Wiley
International Journal of Agronomy
Volume 2025, Article ID 1085333, 9 pages
https://doi.org/10.1155/ioa/1085333

WILEY

Research Article

Nitrogen-Dependent Growth and Yield Attributes in Mutant Lines of *Solanum villosum*: A Pathway to Enhanced Leafy Production

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Received 21 May 2025; Revised 13 October 2025; Accepted 1 November 2025

Academic Editor: Nidhi Chaudhary

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This study investigates the response of selected improved mutant lines of *Solanum villosum* to varying nitrogen levels, focusing on their agronomic trait performance to enhance yield production. Nine *Solanum villosum* mutant (*svm*) lines were evaluated across four nitrogen (N) levels to assess growth and yield attributes. The results revealed significant genotype-by-nitrogen interaction effects on growth and yield parameters. Notably, the line *svm188-1* exhibited the highest leaf yield of 57.79 g at an application rate of 5 g $Nplant^{-1}$, compared to 15 g of control-WT. In the absence of nitrogen application, the line *svm62-5* produced a high total leafy yield of 25.5 g compared to 11.1 g of control-WT. Leaf production increased by 2.7–3.8 times when nitrogen was applied and 1.7 times without nitrogen application. Key determinants of leaf production included leaf number and leaf area. The study recommends the genotypes *svm188-1* and *svm62-5* as promising candidates for direct use in leafy biomass production due to their superior performance when 5 g of nitrogen was applied per plant. Further research is suggested to evaluate seasonal variations in leafy yield. This work contributes to agronomic performance improvement of nightshade toward increased productivity.

Keywords: genotypes; leaf yield; mutant; nitrogen; production; *Solanum villosum*

1. Introduction

Solanum villosum (nightshade) is among the widely consumed indigenous leafy vegetables in sub-Saharan African (SSA) countries. The crop is of outstanding potential due to its economic benefits and healthy and nutritional potential. Tanzania and Kenya are the leading countries in East Africa for its production [1, 2]. In Tanzania, it is mainly grown in Arusha, Kilimanjaro, Morogoro, and Tanga regions whereby Arusha comprises 75% of the total production [3]. Utilization of *S. villosum* gained popularity and increased in larger cities whereby 90% of produce are consumed while the major production grounds are still in rural areas [4–6]. The nightshade is very rich in health promoting micronutrients including vitamin C and E, β-carotene, minerals (iron, zinc, and calcium), and dietary fiber also, antioxidants and other health-related biochemical compound possess anticancer and antigenotoxic properties [6–11]. It has been reported that the proper consumptions of this vegetables can subsidize to ending hidden hunger, mainly in children and pregnant women in rural especially areas and ensure the food security [5].

The largely and readily available cultivated genotypes of *S. villosum* are wild types that produce moderate leaf size with the high ability of forming a large number of flowers and fruits [12]. Low leafy productivity due to high reproductive function of the crop has been reported as a limiting factor for the commercial production. Short life cycle of this crop addressed by early and prolific flowering occurred immediately at 14 days after transplanting resulting into low leafy biomass. The potential utilization of CMS system has been reported of improving yield in various

leafy vegetables especially in nightshade and brassica species [13, 14]. Most CMS-associated genes are co-transcribed with mitochondrial genes encoding ATPase, cytochrome oxidase, or ribosomal proteins [14]. A CMS protein causes mitochondrial deficiencies, such that energy requirements during male reproductive development are not met [15]. Due to reproductive dysfunction caused by the CMS gene, crop invests the energy to vegetative potential resulting in prolific leaf formation [16]. Owing to the stable expression of CMS in diverse environmental condition, the gene has been fully utilized in improving the agronomic traits in various vegetable crops. Male sterility and the accompanying change in reproductive:vegetative balance are clearly useful tools for circumventing source–sink imbalances that reduce leaf yields after anthesis in African nightshades [10].

The production of this vegetable is limited due to lack of improved agronomic practices especially the use of low-yield seed inputs and low nutrient use efficiency. Currently, the vegetable is still under wild collection, and this crop is grown in small plots in backyard gardens using local and conventional improved seeds. The current reported leafy yield biomass was 1.2 tons/ha while the actual potential yield can reach up to 4 tons/ha under proper management [17, 18]. Improved mutant cultivar characterized with late flowering, reduced flower and fruits set which is improved features for increased leaf vegetable production of this crop [18–24]. It is hypothesized that under appropriate good agronomic conditions, mutant genotypes developed have the capacity to diverge some of their resources that are no longer required for reproductive function and could devote more of their resources to leaf production, potentially yielding higher leafy production available wild-type cultivars [10, 12]. The response of these mutant lines to nitrogen application in agronomic trait productivity has not been fully utilized and studied and it is the objective of this study.

2. Materials and Methods

2.1. Planting Materials. A total of nine genotypes including eight cytoplasmic male sterile mutant genotypes (svm188-1, svm242-9, svm188-4, svm204-3, svm34-4, svm135-1, svm62-5, and svm57-1) characterized as *Solanum villosum* mutants (svms) of nightshade leafy vegetable and one nonmutant wild type used as check were utilized in this study. The mutants were selected based on dry weight, number of branches per plant, and number of flowers per plant. The CMS mutant was developed by physical radiation using gamma rays and characterized by sequenced characterization [24].

2.2. Description of the Study Area. The study was conducted at University of Dar es Salaam (UDSM), College of Agriculture and Food Technology (CoAF) demonstration plots located 6°49′00″S, 39°17′00″, Dar es Salaam, Tanzania, altitude of 100 m from the sea level. The area received annual mean rainfall of 1148 mm and monthly average temperature of 27.9°C and 25°C during the dry and rainy season, respectively. Experiments were conducted in two phases, during the dry season (July to October) in 2023/24 and the rainy season (December to April) in 2023/2024. The soil of the field where this study was conducted was characterized as friable sandy clay with low pH (< 7.0), deficient in the most essential plant nutrients (NPK). The incorporation of farmyard manure at the rate of 7 t/ha prior to planting was done to raise the NPK condition of the soil as recommended.

2.3. Experimental Design, Layout, and Experimentation. The field experiments were conducted to investigate the effect of nitrogen fertilizer rates in different genotypes. Seeds were sown on 20th December 2024 in 200-hole plastic seedling trays filled with forest soil. The site was cleared and was manually leveled and ridged 75 cm apart. The area was then marked into plots. Plants of the eight mutant genotypes (svm188-1, svm242-9, svm188-4, svm204-3, svm34-4, svm135-1, svm62-5, and svm57-1) and control-WT were subjected to four nitrogen fertilizer levels: 0 g N plant^{-1}, 2.5 g N plant^{-1}, 5.0 g N plant^{-1}, and 7.5 g N plant^{-1} which is equivalent to 60 kg N ha^{-1}, 120 kg N ha^{-1}, and 180 kg N ha^{-1} (CAN 26% as source of N). This gave a 9×4 factorial arrangement which was fitted into randomized complete block design (RCBD) with three replications. Transplanting was carried out at the fifth true leaf stage, 21 days after sowing. Seedlings were transplanted 50 cm apart on the ridges at one per stand (eight seedlings per row). The area of a replicate was 135.625 m^2 (17.5 m × 7.75 m) in dimension while a gap of 1.0 m separated the adjacent replicates. The total experimental area was 441.88 m^2 (25.25 m × 17.5 m). Nitrogen was applied in two equal splits: the first application at 7 days after transplanting and the second at 14 days after transplanting. The nitrogen was applied in a ring form, 20 cm away from the plant, to avoid direct contact. Phosphorus and potassium were applied at recommended rates and kept constant across all treatments. To manage insect pests, a systemic insecticide (Attakan C344SE) was applied at a rate of 15 mL per 20 L of water at 7-day intervals, starting 15 days after transplanting.

2.4. Data Collection. Data were collected from three systematically selected plants in the two middle rows of each subplot. The collected data included growth parameters such as (i) plant height (cm), measured three times at 7-day intervals until a constant height was achieved; (ii) the number of leaves, branches, and nodes per plant; and (iii) leaf dimensions (length and width), measured using a metric ruler. Leaf area was calculated using the formula: LA = Length (cm) × Width (cm) × 2.235, as proposed in [25]. Leaf harvesting began 21 days after transplanting and continued at biweekly intervals for three harvests. Harvesting was conducted early in the morning (between 6:00 a.m. and 7:30 a.m.) by pinching tender tissues and newly emerging leaves. The fresh weight of the harvested leaves was measured immediately in the field using a sensitive digital balance and recorded in grams.

2.5. Statistical Analysis. The data collected were analyzed for the effects of treatments on the experimental unit using STATA software applied in two-way statistical mode

Table 1: Analysis of variance (ANOVA) of various growth and yield characteristics of different genotypes of male sterile mutants of *S. villosum* tested in different nitrogen rates.

S.V	DF	Ph (cm)	ND	NL	LL	LW (cm)	MLA	NBR	Y/P (g)	Y/ha (t/ha)
G	9	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}
N	3	0.001^{***}	0.009^{**}	0.001^{***}	0.001^{***}	0.004^{**}	0.002^{**}	0.001^{***}	0.001^{***}	0.001^{***}
GXN interaction	27	0.027^{*}	0.001^{***}	0.023^{*}	0.006^{**}	0.001^{***}	0.051^{*}	0.002^{**}	0.001^{***}	0.001^{***}

Note: Ph: plant height (cm), ND: number of nodes per plant, LL: leaf length (cm), LN: number of leaves per plant, LW: leaf width (cm), MLA: measured leaf area (cm^2), NBR: number of branches per plant, Y/P(g): yield per plant (g), G: genotype, and Nrate: nitrogen rate.
Abbreviation: DF, degree of freedom.
*,**,***Statistically significantly different at probability level of 0.05, 0.01, and 0.001, respectively.

Table 2: Mean comparison of significant yield and yield attributes of *Solanum villosum* mutants in different levels of applied nitrogen.

Genotypes	g N plant−1	Plant height (cm)	Leaf number	Leaf area	Yield (g/plant)
svm62-5	0	16.7 ± 1.14abc	129.3 ± 18.7abc	13.6 ± 1.8abc	239.5 ± 37.5bcdefg
	2.5	15.5 ± 0.75abcdef	113.6 ± 17.5abc	11.8 ± 1.89abc	342.4 ± 78.7abcdefg
	5	12.6 ± 1.05bcdef	96.5 ± 13.6abc	10.1 ± 1.44abc	297.0 ± 41.8bcdefg
	7.5	12.7 ± 1.02bcdef	85.6 ± 23.97abc	10.8 ± 1.56abc	334.9 ± 50.4abcdefg
svm204-3	0	15.5 ± 1.0abcdef	122.3 ± 21.55abc	9.6 ± 1.6abc	148.1 ± 25.1cdefg
	2.5	16.3 ± 1.01abcd	**145** ± 12.51bc	12.4 ± 2.17abc	386.2 ± 31.7abcd
	5	14.2 ± 1.1abcdef	106.6 ± 23.54abc	**14**.1 ± 2.03ab	**415.1 ± 70.8ab**
	7.5	11.0 ± 1.92cdef	51.8 ± 11.12bc	5.2 ± 0.98abc	98.01 ± 24.2g
svm188-1	0	**19**.0 ± 0.28a	**130**.6 ± 17.09abc	**14.4** ± 2.07a	201.7 ± 21.3bcdefg
	2.5	16.9 ± 0.86ab	80.8 ± 16.92abc	12.1 ± 2.37abc	273.6 ± 36.7bcdefg
	5	16.3 ± 1.04abcd	**154**.3 ± 29.48a	**14.1** ± 1.39ab	**577.9 ± 74.3a**
	7.5	15.2 ± 0.92abcde	85.8 ± 11.94abc	11.2 ± 1.95abc	258.4 ± 100bcdefg
svm34-4	0	16 ± 1.21abcde	96.5 ± 11.37abc	12.5 ± 1.27abc	174.3 ± 17.7bcdefg
	2.5	12.2 ± 1.61bcdef	69 ± 17.41abc	7.8 ± 2.57abc	188.6 ± 53.9bcdef
	5	14.4 ± 1.24abcdef	101.5 ± 19.06abc	14.4 ± 2.27a	382.5 ± 41.53abcde
	7.5	13.1 ± 0.7bcdef	97.6 ± 17.67abc	11.5 ± 1.61abc	302.8 ± 40.21bcdefg
svm188-4	0	13.9 ± 0.93abcdef	88.5 ± 12.2abc	9.2 ± 1.15abc	137.6 ± 16.55cdefg
	2.5	13.2 ± 1.5bcdef	67 ± 18.8abc	8.5 ± 2.0abc	245.01 ± 27.0bcdefg
	5	15.8 ± 0.7abcdef	110.6 ± 22.88abc	11.9 ± 1.02abc	393.1 ± 31.7abc
	7.5	11.270.35bcdef	73 ± 9.44abc	8.7 ± 1.08abc	349.5 ± 43.9abcdefg
svm135-1	0	13.8 ± 0.77abcdef	97.6 ± 19.51abc	8.06 ± 1.75abc	123.2 ± 24.4efg
	2.5	13.2 ± 1.12bcdef	82.3 ± 8.22abc	8.2 ± 1.14abc	259.4 ± 41.55bcdefg
	5	12.8 ± 0.79bcdef	97.3 ± 18.48abc	9.7 ± 1.32abc	360.2 ± 34.6abcdef
	7.5	10.2 ± 0.55ef	70 ± 12.01abc	7.1 ± 1.27abc	219.7 ± 51.1bcdefg
svm242-9	0	11.0 ± 1.6cdef	74.3 ± 14.22abc	5.5 ± 1.93abc	110.1 ± 28.0fg
	2.5	14.1 ± 0.49abcdef	89.5 ± 24.64abc	10.3 ± 0.69abc	321.3 ± 34.8abcdefg
	5	13.1 ± 0.39bcdef	118 ± 20.37abc	12.0 ± 1.5abc	398.1 ± 17.1abcd
	7.5	10.9 ± 1.36cdef	92 ± 24.15abc	8.9 ± 1.56abc	284.6 ± 22.7bcdefg
svm148-1	0	13.5 ± 1.48abcdef	84.8 ± 16.34abc	8.9 ± 2.53abc	127.9 ± 33.2defg
	2.5	12.8 ± 0.62abcdef	75.1 ± 11.01abc	8.7 ± 1.38abc	198.6 ± 22.5bcdefg
	5	13.5 ± 1.13abcdef	133.8 ± 33.9abc	11.1 ± 1.34abc	288.5 ± 51.5bcdefg
	7.5	11.5 ± 0.66bcdef	46 ± 9.36c	8.8 ± 0.91abc	388.1 ± 116abcd
svm57-1	0	11.3 ± 1.01bcdef	67.6 ± 6.13abc	5.6 ± 0.8abc	92.4 ± 20.7g
	2.5	12.8 ± 1.42bcdef	46.3 ± 14.02c	4.9 ± 1.02c	114.4 ± 28.8fg
	5	14.5 ± 1.17abcdef	87.5 ± 18.5abc	12.5 ± 2.25abc	327.5 ± 77.2abcdefg
	7.5	12.2 ± 1.1bcdef	55.16 ± 9.89bc	8.6 ± 0.84abc	240.1 ± 19.1bcdefg
Control-WT	0	12.6 ± 0.91bcdef	67.3 ± 8.84abc	8.7 ± 1.85abc	110.9 ± 22.1fg
	2.5	10.7 ± 0.6def	60.6 ± 9.48abc	5.1 ± 0.92c	161.5 ± 39.3bcdefg
	5	10.1 ± 0.58f	40 ± 3.05c	7.8 ± 0.42abc	152.8 ± 27.5cdefg
	7.5	11.7 ± 0.94bcdef	77 ± 13.2	7.6 ± 0.88abc	277.3 ± 52.6bcdefg
P value		0.01^{*}	0.01^{*}	0.01^{*}	0.01^{*}

Note: Means that do not share a letter are significantly different at $p < 0.05$. Values are expressed as mean and standard error of mean (mean ± SEM). The bold values represent the high mean value for each indicated parameter.

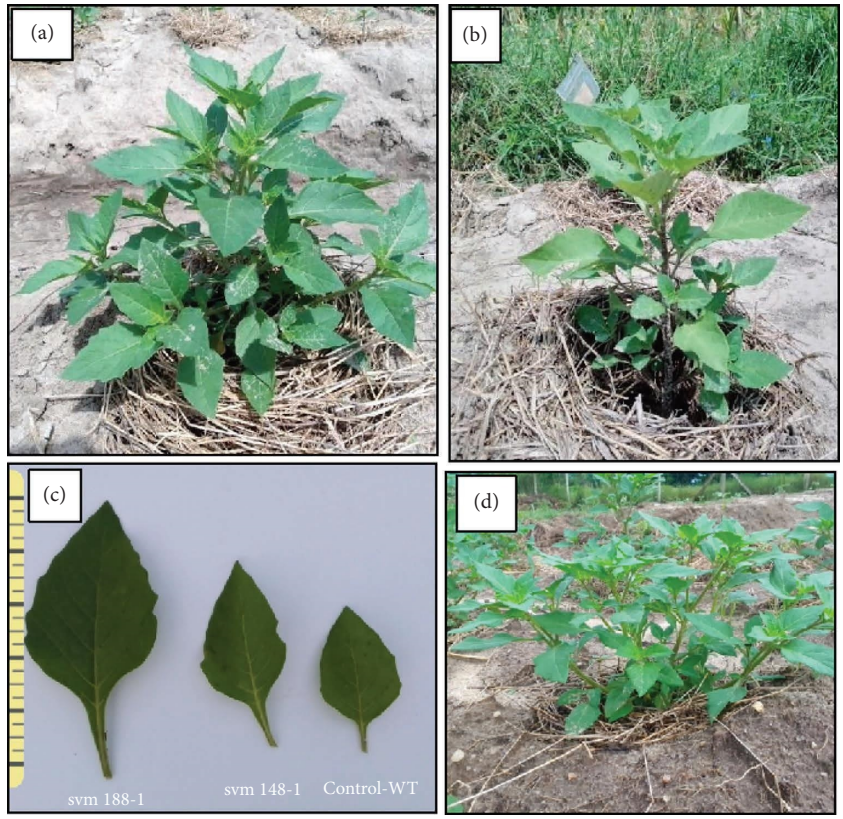


Figure 1: Yield attribute differences across mutant genotypes of *S. villosum* compared to wild type: (a) vigorous leaf number of mutant genotype; (b) wild type control plant with fewer and small sized leaf; (c) differentiated leaf dimension of mutants and wild type; (d) branched plant of mutant genotype.

$Y_{ij} = \mu + \tau_i + \beta_{j+} + \gamma_{ij} + \epsilon_{ijk}$, where Y_{ij} is the overall response due to the effects of nitrogen level in mutant genotype, μ is the overall mean response, τi is the effect due to the ith nitrogen levels, βj is the effect due to the mutant genotypes, and γij is the interaction effect of nitrogen and mutant genotypes. The significant treatment means were subjected to Tukey test for multiple comparisons at 5% level of statistic. Then, the means were subjected to Pearson matrix correlation analysis technique to determine the relationship between yield and plant height to different growth parameters and under different rates of nitrogen fertilizer and mutant genotypes. Step-wise regression analysis was then used to select the critical factors and yield components influencing leaf yield of mutants of *S. villosum*.

3. Results and Discussion

3.1. Response of the Different Applied Nitrogen Levels in Yield and Yield Attributes of svm Genotypes. The results showed significant difference in all growth and yield trait performance in different mutant genotypes applied with various nitrogen fertilizers (Tables 1 and 2). The traits and productivity performance were largely depending on the combined effects of mutant genotypes selected in various applied nitrogen levels. Highest plant height of 19.0 ± 0.28 was obtained at svm 188-1 in plot applied with 0 g N plant^{-1} followed by 16.9 cm in the same mutant genotype in 2.5 g N plant^{-1}. Leaf number, leaf area, and leaf weight of 154.3 ± 29.48, 14.1 ± 1.39, and 577.9 ± 74.3 in svm188-1 plot applied with 5 g N plant^{-1} were recorded (Figure 1). Control-WT showed the least value in all measured parameters whereby the lowest value of growth parameters was observed in plot with 0 g N plant^{-1} while the highest was observed in 7.5 g N plant^{-1}. Performance of various mutant genotypes of *S. villosum* was different in various levels of nitrogen and was highest compared to control wild types. Nitrogen exerted its effects on the observable parameters; it has been associated with a number of physiological processes that control growth and development of plant. It plays an important role in cell division and elongation, which in turn increase the vegetative plant growth. Also, nitrogen affects the leaf area index which increases the light interception during photosynthesis [18, 26–28]. The authors of [29] reported similar findings and postulated that applying nitrogen to *Arabidopsis* spp. increased the shoot branches and affected the rate of mesophyll cell division and leafy blade elongation, which in turn increased the size of the leaves [30–32]. Productivity of the wild type increased with increased nitrogen levels compared to mutant genotypes where the highest performance leaf weight of 277.3 ± 52.6 g plant^{-1} was observed in 7.5 g N plant^{-1}. This was anticipated to be associated with least nitrogen use efficiency of the control wild type compared to that of svms.

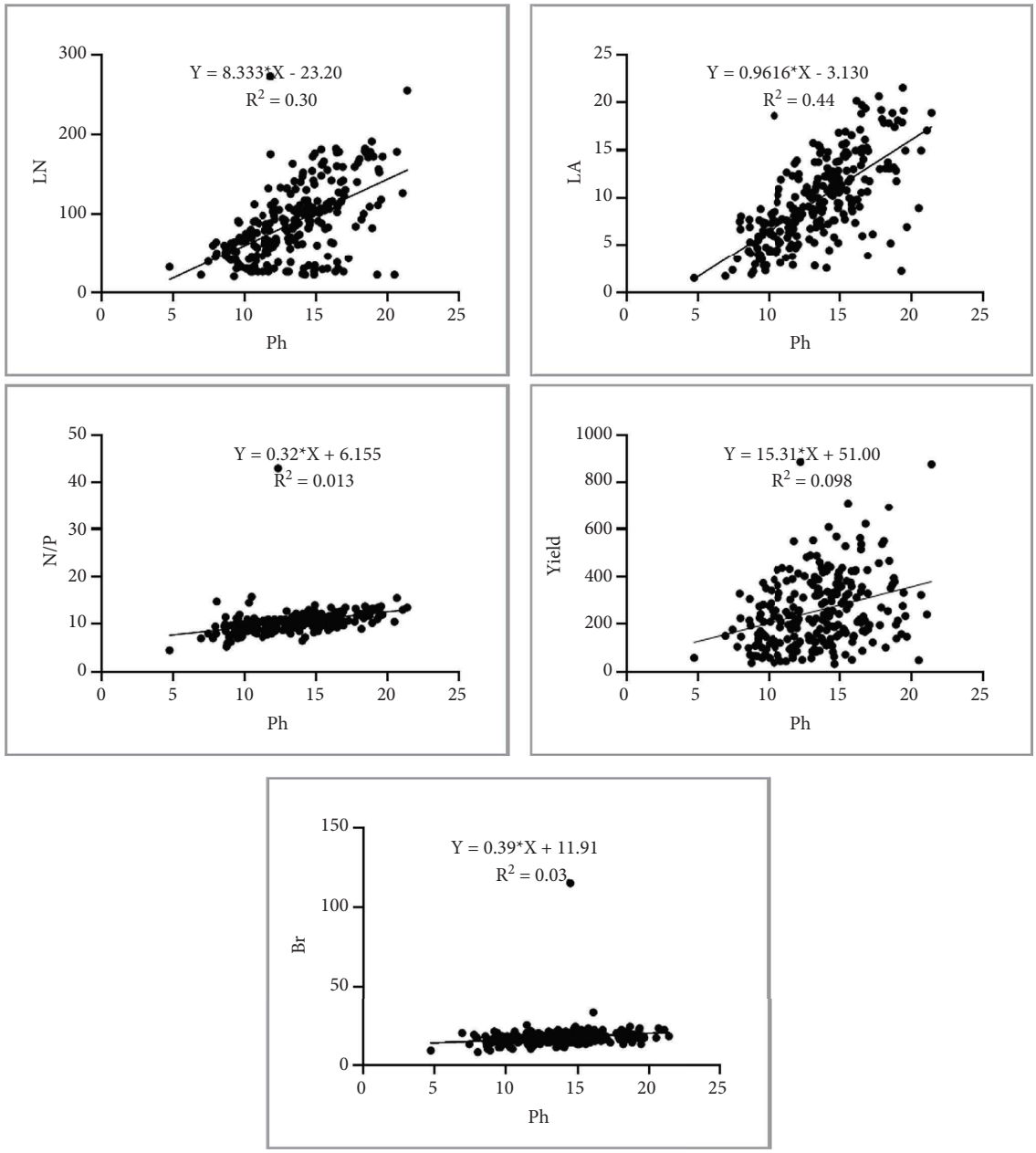


FIGURE 2: Linear regression graph indicating the association between plant height and other agronomic parameters. *Note:* LA: leaf area in meter square, LN: leaf number per plant, N/P: number of nodes per plant, Yield: fresh leaf weight per plant in gram, Ph: plant height and R_2: coefficient of determination.

The results observed a decrease in leaf weight per plant as the nitrogen level increased above 5.0 g N plant^{-1} in all mutant genotypes; yield of svm 188-1 was decreased from 577.9 ± 74.3 t ha^{-1} in 5.0 g N plant^{-1} to 258.4 ± 100 in plot applied with 7.5 g N plant^{-1}. Excessive application of nitrogen was anticipated to be associated with least nitrogen use efficiency due to excess nitrogen lost by leaching. Various researchers reported the negative effects of excessive application of nitrogen in growth of plant. For instance [16] reported the negative effects of excessive application of nitrogen in yield that results were due lower nitrogen root uptake. Also [29, 33] reported the excessive nitrogen application beyond the optimal amount that plant can uptake resulted to lower nitrogen use efficiency hence, losses occurred due to leaching and denitrification. The total leaf fresh weight in 5.0 g N plant-1 increased from 152.8 ± 27.5 in control-WT to 577.9 ± 74.3 g plant^{-1} in svm188-1 and to 415.1 ± 70.8 in svm 204-3; this was equivalent to 3 to 4 times the yield of control-WT. Similar findings were found by Mauyo et al. [34] in *Solanum retroflexum* and *Chlorophytum comosum* plants. In our results, the interaction between genotypes and applied nitrogen levels has significantly contributed to these increased leaf weight and significant variations of other growth and yield components. Also,

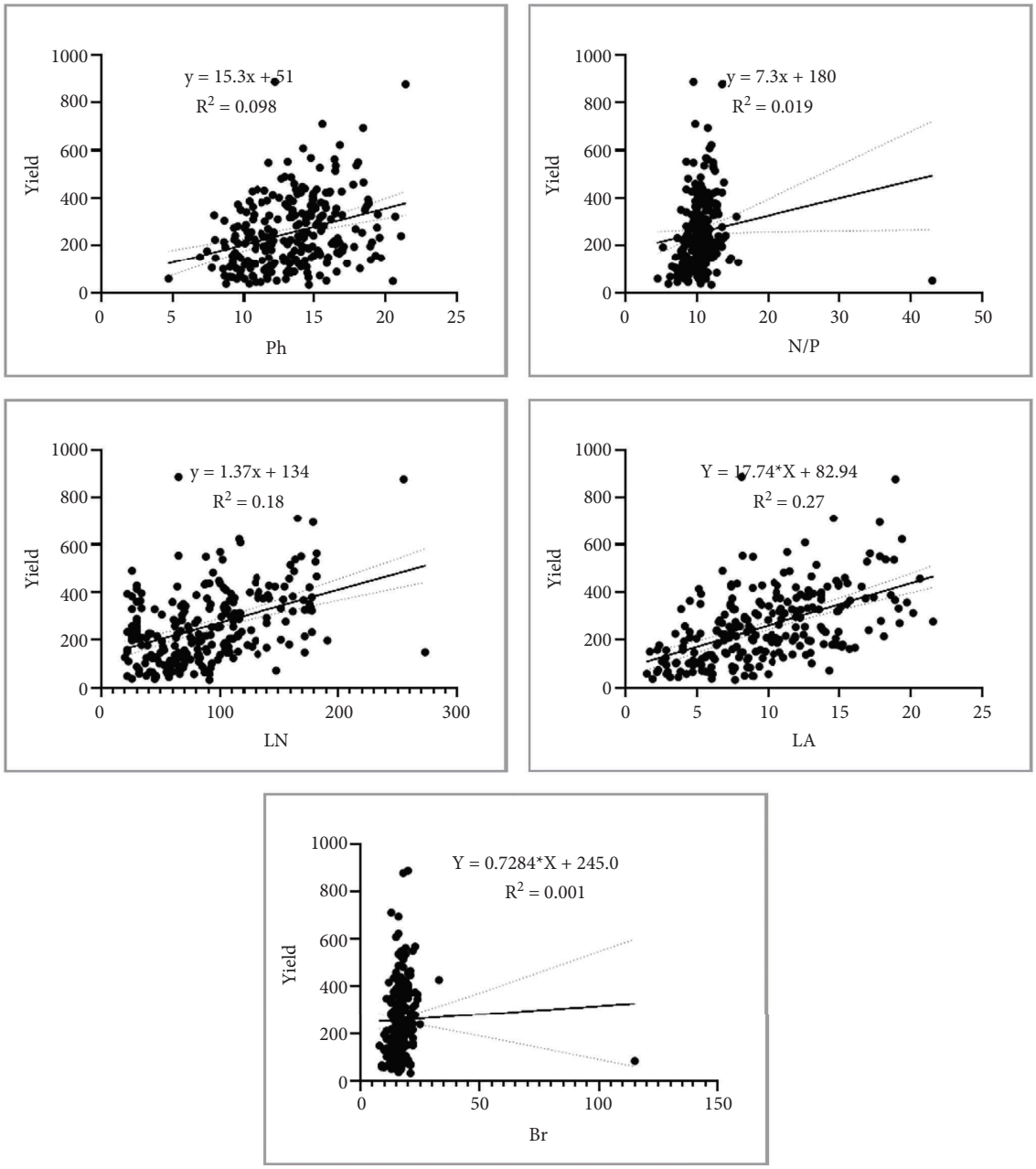


Figure 3: Simple linear relationship between the yield and other agronomic parameters. *Note:* LA: leaf area in meter square, LN: leaf number per plant, N/P: number of nodes per plant, Yield: fresh leaf weight per plant in gram, Ph: plant height and R^2: coefficient of determination.

Ojiewo et al. [35] reported that the fresh leaf weight of OCT-5 increased 2-fold compared to control when 2.7 g Nplant^{-1} was applied.

3.2. Linear Association on Various Growth and Yield Parameters in Applied Levels of Nitrogen of Mutant Genotypes. Pearson's correlation coefficients were initially estimated to verify the association between yield and the optimal plant height, and the results are shown in Figure 2. The results showed the increased in leaf number per plant and leaf area per plant have been high associated with the increase of plant height as indicated in coefficient of determination $R^2 = 0.30$ and 0.44 for leaf number and leaf area respectively. The number nodes, branches number and leaf weight were less associated with the plant height indicated by coefficient of determination $R^2 = 0.013$, 0.03 and 0.098 respectively. Our results are in contrary with our findings of [36] who reported the highly association of plant height in increased yield of *Vicia faba* L.

3.3. Association Between the Yield and Yield Components on the Mutant Genotypes Applied With Different Nitrogen Levels. Pearson's correlation coefficients were estimated to identify the association of growth parameter response contribution to the total final leaf weight, and the results are shown in Figure 2. The results showed that the leaf area ($R^2 = 0.27$) and

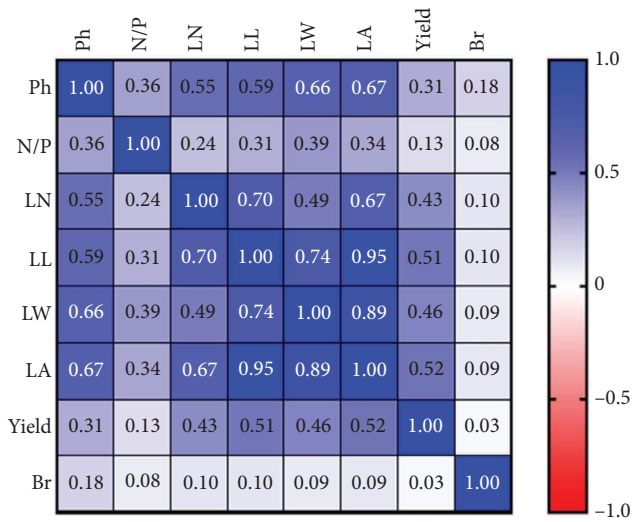


FIGURE 4: Pairwise relationship between the growth and yield components of mutant genotypes of *S. villosum* by Pearson's correlation coefficient. The results suggest that there is a level of correlation among the studied parameters.

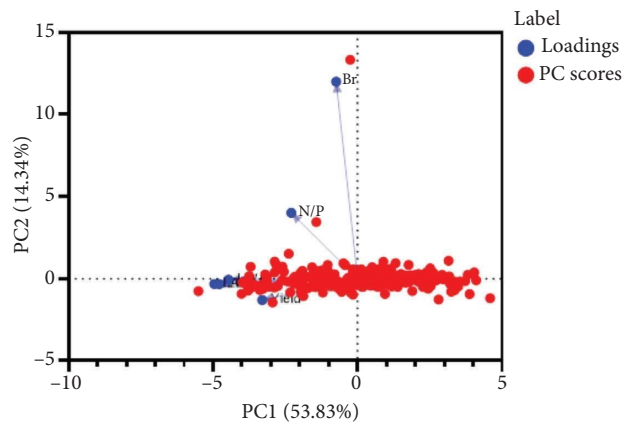


FIGURE 5: Principal component analysis of various yield components associated with increased leaf production of *S. villosum* mutant genotypes applied with different applied nitrogen levels.

leaf number ($R^2 = 0.18$) correlated with the increased final leaf weight compared to plant height ($R^2 = 0.098$), number of nodes ($R^2 = 0.019$), and number of branches ($R^2 = 0.001$). This means that the final leaf weight of mutant genotypes contributed to the increased leaf area and leaf number as shown in Figure 3. Similar results were found in [15].

3.4. Relationship Between the Yield and Yield Components of Mutant Genotypes of S. villosum Applied With Different Fertilizers. Leaf length contributed significantly on total leaf area (0.95, $p < 0.01$)) of studied mutants while leaf width contributes secondly to leaf area based on the person correlation coefficient (0.89, $p < 0.01$). Plant height of the mutant genotypes causes the variation contribution of leaf area (0.67, $p < 0.01$) while less correlated with number of branches (0.18) and yield (0.31). Variation of yield of mutant genotypes contributed and much correlated with leaf area (0.52, $p < 0.01$) and leaf number (0.43). In this study, branches of plant less contribute to the changes of other growth component studied (Figure 4). The results from this study generalized that the plant height, leaf number and leaf area and yield are the well correlated with each other, Plant height contribute correlated significantly with the leaf dimensions which are the main component of the total final leaf production of svms.

3.5. Yield Components Associated With the Increased Leaf Production of Mutant Genotypes of S. villosum Applied With Different Nitrogen Levels. Principal component analysis was conducted to screen the parameters that contributed to the greatest of variations in svm genotypes under study (Figure 5). Two principal components explain 68.17% of the total variations of yield and yield components detected in this study, of which 53.83% is contributed by PC1 and 14.34% is contributed by PC2. In this study, the total final yield was counted as a weight of leaves per plant. The total final leaf yield, leaf number per plant, leaf area, leaf length, and leaf width were the parameters which highly correlated and contributed to the highest total variations between the mutant varieties compared to plant height, node number per plant, and branch number per plant, respectively. These findings are contrary to the results reported in [25].

4. Conclusion

In this study, multiple comparison tests justified that the total leaf weight was significantly affected by the interaction between the mutant lines and applied levels of nitrogen. Leaf area and number of leaves per plant were the key parameters that contributed significantly to the high leaf production observed in *S. villosum*. 68% of the total variations of final weight of leaf production were contributed by leaf number and leaf area. Optimal production of the tested mutant lines was anticipated due to contribution of male sterility trait characteristics of the mutants with interaction of applied nitrogen. Further studies are recommended for understanding the stability of these agronomic traits under different seasons and various environments.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Faraja Makwinja: writing–original draft, validation, software, methodology, investigation, formal analysis, and data

curation. Joseph O. Charles: writing–review and editing, supervision, project administration, methodology, and conceptualization. Mkabwa L. K. Manoko: writing–review and editing, supervision, validation, and methodology.

Funding

The authors did not receive support from any organization for the submitted work.

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