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Growth dynamics of soybean (*Glycine max* L.) under integrated nutrient management

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ABSTRACT

Growth analysis was carried out in a field experiment conducted during kharif 2025 on a clayey Vertisol at the College of Agriculture, Latur, Maharashtra, to understand how integrated nutrient management (INM) modifies the growth processes of soybean cv. MAUS-158. Seven treatments comprising control, recommended dose of fertilizers (RDF, 30:60:30 kg N:P₂O₅:K₂O ha⁻¹) and RDF combined with farmyard manure (FYM, 5 t ha⁻¹), neem cake powder (NC, 3 q ha⁻¹) and multi-micronutrient Grade-I (MMN, 25 kg ha⁻¹) were evaluated in a randomized block design with three replications. Absolute growth rate (AGR) of dry matter increased to a peak during 46–60 DAS and was highest under RDF + FYM + NC + MMN (T7, 1.01 g day⁻¹ plant⁻¹) against 0.59 g day⁻¹ plant⁻¹ in the control. Relative growth rate (RGR) was maximum during 31–45 DAS (0.090–0.103 g g⁻¹ day⁻¹), higher under INM than in the control, and declined thereafter. Leaf area index (LAI) peaked at 60 DAS, reaching 4.31 in T7, at par with T5 (4.27) and T6 (4.18), compared with 1.90 in the control. Leaf area duration over 30–75 DAS was 151 days in T7 against 73 days in the control, whereas net assimilation rate (NAR) was similar or lower under INM from 45 DAS onwards. The higher biomass production under INM was therefore driven mainly by a larger and more persistent leaf canopy rather than by higher photosynthetic efficiency per unit leaf area.

Keywords: Soybean, Growth analysis, Absolute growth rate, Relative growth rate, Leaf area index, Leaf area duration, Net assimilation rate, Integrated nutrient management

Introduction

Final yield of a crop reflects both the size of its photosynthetic system and the efficiency with which that system produces dry matter over time. Classical growth analysis separates these components through indices such as absolute growth rate (AGR), relative growth rate (RGR), leaf area index (LAI), leaf area duration (LAD) and net assimilation rate (NAR) (Blackman, 1919; Watson, 1947; Radford, 1967) [1, 2, 3]. These indices help explain why a management practice increases yield, which is not evident from final growth measurements alone.

In soybean [*Glycine max* (L.) integrated nutrient management (INM) combining fertilizers with organic manures and micronutrients has been shown to improve growth and productivity (Singh *et al.*, 2013; Nwe *et al.*, 2022; Paramesh *et al.*, 2023) [5, 4, 6]. Organic sources such as farmyard manure improve the physical condition of Vertisols (Bandyopadhyay *et al.*, 2010) [7] and supply nutrients over a longer period, which may prolong the functional life of leaves. Whether INM increases soybean biomass by expanding the canopy, by raising its efficiency, or both, has rarely been examined. This study analysed the growth of soybean under different INM practices on a Vertisol of Marathwada using standard growth indices.

Materials and Methods

Experimental site, soil and weather

The field experiment was conducted during the kharif (rainy) season of 2025 at the Experimental Farm, Department of Agronomy, College of Agriculture, Latur, Maharashtra, India. Latur lies in the semi-arid tropical Marathwada region and receives a mean annual rainfall of about 795 mm. The soil of the experimental field was a medium-deep black Vertisol, clayey in texture (clay 44.21%, silt 29.53% and sand 25.68%), moderately alkaline (pH 7.4) and non-saline (EC 0.24 dS m⁻¹), with 0.58% organic carbon. It was low in available nitrogen (112.9 kg ha⁻¹; alkaline KMnO₄ method, Subbiah and Asija, 1956) [8], contained 7.46 kg ha⁻¹ Olsen-P (Olsen *et al.*, 1954) [9] and was high in available potassium (1145.6 kg ha⁻¹; neutral normal ammonium acetate, flame photometry; Jackson, 1967) [10]. Soybean–chickpea had been the preceding sequence on the field for the previous three years. A total of 1136.2 mm rainfall was received in 30 rainy days during the crop season (standard meteorological weeks 29–43), and the weather was generally favourable for crop growth.

Treatments and experimental design

The experiment was laid out in a randomized block design (RBD) with seven treatments replicated three times: T₁, control (no fertilizer); T₂, 100% recommended dose of fertilizers (RDF, 30:60:30 kg N:P₂O₅:K₂O ha⁻¹); T₃, RDF + farmyard manure (FYM) @ 5 t ha⁻¹; T₄, RDF + neem cake powder (NC) @ 3 q ha⁻¹; T₅, RDF + FYM @ 5 t ha⁻¹ + multi-micronutrient Grade-I (MMN) @ 25 kg ha⁻¹; T₆, RDF + NC @ 3 q ha⁻¹ + MMN @ 25 kg ha⁻¹; and T₇, RDF + FYM @ 5 t ha⁻¹ + NC @ 3 q ha⁻¹ + MMN @ 25 kg ha⁻¹. The gross and net plot sizes were 5.4 m × 4.5 m and 4.5 m × 3.9 m, respectively. Nitrogen, phosphorus and potassium were supplied through urea (46% N), single superphosphate (16% P₂O₅) and muriate of potash (60% K₂O), respectively, and were applied as basal dose at sowing along with the organic sources and the micronutrient mixture as per treatment.

Crop management

The land was ploughed to 20 cm depth with a tractor-drawn reversible mould-board plough and harrowed twice. Soybean cv. MAUS-158 was sown on 18 July 2025 by dibbling at 45 cm × 5 cm spacing using a seed rate of 65 kg ha⁻¹, after seed treatment with fungicide. Gap filling and thinning were done 10 days after sowing. One hand weeding and one hoeing were given. Insect pests and foliar diseases were managed with need-based sprays of thiamethoxam 12.6% + lambda-cyhalothrin 9.5% ZC, emamectin benzoate 5% SG, tebuconazole 10% + sulphur 65% WG and flubendiamide 20% WG. The crop was harvested at physiological maturity on 27 October 2025 (101 DAS), sun-dried and threshed manually.

Observations

Plant height, leaf area plant⁻¹ and dry matter plant⁻¹ were recorded at 30, 45, 60 and 75 DAS and dry matter also at harvest (101 DAS), as described in a companion paper. Leaf area (*L*) was estimated from leaf length × breadth × number of leaves × 0.786 and dry matter (*W*) by oven-drying above-ground parts at 65 ± 2 °C. Growth indices were computed from treatment means for each interval *t*₁–*t*₂ as follows (Radford, 1967) [3]: AGR = (*W*₂ – *W*₁)/(*t*₂ – *t*₁), g day⁻¹ plant⁻¹ (and

similarly for plant height, cm day⁻¹ plant⁻¹); RGR = (ln *W*₂ – ln *W*₁)/(*t*₂ – *t*₁), g g⁻¹ day⁻¹ (Blackman, 1919) [1]; LAI = leaf area plant⁻¹/ground area plant⁻¹ (45 cm × 5 cm = 2.25 dm²) (Watson, 1958) [11]; LAD = [(LAI₁ + LAI₂)/2] × (*t*₂ – *t*₁), days; and NAR = [(*W*₂ – *W*₁)/(*t*₂ – *t*₁)] × [(ln *L*₂ – ln *L*₁)/(*L*₂ – *L*₁)], g dm⁻² day⁻¹ (Watson, 1947) [2]. LAI, being a constant multiple of leaf area, was subjected to analysis of variance through leaf area; the remaining indices were interpreted on mean values.

Statistical analysis

Data were analysed by the analysis of variance technique appropriate to RBD (Panse *et al.*, 1967) [12]. Treatment means were compared using critical difference (CD) at 5% probability wherever the *F*-test was significant.

Results and Discussion

Absolute growth rate

AGR for plant height was greater during 31–45 DAS (mean 1.41 cm day⁻¹ plant⁻¹) than during 0–30 DAS (0.63 cm day⁻¹ plant⁻¹), coinciding with the phase of rapid stem elongation before flowering (Table 1). During 0–30 DAS, height AGR increased progressively from the control (0.52) to T₇ (0.76 cm day⁻¹ plant⁻¹); during 31–45 DAS it was highest in T₇ (1.50) and T₅ (1.49), although differences among the remaining treatments were small.

AGR of dry matter increased from the early vegetative phase to a maximum during 46–60 DAS (mean 0.83 g day⁻¹ plant⁻¹), corresponding to flowering and early pod development, and then declined, falling sharply after 75 DAS as leaves senesced and the crop approached maturity (Table 1). T₇ recorded the highest AGR in every interval (0.12, 0.91, 1.01, 0.79 and 0.30 g day⁻¹ plant⁻¹), followed by T₅ and T₆, while the control recorded the lowest (0.08, 0.47, 0.59, 0.69 and 0.18 g day⁻¹ plant⁻¹). The advantage of INM was greatest during 31–60 DAS, when AGR under T₇ was 73–94% higher than in the control; differences narrowed during 61–75 DAS. Higher AGR under combined nutrient sources reflects the greater leaf area available for photosynthesis and a sustained nutrient supply during the period of peak demand (Singh *et al.*, 2013; Biswas *et al.*, 2024) [5, 13].

Table 1. Absolute growth rate of plant height (cm day⁻¹ plant⁻¹) and dry matter (g day⁻¹ plant⁻¹) of soybean during different growth intervals as influenced by integrated nutrient management

Treatment	Height 0–30	Height 31–45	DM 0–30	DM 31–45	DM 46–60	DM 61–75	DM 76–H
T ₁ : Control	0.52	1.37	0.08	0.47	0.59	0.69	0.18
T ₂ : RDF	0.54	1.44	0.09	0.60	0.73	0.65	0.21
T ₃ : RDF + FYM	0.59	1.35	0.10	0.65	0.77	0.69	0.23
T ₄ : RDF + NC	0.65	1.31	0.10	0.70	0.82	0.70	0.25
T ₅ : RDF + FYM + MMN	0.68	1.49	0.11	0.83	0.95	0.72	0.29
T ₆ : RDF + NC + MMN	0.67	1.39	0.11	0.79	0.93	0.70	0.29
T ₇ : RDF + FYM + NC + MMN	0.76	1.50	0.12	0.91	1.01	0.79	0.30
Mean	0.63	1.41	0.10	0.71	0.83	0.71	0.25

Intervals in days after sowing; H, harvest (101 DAS); DM, dry matter. RDF, recommended dose of fertilizers (30:60:30 kg N:P₂O₅:K₂O ha⁻¹); FYM, farmyard manure @ 5 t ha⁻¹; NC, neem cake powder @ 3 q ha⁻¹; MMN, multi-micronutrient Grade-I @ 25 kg ha⁻¹; DAS, days after sowing; NS, non-significant.

Relative growth rate

RGR was highest during 31–45 DAS (mean 0.099 g g⁻¹ day⁻¹) and declined steadily to 0.043, 0.023 and 0.006 g g⁻¹ day⁻¹ in the subsequent intervals (Table 2). This decline is characteristic of annual crops, as an increasing proportion of the biomass consists of structural

and non-photosynthetic tissue and mutual shading increases (Blackman, 1919; Radford, 1967) [1, 3]. During 31–45 DAS, RGR increased from 0.090 in the control to 0.102–0.103 g g⁻¹ day⁻¹ under T₅, T₆ and T₇, indicating faster early growth under INM. In later intervals, RGR differed little among treatments, and the control showed slightly higher RGR during 61–75 DAS because RGR is expressed per unit of existing biomass, which was smallest in that treatment. Thus the treatment differences in final biomass were built mainly in the early vegetative phase, when INM combined a higher RGR with a larger initial biomass.

Table 2. Relative growth rate ($\text{g g}^{-1} \text{ day}^{-1}$) of dry matter in soybean during different growth intervals as influenced by integrated nutrient management

Treatment	31–45 DAS	46–60 DAS	61–75 DAS	76 DAS–Harvest
T ₁ : Control	0.0900	0.0439	0.0301	0.0060
T ₂ : RDF	0.0965	0.0437	0.0236	0.0060
T ₃ : RDF + FYM	0.0977	0.0431	0.0237	0.0060
T ₄ : RDF + NC	0.0989	0.0428	0.0227	0.0064
T ₅ : RDF + FYM + MMN	0.1024	0.0427	0.0205	0.0064
T ₆ : RDF + NC + MMN	0.1025	0.0436	0.0206	0.0067
T ₇ : RDF + FYM + NC + MMN	0.1030	0.0421	0.0208	0.0063
Mean	0.0987	0.0431	0.0231	0.0063

RDF, recommended dose of fertilizers (30:60:30 kg N:P₂O₅:K₂O ha⁻¹); FYM, farmyard manure @ 5 t ha⁻¹; NC, neem cake powder @ 3 q ha⁻¹; MMN, multi-micronutrient Grade-I @ 25 kg ha⁻¹; DAS, days after sowing; NS, non-significant.

Leaf area index

LAI increased from 30 to 60 DAS and declined at 75 DAS owing to senescence and shedding of lower leaves (Table 3). Treatment differences were significant at all stages. T₇ recorded the highest LAI at every stage (1.72, 3.63, 4.31 and 2.56), at par with T₅ and T₆ and signif-

icantly superior to the other treatments. At 60 DAS, the LAI of T₇ was 2.3 times that of the control (1.90) and twice that of RDF (2.16). Adding FYM or neem cake to RDF raised LAI at 60 DAS by 61–67%, and the further inclusion of MMN raised it by another 16–23%. An LAI of about 4 around flowering and pod set is generally close to that required for near-complete interception of radiation by a soybean canopy, a level reached only by the MMN-containing INM treatments. Similar increases in LAI under INM were reported by Nwe *et al.* (2022) [4].

Table 3. Leaf area index of soybean at different growth stages as influenced by integrated nutrient management

Treatment	30 DAS	45 DAS	60 DAS	75 DAS
T ₁ : Control	1.08	1.68	1.90	1.45
T ₂ : RDF	1.17	1.82	2.16	1.52
T ₃ : RDF + FYM	1.34	3.17	3.48	2.08
T ₄ : RDF + NC	1.40	3.18	3.61	2.08
T ₅ : RDF + FYM + MMN	1.71	3.53	4.27	2.53
T ₆ : RDF + NC + MMN	1.64	3.50	4.18	2.49
T ₇ : RDF + FYM + NC + MMN	1.72	3.63	4.31	2.56
SE(m) ±	0.09	0.14	0.17	0.12
CD (<i>P</i> = 0.05)	0.28	0.43	0.50	0.37
Mean	1.44	2.93	3.42	2.10

SE and CD derived from the analysis of leaf area plant⁻¹. RDF, recommended dose of fertilizers (30:60:30 kg N:P₂O₅:K₂O ha⁻¹); FYM, farmyard manure @ 5 t ha⁻¹; NC, neem cake powder @ 3 q ha⁻¹; MMN, multi-micronutrient Grade-I @ 25 kg ha⁻¹; DAS, days after sowing; NS, non-significant.

Leaf area duration and net assimilation rate

LAD, which integrates both the size and persistence of the canopy, was highest during 46–60 DAS (Table 4). Over 30–75 DAS, total LAD ranged from 72.6 days in the control and 79.9 days with RDF to 148.8–151.3 days under T₅ and T₇, i.e. INM approximately doubled the canopy available for photosynthesis over the season. The addition of FYM or neem cake to RDF alone increased total LAD by 57–60%, and inclusion of MMN added a further 14–19%.

NAR, the rate of dry matter production per unit leaf area, was highest during 30–45 DAS (mean 0.152 g dm⁻² day⁻¹) and lower in later intervals (Table 4). From 45 DAS onwards, NAR was higher in the control and RDF treatments (0.146–0.185 g dm⁻² day⁻¹) than under the INM treatments (0.096–0.114 g dm⁻² day⁻¹). This inverse relationship is expected, because the smaller canopies of the control and RDF plots suffer less mutual shading, so each unit of leaf receives more light (Watson, 1958) [11]. Taken together, the results show that INM increased dry matter production primarily by enlarging and prolonging the leaf canopy (higher LAI and LAD) rather than by raising photosynthetic efficiency per unit leaf area. Practices that promote rapid early canopy development and delay leaf senescence should therefore be emphasized in soybean nutrient management on these soils.

Table 4. Leaf area duration (LAD, days) and net assimilation rate (NAR, g dm⁻² day⁻¹) of soybean during different growth intervals as influenced by integrated nutrient management

Treatment	LAD 30–45	LAD 46–60	LAD 61–75	LAD total	NAR 30–45	NAR 46–60	NAR 61–75
T ₁ : Control	20.7	26.8	25.1	72.6	0.153	0.146	0.185
T ₂ : RDF	22.4	29.9	27.6	79.9	0.182	0.163	0.157
T ₃ : RDF + FYM	33.8	49.9	41.7	125.5	0.136	0.103	0.112
T ₄ : RDF + NC	34.3	50.9	42.7	127.9	0.143	0.107	0.112
T ₅ : RDF + FYM + MMN	39.3	58.5	51.0	148.8	0.147	0.109	0.097

(continued on next page)

Treatment	LAD 30–45	LAD 46–60	LAD 61–75	LAD total	NAR 30–45	NAR 46–60	NAR 61–75
T ₆ : RDF + NC + MMN	38.6	57.6	50.0	146.3	0.143	0.108	0.096
T ₇ : RDF + FYM + NC + MMN	40.2	59.6	51.6	151.3	0.157	0.114	0.105
Mean	32.8	47.6	41.4	121.8	0.152	0.121	0.123

Intervals in days after sowing; values computed from treatment means. RDF, recommended dose of fertilizers (30:60:30 kg N:P₂O₅:K₂O ha⁻¹); FYM, farmyard manure @ 5 t ha⁻¹; NC, neem cake powder @ 3 q ha⁻¹; MMN, multi-micronutrient Grade-I @ 25 kg ha⁻¹; DAS, days after sowing; NS, non-significant.

Conclusion

Integrated application of RDF with FYM, neem cake and multi-micronutrient Grade-I increased the absolute growth rate of soybean, especially during 31–60 DAS, raised the relative growth rate in the early vegetative phase, and doubled the leaf area duration compared with the control and RDF alone, with LAI reaching about 4.3 at 60 DAS. Net assimilation rate did not increase under INM, showing that the higher biomass resulted from a larger and longer-lasting canopy. RDF + FYM + NC + MMN and RDF + FYM + MMN were the most effective treatments. These single-season results need confirmation over additional seasons.

Conflict of interest

The authors declare no conflict of interest.

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