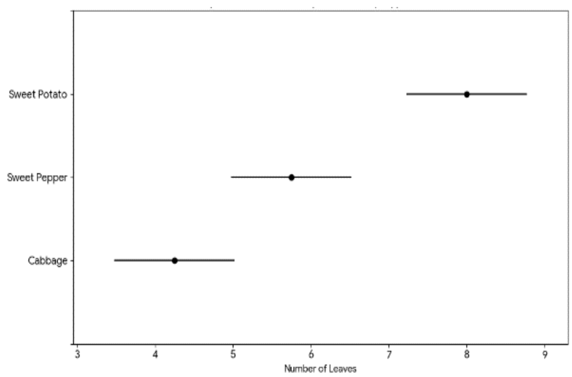

Figure 4: Tukey HSD Post-Hoc Pairwise Comparisons of Mean Leaf Count Across Crop Species at 4 Weeks Post-Treatment

The results in table 6 revealed that the type of crop was significantly important for determining the number of leaves at week six ($F = 20.03$, $p = 0.002$), while the concentration of Sodium Azide was not statistically significant ($F = 0.514$, $p = 0.688$). At this point, crop type remained the most important variable, since the concentration had no effect anymore. Moreover Fig 5 shows that sweet potatoes had a significantly higher average number of leaves (M=10.25, group a) compared to both sweet peppers (M=7.50, group b) and cabbage (M=5.75, group b) ($p < 0.05$), while there was no significant difference between sweet peppers and cabbage ($p > 0.05$).

Table 6: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Leaf Count at 6 Weeks Post-Planting

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	1.583	3	0.528	0.514	0.688
Crop Type	41.167	2	20.583	20.027	0.002
Residual (Error)	6.167	6	1.028	-	-

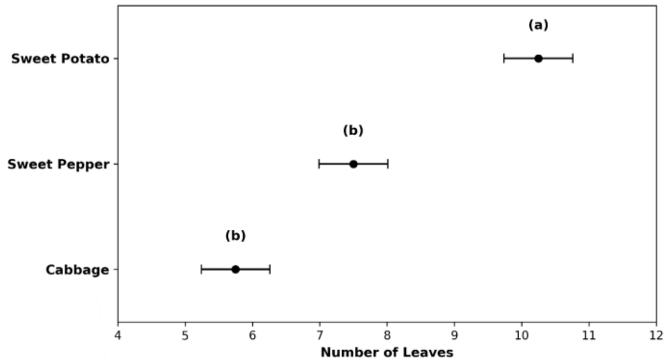

Figure 5: Pairwise Comparisons of 6-Week Leaf Count Across Crop Species Following Sodium Azide (NaN_3) Exposure

The findings indicate that the type of crop had a significant impact on fresh biomass ($F = 24.15$, $p = 0.001$), whereas the concentration of Sodium Azide did not demonstrate a significant effect ($F = 3.60$, $p = 0.085$). Crop type continued to be the primary factor influencing biomass production, while concentration exhibited merely a potential trend. Nevertheless, according to Fig 6, sweet potato has significantly higher mean plant fresh biomass (M=470g, group a) compared to sweet pepper (M=185g, group b) and cabbage (M=125g, group b) ($p < 0.01$). There was no significant difference between sweet pepper and cabbage in plant fresh biomass accumulation ($p > 0.05$).

Table 7: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Plant Fresh Biomass (g)

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	61004.89	3	20334.96	3.601	0.085
Crop Type	272715.17	2	136357.58	24.147	0.001
Residual (Error)	33881.27	6	5646.88	-	-

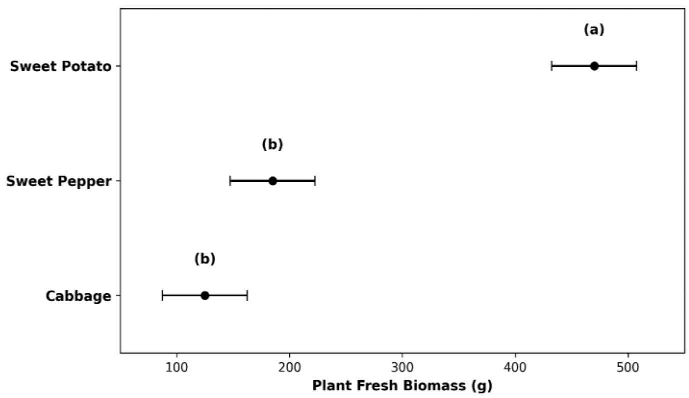

Figure 6: Pairwise Comparisons of Plant Fresh Biomass (g) Across Crop Species Following Sodium Azide (NaN_3) Exposure

The findings indicated that the type of crop had a significant impact on dry biomass ($F = 20.18$, $p = 0.002$), whereas the concentration of Sodium Azide did not exhibit a significant effect ($F = 3.30$, $p = 0.100$). Consequently, dry biomass was predominantly determined by the crop type, with varying concentration levels showing no observable differences. On the other hand, Figure 7 reveals That, Sweet Potato had a considerably high mean plant dry biomass (52g) than Sweet Pepper (20.5g) and Cabbage (14g) respectively as shown from the distinct significance letter (a). However, for Sweet Pepper and Cabbage, the same letter (b) was used for the biomass values showing no statistical significance between them ($p > 0.05$). Generally, Sweet Potato showed better biomass accumulation than the other two crops.

Table 8: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Plant Dry Biomass (g)

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	817.88	3	272.63	3.296	0.100
Crop Type	3339.02	2	1669.51	20.181	0.002
Residual (Error)	496.35	6	82.73	-	-

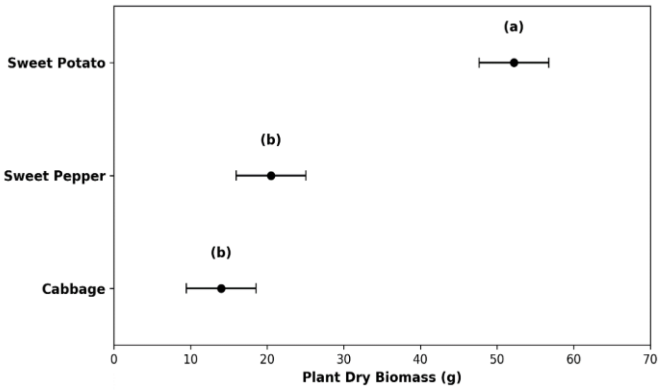

Figure 7: Pairwise Comparisons of Plant Dry Biomass (g) Across Crop Species Following Sodium Azide (NaN_3) Exposure

The findings indicated that both the concentration of Sodium Azide and the type of crop had a significant impact on root length ($p < 0.001$). The type of crop exerted a considerably greater influence ($F = 2045.68$) than the concentration ($F = 23.75$), suggesting that crop characteristics primarily dictated root development, with treatment levels contributing additional effects. But in all the factors examined, there were distinct differences in terms of root length in relation to the crop species and different concentrations used. From the different crop species tested (Figure 1), Sweet Potato had a significantly higher root length (~8.3 cm, a) compared to Sweet Pepper (~3.2cm, b) and Cabbage (~2.9cm, c) such that each of the crops differed significantly from one another ($p < 0.05$). From the different concentrations used (Figure 2), the root length significantly reduced with increase in concentration, the highest being at 0.0 mM Control (~5.25cm, a) and the lowest at 1.5 mM (~4.4cm, c).

Table 9: Main Effects of Sodium Azide (NaN_3) Concentration and Crop Species on Root Length (cm)

Source of Variation	Sum of Squares (SS)	DF	Mean Square (MS)	F-Ratio	P-value
Concentration	1.287	3	0.429	23.754	<0.001
Crop Type	73.872	2	36.936	2045.677	< 0.001
Residual (Error)	0.108	6	0.018	-	-

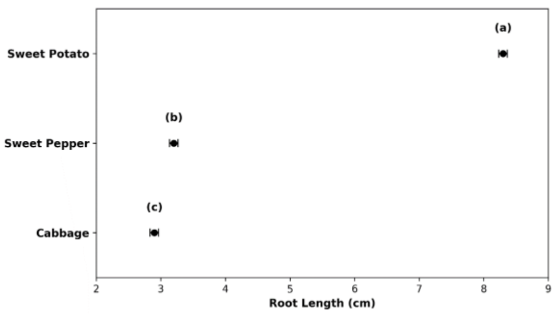

Figure 8: Pairwise Comparisons of Plant Root Length (cm) Across Crop Species Following Sodium Azide (NaN_3) Exposure

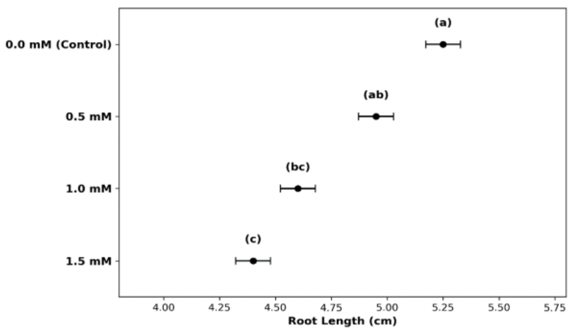

Figure 9: Pairwise Comparisons of Plant Root Length (cm) Across Sodium Azide (NaN_3) Concentration Levels

Discussion

Sodium azide (NaN_3) is a known chemical mutagen that is used in the development of genetic variability through its metabolism to azidoalanine that results in (G:C) to (A:T) base pair mutations in genomic DNA. In this experiment, the statistically non-significant relationship between NaN_3 concentration and seed germination percentage ($p = 0.322$) means that the concentration range used (0.5 to 1.5 mM) was not beyond the cytotoxic level needed for the inhibition of seed germination.

On the other hand, vegetative growth and yield characteristics were shown to be dose- and species-specific sensitive. Parameters related to plant height, leaf production, and biomass were mostly controlled by the crop species ($p<0.01$), where *Ipomoea batatas* was always more favorable in terms of growth parameters when compared to *Capsicum annuum* and *Brassica oleracea* because of inherent physiological vigor and vegetative propagation capabilities of different species. In this context, the concentration of NaN_3 had a considerable inhibiting effect on root length ($F=23.754$; $p<0.001$), which reduced gradually from the control (5.25 cm) to 1.5mM (4.4 cm). Root inhibition is supported by studies by Khan *et al.,* 2024, and Turanlı *et al.,* 2025, and this phenomenon is related to the physiological effect of sodium azide that suppresses active cell division in the apical root meristems due to the inhibition of cytochrome oxidase and cellular respiration. While main yield-related characteristics such as fresh and dry biomass showed no concentration effect ($p>0.05$), observed physiological variation supports 0.5 to 1.5Mm NaN_3 as a sublethal concentration for phenotypical variation without mortality.

The findings of the study imply that the concentration of 0.5 to 1.5 mM applied in the study provides an adequate basis for inducing mutations while maintaining reasonable levels of

plant survival and growth. It is consistent with the suggestions made by (Adamu and Aliyu, 2007) regarding the significance of keeping the LD_{50} level to ensure seed viability and genetic variability.
As pointed out by many researchers, the full expression of mutations induced by sodium azide may only become apparent at the M_2 generation or beyond. According to (Hussain *et al.* 2017), even though M_1 plants showed reduced germination percentage, height, number of leaves, and seed set, chlorophyll deficient seedlings were seen for the first time in the M_2 generation, and among these, the most frequently observed type was viridis, followed by chlorina, xantha, and albina type chlorophyll mutations. In a similar fashion, (Turanlı *et al.* 2025) found that even though there were many differences observed in plant height, height of the first branch, and 1000-seed weight in M_1 plants, there was no difference in the yield per plant in the M_1 generation.

CONCLUSION

The present study demonstrates that sodium azide exerts significant effects on the germination, growth and yield parameters of sweet pepper, cabbage and sweet potato, with response patterns varying considerably among the three species. The dose-dependent nature of these effects, particularly the significant influence of sodium azide concentration on root length and the near-significant effects on biomass parameters, confirms that sodium azide is an effective mutagenic agent capable of inducing measurable phenotypic variation in these economically important crops.
The highly significant crop type effects observed across nearly all parameters underscore the necessity of developing species-specific optimisation protocols for sodium azide application. While the 0.5–1.5 mM concentration range employed in this study proved suitable for inducing detectable variation while maintaining adequate plant survival, further optimisation may be required to maximise mutagenic efficiency for each crop species.

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