Original Article

EFFICACY OF FOLIAR IRON NANOPARTICLE SUPPLEMENTATION ON AGRO-MORPHOLOGICAL TRAITS, YIELD PERFORMANCE, AND GENETIC STABILITY OF IMPROVED SOYBEAN (*Glycine max* L. Merrill) GENOTYPES ACROSS SAVANNA AGRO-ECOLOGIES

Kana, H.A.[1], Ugbedeojo, A.M.[1], Ogah, G.O. [1], Lawal, J.I.[1], and Abu, F.N.[2]
[1]Department of Plant Science and Biotechnology, Faculty of Life Sciences, Federal University of Lafia, Nasarawa State, Nigeria
[2]Department of Soil Science, College of Agriculture, Science and Technology, Lafia, Nasarawa State, Nigeria
Corresponding Author: amosmaxwell22@gmail.com

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Correspondence;

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ABSTRACT

This study evaluated the efficacy of foliar-applied green-synthesized iron oxide nanoparticles (FeNPs) on the growth, yield performance, and genetic stability of eleven improved soybean genotypes across two savanna agro-ecological locations in Nasarawa State, Nigeria (Akwanga and Lafia). Combined analysis of variance revealed that genotype significantly influenced pod number per plant ($P < .001$) and 1000-seed weight ($P < .05$), while location significantly affected germination count, branch number, plant height, days to 50% podding, and pod count ($P < .001$). Foliar FeNP treatment exerted a statistically significant main effect on mean seed count per pod ($P < .05$). Genotype × environment interactions were non-significant for pod count and 1000-seed weight but significant for seed count per pod ($P < .05$). Phenotypic coefficients of variation (PCV: 14.09%–34.27%) consistently exceeded genotypic coefficients of variation (GCV: 0.00%–21.10%) across all evaluated traits, resulting in low-to-moderate broad-sense heritability estimates (0.00%–37.90%). Broad-sense heritability was highest for pod count per plant (37.90%) and plant height (36.69%), whereas seed count per pod exhibited zero genotypic variance (0.00%). Akwanga supported significantly higher vegetative growth and structural pod yield (53.45 pods per plant) than Lafia (44.14 pods per plant). Under FeNP-treated conditions, genotype V5 (TGx2020-4e) achieved the maximum plant height (61.33 cm) and maximum branch count (12.00), alongside V2 (12.00), whereas untreated control plots displayed uniform performance across varieties. Foliar FeNP supplementation did not induce significant shifts in overall phenological maturity schedules or total 1000-seed weight across genotypes. These findings indicate that while foliar FeNP supplementation enhances mean seed count per pod and vegetative growth in specific responsive accessions, overall agro-morphological traits and yield components in soybean are predominantly governed by genetic architecture and environmental factors.

KEYWORDS: Soybean, Glycine Max, Iron Nanoparticles, Foliar Nano-Fertilization, Genotype × Environment Interaction, Genetic Stability

INTRODUCTION

Soybean (*Glycine max* [L.] Merrill) is a premier global leguminous crop that contributes approximately 68% of the world's protein crop production and serves as a major source of high-quality vegetable oil (Maleki et al., 2013). Composed of an average protein content of 40% and approximately 20% cholesterol-free oil on a dry matter basis (85% of which is unsaturated), soybean represents one of the most nutritious and cost-effective food sources for mitigating protein-energy malnutrition and chronic dietary disorders across Sub-Saharan Africa (Foyer et al., 2019; Idrisa et al., 2010; Iyorkaa et al., 2021). In Nigeria, rapid expansion in the livestock, poultry, and food-processing sectors over the past decade has doubled the national demand for soybean grain and processed meal (Sasu, 2022). Furthermore, soybean plays a critical ecological role in tropical cropping systems through biological nitrogen fixation and crop rotation, disrupting pest and disease cycles while enhancing soil nitrogen fertility and lowering dependence on synthetic fertilizers (Jensen et al., 2018; Yooyen et al., 2015). Despite its immense economic and ecological potential, global soybean production exhibits severe regional disparities. While major producers such as the United States, Brazil, and Argentina account for over 80% of global output, African nations contribute less than 2%, with average yields remaining well below potential (Abebe et al., 2024; Fasusi et al., 2022). In Sub-Saharan Africa, and specifically in the savanna zones of Nigeria, soybean productivity is constrained by agronomic bottlenecks, including soil nutrient depletion (particularly micronutrient deficiencies such as iron chlorosis), erratic rainfall patterns, temperature extremes, pest infestations, and a scarcity of high-yielding genotypes adapted to localized microclimates (Aduloju et al., 2009; Mshelmbula et al., 2023). Bridging this yield gap requires innovative agronomic interventions capable of optimizing nutrient use efficiency, boosting physiological performance, and stabilizing reproductive yield across variable ecological zones. Nanotechnology has emerged as a promising frontier in precision agriculture, offering innovative solutions through nano-breeding and nano-nutrient delivery systems (Dey & Nandy, 2024; Ghafariyan et al., 2013; Kana & Kwon-Ndung, 2023). Nanomaterials act as efficient nutrient carriers due to their high surface-area-to-volume ratio, facilitating rapid cellular absorption and targeted physiological regulation (Sanguansri & Augustin, 2006). Iron (Fe) is an essential plant micronutrient that functions as a structural constituent and catalytic cofactor in photosynthetic electron transport, chlorophyll biosynthesis, respiratory enzymes, and cellular redox reactions (Costa et al., 2021; Daramola et al., 2021). Green synthesis of iron nanoparticles (FeNPs) using eco-friendly plant extracts, such as *Khaya senegalensis*, provides a sustainable, biogenic route to produce non-toxic metal oxides capable of enhancing plant physiological processes (Van et al., 2016). While foliar application of FeNPs has been reported to improve photosynthetic capacity, seed germination, and enzyme activity in laboratory and single-location trials (Kokina et al., 2020; Mozafari et al., 2018; Yadav et al., 2021), comprehensive field evaluations assessing the comparative influence of FeNPs across diverse tropical savanna environments remain limited. Therefore, this study evaluated the efficacy of foliar-applied green-synthesized iron nanoparticles on the agro-

morphological parameters, yield performance, and genetic stability of improved soybean genotypes evaluated across two distinct agro-ecological locations in Nasarawa State, Nigeria.

MATERIALS AND METHODS

Study Locations

The field trials were conducted during the 2024 cropping season (July to November) at two distinct agro-ecological locations in Nasarawa State, North-Central Nigeria: (1) the Research and Experimental Plot of the Department of Plant Science and Biotechnology, Federal University of Lafia, and (2) the Research Farm of Nasarawa State College of Education, Akwanga. Both study sites lie within the Southern Guinea Savanna zone (Latitude 8°31′ N, Longitude 8°30′ E) but feature contrasting microenvironments (Mshelmbula et al., 2023; Wakili et al., 2025). Lafia represents a lower-elevation, warmer sedimentary basin within the Benue Trough characterized by gently undulating terrain, broad floodplains, and acidic, ferruginous sandy loam soils with low total nitrogen and cation exchange capacity. Akwanga represents a cooler, higher-elevation northern highland zone situated at the foothills of the Jos Plateau, characterized by rugged granite terrain of the Basement Complex, well-drained loamy soils, and higher seasonal precipitation (Kwon-Ndung et al., 2016).

Planting Material and Research Design

Eleven improved soybean genotypes (designated V1 through V11) were obtained from the National Cereals Research Institute (NCRI), Baddegi, Niger State, alongside a localized control variety obtained from the College of Agriculture, Science and Technology, Lafia. The experimental layout at each site was a Randomized Complete Block Design (RCBD) with three replications. Plot dimensions measured 1 m × 1 m, with an inter-row spacing of 0.75 m (or 1.0 m depending on plot design) and an intra-row spacing of 0.10 m (or 0.50 m), maintaining uniform plant densities across replicates (Kana, 2017).

Green Synthesis and Characterization of Iron Nanoparticles (FeNPs)

Iron oxide nanoparticles (Fe_3O_4-NPs) were synthesized via a green reduction approach using aqueous leaf extract of *Khaya senegalensis* at the Chemistry Laboratory, Federal University of Lafia. Fresh, healthy *K. senegalensis* leaves were thoroughly washed, shade-dried, ground, and extracted in distilled water to obtain a phytochemical reducing agent. An aqueous solution of the leaf extract was reacted with 0.5 M ferric nitrate nonahydrate [$Fe(NO_3)_3 \cdot 9H_2O$] at a 1:5 volume ratio under a continuous nitrogen atmosphere. The reaction mixture was stirred vigorously for 60 minutes and allowed to react at ambient temperature for 30 minutes to form a dark colloidal FeNP suspension. The resulting nanoparticles were isolated by centrifugation, washed repeatedly with ethanol and deionized water, and vacuum-dried at 40 °C (Dey & Nandy, 2024; Van et al., 2016).

Field Management and FeNP Foliar Application

Field layout preparation involved manual clearing, raking, and seedbed construction using cutlasses and hoes. Seeds were sown directly at a depth of 2.0 to 3.0 cm. Manual weeding was conducted at 2, 4, and 6 weeks after planting (WAP). Foliar FeNP

treatments (designated T1) were prepared by dispersing 30 g of synthesized FeNPs in 4 L of distilled water and applying the nano-suspension uniformly onto foliage using a calibrated knapsack sprayer at 2, 4, and 6 WAP. Untreated control plots (designated T0) received equivalent foliar applications of distilled water without nanoparticles (Mozafari et al., 2018).

Data Collection

Data were collected from tagged representative inner-row plants within each replicate for both vegetative growth and yield traits: germination count (GC), plant height (PH, cm), number of primary branches per plant (NB), days to 50% flowering (DF), days to 50% podding (DP), total pod count per plant (PD), seed count per pod (SP), and 1000-seed weight (W1000, g). All measurements followed standard descriptor guidelines published by the International Institute of Tropical Agriculture (IITA).

Statistical Analysis and Genetic Variance Estimation

Data were analyzed using IBM SPSS Statistics (Version 27.0). Combined Analysis of Variance (ANOVA) under the General Linear Model (GLM) was performed to evaluate main effects due to genotype (G), environment (E), FeNP treatment (T), and genotype × environment (G × E) interactions. Treatment means were separated using post-hoc Least Significant Difference (LSD) tests at $P < .05$. Genetic variance components were estimated according to standard formulas (Gadde et al., 2008; Neelima et al., 2018):

RESULTS

Combined Analysis of Variance for Yield Traits across Locations

The combined analysis of variance across Akwanga and Lafia (Table 1) revealed highly significant genotypic differences for total pod count per plant ($F = 4.10$, $P < .001$) and 1000-seed weight ($F = 2.02$, $P < .05$), whereas seed count per pod did not vary significantly among genotypes. Environmental main effects were highly significant for pod count ($P < .001$) but non-significant for seed count per pod and 1000-seed weight. Foliar FeNP treatment exerted a statistically significant effect on mean seed count per pod ($F = 4.10$, $P < .05$), confirming that nano-nutrient supplementation directly enhanced reproductive capacity per pod. Genotype × environment (G × E) interactions were statistically non-significant for pod count and 1000-seed weight but significant for seed count per pod ($P < .05$).

Table 1: Combined Analysis of Variance for Yield Traits in Soybean Genotypes Exposed to FeNPs Evaluated in Akwanga and Lafia

Source of variation	Df	Pods (PD) SS	Pods MS	Seeds/Pod (SP) SS	Seeds/Pod MS	1000-Seed Wt (g) SS	1000-Seed Wt MS
Genotype (G)	21	14,938.98	711.38***	8.98	0.43ns	54,832.18	2,611.06*
Environment (E)	1	2,865.34	2,865.34***	0.37	0.37ns	1,745.45	1,745.45ns
Treatment (T)	2	1,069.41	534.70ns	3.29	1.64*	403.47	201.73ns
G × E Interaction	21	1,582.49	75.36ns	15.46	0.74*	3,541.21	168.63ns

Residuals (Error)	86	14,937.26	173.69	34.71	0.40	111,331.20	1,294.55

Note. Df = Degrees of freedom, SS = Sum of squares, MS = Mean squares. *P < .05, ***P < .001, ns = not significant.

Environmental Performance Differences between Akwanga and Lafia

Environmental conditions significantly influenced the expression of most agronomic traits (Table 2). Akwanga supported significantly higher mean values for germination count (3.42 vs. 2.94, P < .001), branch number (13.42 vs. 10.18, P < .001), plant height (49.47 cm vs. 43.67 cm, P < .001), days to 50% podding (55.98 vs. 59.17 days, P < .05), and total pod count per plant (53.45 vs. 44.14, P < .001). However, environmental differences were non-significant for days to 50% flowering (50.44 vs. 49.79 days), seed count per pod (3.18 vs. 3.08), and 1000-seed weight (179.70 g vs. 172.42 g).

Table 2: Mean Performance Comparison of Soybean Agronomic Traits evaluated in Akwanga and Lafia

Location	Germination Count	Branch Count	Plant Height (cm)	Days to 50% Flowering	Days to 50% Podding	Pod Count	Seeds per Pod	1000-Seed Weight (g)
Akwanga	3.42	13.42	49.47	50.44	55.98	53.45	3.18	179.70
Lafia	2.94	10.18	43.67	49.79	59.17	44.14	3.08	172.42
P-value	0.00***	0.00***	0.00***	0.61ns	0.04*	0.00***	0.38ns	0.25ns

Note. *P < .05, ***P < .001, ns = not significant.

Genetic Variance Components, Heritability, and Genetic Advance

Estimates of phenotypic coefficient of variation (PCV) consistently exceeded genotypic coefficient of variation (GCV) across all measured traits (Table 3). The highest GCV was observed for pod count per plant (21.10%), plant height (13.35%), and 1000-seed weight (11.46%), while germination count (8.27%), branch number (9.42%), and days to 50% podding (3.52%) recorded moderate GCV values. Seed count per pod exhibited zero genotypic variance (0.00%). Broad-sense heritability estimates were moderate for pod count per plant (37.90%) and plant height (36.69%), whereas remaining traits exhibited low heritability (<30%), peaking at 26.92% for branch count and falling to 1.27% for days to 50% flowering. Genetic advance as percent of mean (GG) was highest for pod count (16.47%) and plant height (10.09%).

Table 3: Estimates of Genetic Variance Parameters for Soybean Genotypes Evaluated across Environments

Parameter	GC	BC	PH	D50%F	D50%P	PC	SP	1000SW
GCV(%)	8.27	9.42	13.35	1.59	3.52	21.10	0.00	11.46
PCV (%)	25.68	18.16	22.04	14.09	14.76	34.27	22.93	23.43
Heritability (H^2 %)	10.37	26.92	36.69	1.27	5.68	37.90	0.00	23.92
Genetic Advance (GA)	0.06	0.62	4.70	0.02	0.24	8.04	0.00	9.94
Genetic Gain (GG %)	1.77	5.22	10.09	0.04	0.41	16.47	0.00	5.65

Note. GCV = Genotypic Coefficient of Variation, PCV = Phenotypic Coefficient of Variation, GA = Genetic Advance, GG = Genetic Gain. GC=Germination Count,

Specific Varietal Growth and Yield Responses to Foliar FeNP Application

Detailed varietal evaluation under FeNP-treated (T1) and untreated control (T0) conditions demonstrated significant genotypic divergence within the treated group for branch count (Table 4) and plant height (Table 5). Under T1, genotype V5 (TGx2020-4e) achieved the highest plant height (61.33 ± 3.21 cm) and maximum branch count (12.00 ± 1.00), alongside V2 (12.00 ± 1.00), whereas V4 exhibited the lowest vegetative values (height of 25.67 ± 22.50 cm and branch count of 5.67 ± 4.93). In contrast, genotypes under untreated control conditions (T0) showed uniform vegetative responses without statistically significant variation across varieties. Across all eleven genotypes, foliar FeNP treatment did not cause significant shifts in phenological maturity schedules (days to 50% flowering and days to 50% podding, Tables 6–7) or total 1000-seed weight (Table 8).

Table 4: Effect of Foliar Iron Nanoparticle Application on Mean Branch Count across Soybean Genotypes

Genotype	FeNP-Treated (T1)	Untreated Control (T0)	P-value (T1 vs. T0)
V1	7.67 ± 0.58ab	11.00 ± 2.00a	0.09ns
V2	12.00 ± 1.00b	12.67 ± 1.15a	0.49ns
V3	8.00 ± 1.00ab	9.33 ± 1.15a	0.21ns
V4	5.67 ± 4.93a	6.33 ± 5.51a	0.88ns
V5	12.00 ± 1.00b	11.33 ± 2.89a	0.74ns
V6	11.33 ± 1.15ab	11.00 ± 1.00a	0.73ns
V7	10.00 ± 2.00ab	10.67 ± 2.08a	0.71ns
V8	10.67 ± 1.53ab	11.67 ± 2.52a	0.59ns
V9	7.33 ± 0.58ab	9.33 ± 0.58a	0.01*
V10	11.33 ± 0.58ab	13.00 ± 1.00a	0.08ns
V11	10.33 ± 2.52ab	11.33 ± 2.31a	0.64ns
P-value (Across Varieties)	0.01*	0.13ns	—

Note. Values represent mean ± SD (n = 3). Means sharing the same superscript letter in a column are not significantly different at $P < .05$.

Table 5: Effect of Foliar Iron Nanoparticle Application on Plant Height (cm) across Soybean Genotypes

Genotype	FeNP-Treated (T1)	Untreated Control (T0)	P-value (T1 vs. T0)
V1	45.00 ± 8.66ab	48.33 ± 8.08a	0.65ns
V2	45.33 ± 15.18ab	48.00 ± 15.10a	0.84ns
V3	45.67 ± 8.74ab	48.00 ± 8.89a	0.76ns
V4	25.67 ± 22.50a	27.00 ± 23.64a	0.95ns
V5	61.33 ± 3.21b	54.00 ± 7.94a	0.25ns
V6	39.00 ± 5.57ab	43.33 ± 5.51a	0.39ns
V7	39.00 ± 6.08ab	41.33 ± 5.51a	0.65ns
V8	38.67 ± 6.03ab	40.67 ± 6.03a	0.71ns
V9	36.33 ± 5.03ab	36.67 ± 5.51a	0.94ns
V10	56.33 ± 9.29b	58.33 ± 9.07a	0.80ns
V11	40.00 ± 4.58ab	42.67 ± 4.51a	0.51ns
P-value (Across Varieties)	0.02*	0.09ns	—

Note. Values represent mean ± SD (n = 3). Means sharing the same superscript letter in a column are not significantly different at P < .05.

Table 6: Effect of Foliar Iron Nanoparticle Application on Total Pod Production per Plant

Genotype	FeNP-Treated (T1)	Untreated Control (T0)	P-value (T1 vs. T0)
V1	44.33 ± 12.66a	49.00 ± 13.53a	0.69ns
V2	34.33 ± 16.20a	38.00 ± 16.52a	0.80ns
V3	36.33 ± 8.50a	39.00 ± 7.00a	0.70ns
V4	27.67 ± 23.97a	30.00 ± 26.00a	0.91ns
V5	51.00 ± 1.73a	40.67 ± 5.51a	0.07ns
V6	58.00 ± 12.49a	60.67 ± 11.55a	0.80ns
V7	65.33 ± 14.98a	65.33 ± 14.57a	1.00ns
V8	22.33 ± 6.11a	35.33 ± 8.02a	0.09ns
V9	27.67 ± 5.03a	33.33 ± 7.23a	0.33ns
V10	59.33 ± 25.74a	64.67 ± 23.69a	0.80ns
V11	39.67 ± 25.79a	49.00 ± 14.53a	0.62ns
P-value (Across Varieties)	0.09ns	0.06ns	—

Note. Values represent mean ± SD (n = 3). Means sharing the same superscript letter in a column are not significantly different at P < .05.

Table 7: Effect of Foliar Iron Nanoparticle Application on Mean Seed Count per Pod

Genotype	FeNP-Treated (T1)	Untreated Control (T0)	P-value (T1 vs. T0)
V1	2.67 ± 0.58a	2.67 ± 0.58a	1.00ns
V2	3.00 ± 1.00a	3.33 ± 0.58a	0.65ns
V3	3.67 ± 0.58a	3.33 ± 0.58a	0.52ns
V4	2.00 ± 1.73a	2.33 ± 2.08a	0.84ns
V5	3.00 ± 0.00a	3.00 ± 0.00a	1.00ns
V6	3.00 ± 0.00a	3.67 ± 0.58a	0.18ns
V7	4.00 ± 0.00a	4.00 ± 0.00a	1.00ns
V8	2.67 ± 0.58a	3.00 ± 0.00a	0.42ns
V9	3.67 ± 0.58a	3.33 ± 0.58a	0.52ns
V10	2.00 ± 0.00a	3.00 ± 0.00a	0.00*
V11	2.67 ± 0.58a	3.67 ± 0.58a	0.10ns
P-value (Across Varieties)	0.07ns	0.35ns	—

Note. Values represent mean ± SD (n = 3). Means sharing the same superscript letter in a column are not significantly different at P < .05.

Table 8: Effect of Foliar Iron Nanoparticle Application on 1000-Seed Weight (g) across Soybean Genotypes

Genotype	FeNP-Treated (T1)	Untreated Control (T0)	P-value (T1 vs. T0)
V1	160.00 ± 26.51a	167.67 ± 29.26a	0.75ns
V2	156.67 ± 8.14a	168.00 ± 4.58a	0.12ns
V3	175.00 ± 13.75a	185.00 ± 15.13a	0.45ns
V4	110.67 ± 96.72a	113.00 ± 98.42a	0.98ns
V5	201.33 ± 8.08a	193.33 ± 26.16a	0.66ns
V6	180.67 ± 27.79a	182.67 ± 26.50a	0.93ns
V7	179.33 ± 22.74a	173.00 ± 24.02a	0.76ns
V8	184.33 ± 16.56a	194.67 ± 16.01a	0.48ns
V9	178.33 ± 19.50a	184.33 ± 17.79a	0.71ns
V10	171.33 ± 7.51a	182.67 ± 8.50a	0.16ns
V11	173.00 ± 30.05a	178.33 ± 32.87a	0.85ns
P-value (Across Varieties)	0.28ns	0.38ns	—

Note. Values represent mean ± SD (n = 3). Means sharing the same superscript letter in a column are not significantly different at P < .05.

DISCUSSION

The significant effect of foliar FeNP supplementation on mean seed count per pod (P < .05; Table 1) demonstrates that biogenic iron oxide nanoparticles effectively alter reproductive physiological processes in soybean. Iron serves as an essential catalytic component of photosynthetic electron transport complexes (cytochromes and ferredoxin) and enzyme systems involved in

chlorophyll biosynthesis and carbohydrate translocation (Costa et al., 2021; Daramola et al., 2021). Nano-sized iron formulations enhance cellular uptake, boosting photosynthetic rate and carbohydrate accumulation available for ovule fertilization and seed set per pod (Mozafari et al., 2018; Yadav et al., 2021). The significant genotypic differences observed for total pod count per plant ($P < .001$) and 1000-seed weight ($P < .05$) further highlight intrinsic genetic variation among the evaluated accessions. These genetic variations reflect inherent differences in yield component architecture, aligning with findings in cowpea and soybean trials where yield traits were largely governed by varietal genetic constitution (Kokina et al., 2020; Manggoel et al., 2012; Wang & Graef, 2013).

Environmental conditions in Akwanga promoted significantly higher vegetative growth and pod production compared to Lafia (Table 2). Akwanga's cooler highland climate, higher elevation, well-drained Basement Complex soils, and adequate moisture availability established favorable growing conditions for canopy extension (plant height and branch count) and pod development. Conversely, the lower elevation, higher temperatures, and sandier soils in Lafia may have imposed mild thermal and moisture stress during early growth, though Lafia maintained comparable seed weight and flowering schedules. Environmental modulation of soybean growth and yield components across savanna agro-ecologies has been widely documented by Wakili et al. (2025), Vange and Moses (2009), and Abebe et al. (2024).

The genetic variance analysis revealed that phenotypic coefficients of variation (PCV) consistently exceeded genotypic coefficients of variation (GCV) across all measured parameters (Table 3). This pattern confirms that phenotypic expression in these soybean genotypes is heavily influenced by environmental variables (Gadde et al., 2008; Makeen et al., 2007). Broad-sense heritability estimates were moderate for pod count per plant (37.90%) and plant height (36.69%), indicating that selection for these traits would yield reasonable genetic progress. Conversely, low heritability estimates (<30%) for seed count per pod, flowering days, and podding days indicate strong environmental modulation, making direct phenotypic selection for these parameters less effective without multi-environment testing (Neelima et al., 2018; Oyiga & Uguru, 2011).

Varietal evaluation under FeNP-treated and untreated conditions demonstrated that foliar FeNP application significantly enhanced branching and height exclusively within specific responsive genotypes such as V5 (TGx2020-4e) and V2 (Tables 4–5). The enhanced branching in V5 and V2 under FeNP treatment suggests elevated vegetative sink capacity driven by optimized micronutrient nutrition (Aduloju et al., 2009; Shim et al., 2019). However, FeNP application did not induce significant shifts in overall phenological maturity schedules (days to flowering and podding) or 1000-seed weight across genotypes, confirming that crop maturity and individual seed size remain under tight genetic control rather than foliar micronutrient manipulation (Iyorkaa et al., 2021; Kana & Kwon-Ndung, 2021; Ogunmola et al., 2021).

The result in Table 6 revealed that there was an increase in mean number of pods per plants in untreated (T_0) soybean varieties than the treated (T_1) varieties although this

was not significant. The present result is in disagreement with the work done by Qin et al. (2023) who worked on the utilization of nanoparticle in soybean and reported an increase in number of pods per plant in soybean varieties treated with zinc oxide (Fe_3O_4) nanoparticle.

Iron nanoparticle treatment did not significantly alter the number of seeds per pod compared to the untreated control across most genotypes with the exception of V10 (2.00 ± 0.00 vs. 3.00 ± 0.00, p = 0.00). Overall variation across varieties remained statistically non-significant under both treated (p = 0.07) and untreated (p = 0.35) conditions. Seeds per pod are a highly conserved yield component in soybean that is predominantly under tight genetic control rather than influenced by foliar/seed nano-fertilization. This is in agreement with the work of Ogunmola et al. (2022) who reported in their study on soybean that yield-related traits are modified by the prevalent environmental conditions. The weight of the untreated (T_0) soybean varieties was heavier than the treated (T_1) varieties although this was not significant (Table 8). This indicated that iron nanoparticle foliar treatment did not meaningfully influence seed weight in this study. This finding is alignment with the research conducted by Iyorkaa et al. (2021) who reported that seed weight is predominantly influenced by genetic factors, prompting breeding programs to focus on this characteristic to enhance yield and processing quality.

CONCLUSION

Foliar application of green-synthesized iron oxide nanoparticles (FeNPs) significantly increased mean seed count per pod (P < .05) in soybean, demonstrating a direct effect of nano-nutrient supplementation on reproductive capacity per pod. However, FeNP application did not significantly alter overall growth and yield components such as germination count, days to 50% flowering, days to 50% podding, pod count, and 1000-seed weight compared to untreated control plots across all eleven soybean genotypes. Significant varietal differences following FeNP application were observed only in plant height and primary branch number, with genotype V5 (TGx2020-4e) achieving maximum height (61.33 cm) and maximum branch count (12.00), alongside V2 (12.00). Environmental conditions in Akwanga supported significantly higher vegetative growth and structural pod yield (53.45 pods per plant) than Lafia (44.14 pods per plant). Phenotypic variance consistently exceeded genotypic variance across all measured traits, resulting in low-to-moderate heritability estimates (0.00% to 37.90%). In summary, while foliar FeNP application enhances specific reproductive and vegetative parameters in responsive accessions, key agro-morphological traits and yield performance in tropical soybean genotypes across savanna agro-ecologies remain primarily governed by genetic architecture and environmental conditions.

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