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GROWTH DYNAMICS AND SEED YIELD OF SOYBEAN (*Glycine max* L. Merrill) VARIETIES AS INFLUENCED BY RHIZOBIUM INOCULATION AND SOWING DATE IN THE GUINEA SAVANNA OF NIGERIA

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ABSTRACT

A field experiment was conducted during the 2018 rainy season to evaluate the effects of rhizobium inoculation, sowing date and genotype on growth and seed yield of soybean varieties at the International Institute of Tropical Agriculture (IITA) Research Farm Kubwa, Abuja, and the research farm of the Institute for Agricultural Research (IAR) Samaru, Zaria both of Guinea Savannah Zone of Nigeria. Four soybean varieties (TGx 1904-6F, TGx 1951-3F, TGx 1955-4F and Sambaiba) were evaluated under two sowing dates (late June and early July) and two inoculation levels (inoculated and un-inoculated) in a randomized complete block design with three replications. Crop growth rate (CGR), relative growth rate (RGR), absolute growth rate (AGR), leaf area index (LAI), leaf area duration (LAD), intercepted photosynthetically active radiation (IPAR) and grain yield were determined. Rhizobium inoculation significantly improved CGR at Samaru during early vegetative growth and increased grain yield by approximately 20% at Kubwa (2,145.51 vs 1,789.93 kg ha^{-1}) and 10% at Samaru (2063.68 kg ha^{-1} vs 1869.18 kg ha^{-1}) relative to uninoculated plants. the effects of sowing date on growth indices were variable and stage-dependent: late-June sowing produced higher LAI and LAD during the early vegetative growth at Kubwa, while early-July sowing produced significantly higher AGR at both locations and higher LAI at 12 WAS. Late-June sowing resulted in significantly higher grain yield at Samaru (2035.74 kg ha^{-1}, 1897.11 kg ha^{-1}), though sowing date did not significantly affect grain yield at Kubwa. Significant varietal differences were observed for all measured parameters, with Sambaiba producing the highest grain yield at Samaru (2240.34 kg ha^{-1}), while TGx 1951-3F recorded the highest yield at Kubwa (2172.18 kg ha^{-1}). The results indicate that rhizobium inoculation and timely sowing enhance soybean growth indices, canopy development and grain yield in the Guinea Savanna of Nigeria.

Keywords: Soybean; crop growth rate; leaf area index; radiation interception; rhizobium inoculation; sowing date; grain yield.

INTRODUCTION

Crop growth analysis provides a quantitative approach for evaluating plant growth and productivity by integrating physiological processes with biomass accumulation throughout the growing season (Hunt *et. al.,* 2002). Growth indices such as CGR, RGR, AGR, LAI, LAD, and IPAR are valuable indicators of canopy development, radiation capture, dry matter production, and ultimately seed yield (Hunt, 1990; Gardner *et al*., 1985; Ferreira *et al*., 2024.Improvements in these physiological attributes enhance light interception and photosynthetic efficiency, leading to greater biomass accumulation and higher grain yield.

Soybean (*Glycine max* L. Merrill), is one of the world's most important grain legumes because of its high protein (approximately 40%) and oil (about 20%) contents, making it an essential source of food, feed, and industrial raw materials (Adu-Dapaah *et al*., 2004; MoFA and CSIR, 2005). Beyond its nutritional and economic importance, soybean contributes to sustainable cropping systems through biological nitrogen fixation, thereby reducing dependence on mineral nitrogen fertilizers and improving soil fertility (Soumare *et al*., 2020). In Nigeria, soybean production is concentrated mainly in the Guinea Savanna, where environmental conditions are favourable for crop growth. However, average farmers' yields remain considerably lower than the attainable yields reported under research conditions owing to suboptimal crop management practices, including inappropriate sowing dates and inadequate use of rhizobial inoculants (Ronner *et al*., 2016).

Accordingly, rhizobium inoculation has been widely encouraged (Hungria *et al*., 2013; Ronner *et al*., 2016; Chibeba *et al*., 2018; Ishaq *et al*., 2025) as an effective and economical strategy for improving soybean productivity through enhanced biological nitrogen fixation and plant growth across sub-Saharan Africa, including Nigeria. Effective inoculation improves plant nitrogen nutrition, promotes leaf development and photosynthetic activity, and increases dry matter accumulation, thereby enhancing grain yield, particularly in soils deficient in effective rhizobial populations (Hungria *et al*., 2015; Ronner *et al*., 2016). The magnitude of these responses, however, varies with genotype and prevailing environmental conditions and among the environmental factors influencing soybean growth, sowing date is particularly important because it determines the climatic conditions under which vegetative and reproductive growth occur. Appropriate sowing synchronizes canopy development with favourable temperature and solar radiation, thereby increasing LAI, prolonging LAD, improving radiation interception, and enhancing biomass production and seed yield. Conversely, delayed sowing shortens the vegetative growth period, reduces radiation capture, limits dry matter accumulation, and ultimately decreases grain yield (Egli & Bruening, 2000; Board & Kahlon, 2011; Borowska and Prusinski, 2021).

Although several studies have independently reported the benefits of rhizobium inoculation(Adeshina *et al*., 2024; Kabiru *et al*, 2024) or sowing date (Hu &Wiatrak, 2012; Aba *et al*., 2022; Eseigbe *et al*, 2024) on soybean productivity, an examination of the combined and interactive effects of inoculation, sowing date and genotype on the full suite of growth analysis indices including CGR, RGR, AGR, LAI, LAD and IPAR, and their translation into seed yield under the contrasting edaphic and climatic conditions of the Northern and Southern Guinea Savanna ecologies of Nigeria is needed to provide an understanding of the growth dynamics and canopy attributes that drive biomass accumulation and yield formation. Such information is critical for identifying location-specific management practices that optimize canopy radiation capture, dry matter production and grain yield in smallholder soybean systems across the Guinea Savanna. More so, the differential adaptation of improved Nigerian soybean varieties and exotic genotypes to these two ecologies under varying inoculation and sowing date regimes has not been adequately characterized. Therefore, this study evaluated the effects of rhizobium inoculation and sowing date on the growth dynamics and seed yield of four soybean varieties grown across the Northern and Southern Guinea Savanna of Nigeria.

MATERIALS AND METHODS

Field trials were conducted during the 2018 Rainy Season at the International Institute of Tropical Agriculture (IITA) Research Farm Kubwa, Abuja (Southern Guinea Savanna), and the research farm of Institute for Agricultural Research (IAR) Samaru, Zaria (Northern Guinea Savanna), Nigeria. Soil samples were randomly collected from nine (9) locations on the field within each of the experimental site at 0-30cm depth using hand-held soil auger and composite soil sample was taken after bulking. The composite sample was air dried, sieved through 2mm sieve and subjected to laboratory analysis according to Walkley-Black procedures at the Department of Agronomy, Ahmadu Bello University Zaria and analytical laboratory of International Institute of Tropical Agriculture, Ibadan.

The treatments consisted of four varieties of soybean (TGx 1904-6F, TGx 1951-3F, TGx 1955-4F and Sambaiba), two sowing dates (late June and early July) and two levels of inoculation (inoculation and without inoculation). The treatments were laid out in a Randomized Complete Block Design (RCBD) and replicated three times. Sites were harrowed to fine tilth and ridged. Plots were prepared in ridges with gross plot size of 5.0 x 3.0 m (15 m^2) and a 5 x 1.5m (7.5 m^2) net plot. The inter row and intra row spacing was at 75 x 10cm respectively. Ten kg of the soybean seed was measured and placed in a container. Gum Arabic was dissolved in 100mls of warm water. The gum Arabic solution was allowed to settle down before use. The seeds were moistened with the gum Arabic solution and mixed thoroughly. 100g of the inoculant was sprinkled on the moistened seeds and also mixed thoroughly, ensuring that all the seeds were effectively covered with the inoculant. The moistened inoculated seeds were spread on a dry clean tarpaulin and kept away from direct sunlight for 7 minutes before sowing. Six seeds were sown per hole and later thinned to two plants per stand at 14 days after sowing. Sowing was done on the 23rd of June 2018 and 30th of June 2018 for the Samaru location; and 27th of June 2018 and 4th of July 2018 for the Kubwa.For weed control, the plots were treated with Pendimenthalin as pre-emergence herbicide at the rate of 1.6 kg a.i/ha and complimented with hoe weeding at 4WAS. Fertilizer at the recommended rate of 40 kg P_2O_5 and 40 kg K_2O per hectare was broadcast and incorporated into the soil.

Five (5) plants tagged within each net plot were ear-marked for the periodic (6, 9 and 12 WAS) evaluation of crop's growth, these were used to monitor the studied growth parameters on per plants basis. Crop growth rate (CGR), Relative growth rate (RGR), Leaf area index (LAI), Absolute growth rate (AGR), leaf area duration (LAD) and photosynthetic active radiation (PAR) were the physio-agronomic dynamics studied. CGR was estimated as described by Radford, (1967); thus;

$$CGR = \frac{W_2 - W_1}{T_2 - T_1} (\text{gm}^{-2}\ \text{wk}^{-1})$$

Where W_2 and W_1 are dry weight in plant at time T_2 and T_1 in weeks, respectively. The RGR is expressed in g $g^{-1}wk^{-1}$ and was estimated as suggested by Radford (1967);

$$RGR = \frac{\ln W_2 - \ln W_1}{t_2 - t_1} \; g\,g^{-1}wk^{-1}$$

Where ln = Natural log Where W_2 and W_1 are dry weight in plant at time T_2 and T_1 in weeks, respectively. Leaf area index (LAI) and intercepted photosynthetically active radiation (IPAR) were measured simultaneously in each plot using an AccuPAR ceptometer (Model LP-80) following the procedure described by Fehr and Caviness (1977). The sensor was placed diagonally across the two inner rows at the soil surface below the soybean canopy, with the two ends of the sensor aligned with the crop rows. Five measurements were taken per plot and the displayed average recorded. All measurements were made under cloud-free conditions between 1200 and 1400 h. The percentage of PAR intercepted by the soybean canopy was calculated as:

IPAR = [1.0 – (PARb/PARa)] × 100

Where: IPAR = intercepted PAR, PARa = PAR, μmol $m^2 s^{-1}$, measured above soybean canopy, PARb = PAR measured below soybean canopy.

AGR is the function of amount of growing material present and is influenced by the environment. It gives Absolute values of biomass between two intervals and it was computed as;

$AGR = \frac{h_2 - h_1}{T_2 - T_1}(cmwk^{-1})$ Where, h_1 and h_2 are the plant height at t_1 and t_2 times respectively.

The LAD was estimated as described by Power et al. (1967);

LAD = [(L1 + L2) X (t2 – t1)]/2

Where L1 LAI at first stage, L2 = LAI at second stage and t2-t1 = time interval in days.

Harvested pods were threshed and winnowed to obtain clean grain, thereafter weight of the seeds was recorded using Mettler balance (Toledo 16001) on the basis of seed yield per net plot and seed yield per hectare was extrapolated and expressed in kilograms per hectare.

The data collected were subjected to statistical analysis of variance (ANOVA) using SAS software (Version 9.2) to test treatment effects for significance. The differences between treatments means were compared using Duncan Multiple Range Test (DMRT).

RESULTS

Soil and chemical properties of the experimental sites at 0-30 cm depth are shown in Table 1. The analysis showed that soil at Kubwa site had a sandy loam texture, acidic and moderate in available phosphorus content (15.7 mg kg^{-1}) while the soil in Samaru is loamy, moderately acidic and also moderate in available phosphorus content (19.2 mg kg^{-1}). The percentage of organic carbon was low in Kubwa whereas it was high at samaru and total nitrogen at both sites was low. The exchangeable bases Ca, Mg, and K were low except for Na which was slightly high at both locations while the cation exchange capacity was also low at both sites.

Crop Growth Rate (CGR) and Relative Growth Rate (RGR)

The influence of inoculation, sowing date and soybean varieties on crop growth rate (CGR) during the 2018 rainy season is presented in Figure 1. Inoculation significantly affected CGR at 6–9 WAS at Samaru, where inoculated plants recorded a higher mean CGR (2.20 g m^{-2} wk^{-1}) compared to uninoculated plants (1.84 g m^{-2} wk^{-1}). Inoculation had no significant effect on CGR at Kubwa at either sampling period, or at Samaru at 9–12 WAS. Sowing date did not significantly affect CGR at either location during 6–9 WAS. However, at 9–12 WAS at Samaru, early-July sown plants recorded substantially higher CGR (11.80 g m^{-2} wk^{-1}) than late-June sown plants (4.92 g m^{-2} wk^{-1}), while no significant sowing date effect was observed at Kubwa at this stage.

Varieties did not differ significantly in CGR at 6–9 WAS at both locations. At 9–12 WAS, TGx 1904-6F recorded the highest CGR at Kubwa (9.55 g m^{-2} wk^{-1}), which was significantly superior to Sambaiba (5.09 g m^{-2} wk^{-1}), while at Samaru, Sambaiba recorded the highest CGR (11.58 g m^{-2} wk^{-1}), significantly exceeding TGx 1904-6F (6.41 g m^{-2} wk^{-1}) and TGx 1955-4F (7.03 g m^{-2} wk^{-1}). A significant variety × inoculation interaction for CGR was observed at 6–9 WAS at Samaru (Figure 2), where the highest CGR was recorded by uninoculated TGx 1951-3F (2.43 g m^{-2} wk^{-1}) and uninoculated Sambaiba (2.23 g m^{-2} wk^{-1}), though these were statistically similar to inoculated Sambaiba (2.18 g m^{-2} wk^{-1}).

A similar trend was observed for relative growth rate (RGR) (Figure 1). Inoculation and sowing date had no significant effect on RGR at all sampling periods and locations, except at 9–12 WAS at Samaru where early-July sown plants recorded significantly higher RGR (0.41 g g^{-1} wk^{-1}) than late-June sown plants (0.22 g g^{-1} wk^{-1}). At 9–12 WAS at Kubwa, TGx 1904-6F recorded the highest RGR (0.50 g g^{-1} wk^{-1}), significantly exceeding Sambaiba (0.28 g g^{-1} wk^{-1}). No significant interaction was observed for RGR.

Absolute Growth Rate (AGR) and Leaf Area Duration (LAD)

The effects of inoculation, sowing date and soybean varieties on absolute growth rate (AGR) are presented in Figure 3. Inoculation had no significant effect on AGR at both locations throughout the sampling periods. Sowing date did not significantly influence AGR at Kubwa, whereas at Samaru, early-July sown plants consistently produced significantly higher AGR at both 6–9 WAS (5.75 cm wk^{-1}) and 9–12 WAS (3.49 cm wk^{-1}) compared to late-June sown plants. Among varieties, TGx 1955-4F recorded the highest AGR at Kubwa at 6–9 WAS (7.02 cm wk^{-1}), significantly exceeding all other varieties (range: 4.36–4.80 cm wk^{-1}). At 9–12 WAS, Sambaiba recorded the highest AGR at Kubwa (5.98 cm wk^{-1}), while TGx 1951-3F recorded the highest AGR at Samaru (3.63 cm wk^{-1}), significantly exceeding TGx 1955-4F (2.50 cm wk^{-1}). No significant treatment interaction was observed for AGR.

Leaf area duration (LAD) was not significantly affected by inoculation across both locations and sampling periods (Figure 3). Sowing date significantly influenced LAD at 6–9 WAS at Kubwa, where late-June sowing produced significantly higher LAD (121.38) than early-July sowing (94.08), and at 9–12 WAS at Samaru, where early-July sowing recorded significantly higher LAD (231.42) than late-June sowing (208.74). Among varieties, TGx 1904-6F, TGx 1951-3F and TGx 1955-4F consistently produced significantly higher LAD than Sambaiba at all sampling periods and locations. At 6–9 WAS at Kubwa, Sambaiba recorded the lowest LAD (52.71) compared to values ranging from 117.81 to 132.09 for the TGx varieties. A similar pattern was observed at Samaru, where Sambaiba recorded LAD was 149.73 at 6–9 WAS against a range of 230.16 to 236.67 for the TGx varieties.

Leaf Area Index (LAI) and Intercepted Photosynthetically Active Radiation (IPAR)

The effects of inoculation, sowing date and soybean varieties on LAI and IPAR are presented in Figure 4. Inoculation did not significantly influence LAI and IPAR at all sampling period at both locations. Sowing date significantly affected LAI at Kubwa at 6 WAS and 9 WAS, where late-June sown plants recorded higher LAI (2.32 and 3.46, respectively) than early-July sown plants (1.63 and 2.85, respectively). At 12 WAS, early-July sown plants recorded significantly higher LAI at both locations (Kubwa: 2.67; Samaru: 5.90). Sowing date did not significantly affect IPAR at Samaru throughout the season. At Kubwa, late-June sowing produced significantly higher IPAR at 9 WAS (88.98%), representing a 20% advantage, while early-July sowing recorded significantly higher IPAR at 12 WAS (87.28%).

Sambaiba consistently and significantly recorded the lowest LAI at 6 and 9 WAS at both locations. At 12 WAS, however, Sambaiba's recorded a significantly higher LAI at Kubwa (2.57) than that of TGx 1955-4F (2.16), indicating a shift in canopy dynamics at the later reproductive stage. A corresponding varietal response was observed for IPAR: Sambaiba recorded significantly lower IPAR than the TGx varieties at 6 and 9 WAS at both locations, but by 12 WAS its IPAR was comparable to or exceeded that of TGx 1904-6F and TGx 1951-3F at Kubwa (89.85 and 84.90% respectively). A significant variety × sowing date interaction for LAI was observed at 6 WAS at Samaru (Figure 5), where TGx 1904-6F under late-June sowing recorded the highest LAI (6.18) while Sambaiba under the same sowing date recorded only 1.98, the lowest across all variety-sowing date combinations.

Grain Yield

The effects of inoculation, sowing date and variety on grain yield (kg ha^{-1}) are presented in Figure 6. At both locations, inoculated soybean produced significantly higher grain yield than uninoculated plants. At Kubwa, inoculation increased grain yield from 1,789.93 to 2,145.51 kg ha^{-1}, representing a yield advantage of approximately 20%. At Samaru, inoculated plants yielded 2,063.68 kg ha^{-1} compared to 1,869.18 kg ha^{-1} for un-inoculated plants, an improvement of approximately 10%. Sowing date significantly affected grain yield only at Samaru, where late-June sowing produced 2,035.74 kg ha^{-1} compared to 1,897.11 kg ha^{-1} for early-July sowing, a difference of approximately 7%. Sowing date did not significantly affect grain yield at Kubwa.

Significant varietal differences in grain yield were observed at both locations, with contrasting patterns between sites. At Kubwa, the three TGx varieties produced statistically similar grain yields (TGx 1951-3F: 2,172.18; TGx 1955-4F: 2,085.08; TGx 1904-6F: 2,005.71 kg ha^{-1}), all of which were significantly higher than Sambaiba (1,607.90 kg ha^{-1}). The reverse was observed at Samaru, where Sambaiba produced the highest grain yield (2,240.34 kg ha^{-1}), exceeding TGx 1951-3F (2,034.24 kg ha^{-1}) by approximately 10% and surpassing TGx 1904-6F and TGx 1955-4F (1,787.73 and 1,803.39 kg ha^{-1}, respectively) by approximately 25%.

A significant variety × inoculation interaction for grain yield was observed at Samaru (Figure 7). Inoculated Sambaiba recorded the highest grain yield (2,385.63 kg ha^{-1}), exceeding its un-inoculated counterpart (2,095.05 kg ha^{-1}) by approximately 14%. Non-inoculated TGx 1955-4F recorded the lowest grain yield (1,626.93 kg ha^{-1}), which was statistically comparable to non-inoculated TGx 1904-6F (1,775.28 kg ha^{-1}). Inoculation improved grain yield most markedly in Sambaiba and TGx 1955-4F (21.6% yield gain with inoculation), suggesting differential varietal responses to rhizobia inoculation.

Correlation

Pearson correlation coefficients between growth indices and grain yield, computed from variety means (n = 4) at each location, are presented in Table 10. At Kubwa, LAD at 6–9 WAS was the strongest predictor of grain yield (r = 0.992, P ≤ 0.01), followed by IPAR at 9 WAS (r = 0.984, P ≤ 0.05), LAI at 6 WAS (r = 0.987, P ≤ 0.05), LAI at 9 WAS (r = 0.982, P ≤ 0.05) and IPAR at 6 WAS (r = 0.977, P ≤ 0.05), all of which were significantly and positively correlated with grain yield. AGR at 9–12 WAS was significantly and negatively correlated with grain yield at Kubwa (r = −0.974, P ≤ 0.05), while all other growth indices were not significantly correlated with grain yield at this location. Among the inter-variable relationships at Kubwa, LAI at 9 WAS and IPAR at 9 WAS were very strongly inter-correlated (r = 0.997, P ≤ 0.01), as were LAD at 6–9 WAS with both IPAR at 9 WAS (r = 0.999, P ≤ 0.01) and IPAR at 6 WAS (r = 0.995, P ≤ 0.01), indicating that canopy size, duration and radiation interception formed a tightly coupled physiological system at this location. At Samaru, CGR at 9–12 WAS was the only growth index significantly and positively correlated with grain yield (r = 0.978, P ≤ 0.05), while IPAR at 6 WAS was significantly and negatively correlated with grain yield (r = −0.971, P ≤ 0.05). LAI at 6 WAS was strongly correlated with LAD at 6–9 WAS (r = 0.992, P ≤ 0.01) and IPAR at 6 WAS (r = 0.990, P ≤ 0.01) at Samaru, confirming a consistent structural relationship between early canopy development and radiation capture across both locations.

DISCUSSION

The favourable rainfall distribution (500–850 mm) and relatively stable temperature ranges (21.1–32.6 °C at Kubwa and 18.8–32.3ºC at Samaru) recorded during the growing season provided suitable environmental conditions for soybean establishment and vegetative development. These conditions, together with the available soil phosphorus contents (15.7 and 19.2 mg kg^{-1}), likely promoted vigorous root growth, canopy expansion and biomass accumulation, resulting in improved crop growth and seed yield across the two locations and this further demonstrates the adaptability of soybean to the Guinea Savanna ecology of Nigeria where favourable edaphic and climatic conditions prevail, corroborating the findings of Krishna and Sachdev (2014).

Rhizobium inoculation significantly improved CGR at Samaru during early vegetative growth (6–9 WAS), with inoculated plants recording a CGR of 2.20 g m^{-2} wk^{-1} compared to 1.84 g m^{-2} wk^{-1} in un-inoculated plants, a 20% advantage. This response was probably due to improved biological nitrogen fixation, which enhanced nitrogen availability for chlorophyll synthesis, leaf expansion and photosynthetic activity, thereby increasing dry matter accumulation during the period of rapid vegetative growth. Nitrogen is a major constituent of chlorophyll and photosynthetic enzymes, and its adequate supply promotes canopy development and assimilate production directly reflected in higher growth rates (Hungria and Kaschuk, 2014; Hungria *et al*., 2015). Similar increases in dry matter accumulation following rhizobial inoculation have been reported by Solomon *et al*. (2012). The absence of significant inoculation effects on RGR, LAI, LAD and IPAR suggests that indigenous rhizobial populations at both locations were sufficiently competitive to establish effective symbiosis with soybean, thereby minimizing differences between inoculated and un-inoculated plants for these indices at vegetative growth stage. This agrees with Sanginga and Okogun (2003), who reported that inoculation effectiveness is often reduced in soils with abundant competitive native rhizobia.

The significant improvement in grain yield with inoculation, approximately 20% at Kubwa (2,145.51 vs 1,789.93 kg ha^{-1}) and 10% at Samaru (2,063.68 vs 1,869.18 kg ha^{-1}), confirms that inoculation benefits were most pronounced during reproductive development through improved nitrogen nutrition and enhanced assimilate partitioning to developing seeds, even where vegetative growth indices were not significantly affected. This is consistent with Hungria *et al*. (2015) and Ronner *et al*. (2016), who demonstrated that rhizobial inoculation enhances soybean productivity by improving nitrogen fixation efficiency and overall crop performance.

Sowing date effects on growth indices were variable across locations, growth stages and parameters, reflecting the complexity of the environment x genotype interaction. Late-June sowing produced higher LAI (2.32 vs 1.63 at 6 WAS; 3.46 vs 2.85 at 9 WAS) and LAD (121.38 vs 94.08 at 6–9 WAS) at Kubwa during early vegetative growth, as well as significantly greater IPAR at 9 WAS at Kubwa (88.98 vs 74.23 µmol m^{-2} s^{-1}). However, early-July sowing produced significantly higher AGR at both locations throughout the sampling periods, as well as higher LAI at 12 WAS and higher IPAR at 12 WAS at Kubwa, indicating that the later-sown crop maintained stronger active growth during the reproductive stage. Late-June sowing produced significantly higher grain yield at

Samaru (2,035.74 vs 1,897.11 kg ha⁻¹, a 7% advantage), while grain yield at Kubwa did not differ significantly between sowing dates. These findings indicate that while late-June sowing conferred an early canopy establishment advantage in the Northern Guinea Savanna, the yield advantage of early sowing was not consistent across ecologies. The overall patterns are consistent with Board and Kahlon (2011) and Egli and Bruening (2000), who established that the relationship between sowing date and soybean yield is mediated by the interaction between planting time, canopy development dynamics and the prevailing radiation and temperature environment during reproductive growth.

The significant variety × inoculation interaction for grain yield at Samaru further demonstrates genotypic differences in responsiveness to rhizobial inoculation. Inoculated Sambaiba recorded the highest grain yield (2,385.63 kg ha^{-1}), a 14% improvement over its un-inoculated counterpart (2,095.05 kg ha^{-1}), suggesting a strong dependence on applied inoculant for maximum productivity likely reflecting its limited ability to associate effectively with indigenous rhizobial strains as an exotic genotype. By contrast, TGx 1904-6F showed the least response to inoculation (1,800.18 vs 1,775.28 kg ha^{-1}, a marginal 1.4% difference), consistent with the promiscuous nodulation characteristic of Nigerian-bred TGx varieties that enables effective association with a broad range of indigenous *Bradyrhizobium* strains (Sanginga *et al*., 1996). Non-inoculated TGx 1955-4F recorded the lowest grain yield across all treatment combinations at Samaru (1,626.93 kg ha^{-1}), yet inoculation improved its yield by approximately 22% (1,979.85 kg ha^{-1}), indicating that despite promiscuous nodulation, this variety benefited substantially from supplementary inoculant application. These genotype dependent responses to inoculation are consistent with the observations of Giller *et al*. (2013) and Ronner *et al*. (2016).

The significant positive correlations between early season LAI, LAD, IPAR and grain yield at Kubwa confirm that canopy establishment during the vegetative to early reproductive transition was the primary determinant of yield formation at the Southern Guinea Savanna location. High-yielding soybean cultivars have been shown to maintain greater LAI for longer duration than low-yielding cultivars, and the impact of LAD on yield holds true across legume crops, with extensions in the functional canopy period increasing assimilate availability for seed filling and hence yield (Sun et al., 2025). The strong positive correlation between LAD at 6–9 WAS and grain yield ($r = 0.992$, $P \leq 0.01$) at Kubwa is consistent with this established relationship and confirms that varieties sustaining larger, longer-duration canopies during the pre-reproductive stage were able to intercept greater quantities of photosynthetically active radiation and accumulate more assimilate for subsequent seed filling. Peng *et al*. (2025) reported that the total accumulated PAR over the soybean growing season strongly influences yield formation, especially during the flowering (R2) and pod-filling stages (R5), corroborating the pattern observed at Kubwa where IPAR at 9 WAS, the onset of pod development was among the strongest yield predictors ($r = 0.984$, $P \leq 0.05$). The tight inter-correlations among LAI, LAD and IPAR at both sampling periods ($r = 0.993–0.999$, $P \leq 0.01$) confirm that these indices constitute a coherent canopy radiation capture system, consistent with the physiological principle that canopy light interception is structurally determined by LAI and temporally integrated by LAD (Gardner *et al*., 1985; Board and Kahlon, 2011). The significant negative correlation between AGR at 9–12 WAS and grain yield at Kubwa ($r = -0.974$, $P \leq 0.05$) corresponds to the R3–R6 reproductive stages, the most critical window for yield determination in soybean, during which developing seeds become the dominant sink for photosynthetically fixed carbon and accumulated aboveground dry matter explains approximately 70% of the variation in seed number (Monzon *et al*., 2021; Cerrudo & Naeve, 2025). Any competing vegetative sink operating during this window directly reduces assimilate availability for seed development and compromises final grain yield (Chiluwal *et al*., 2021) at this location, while the higher-yielding TGx varieties exhibited lower late-season AGR. The reduction in stem elongation has been associated with more efficient partitioning of assimilates and nutrients into grain development relative to vegetative growth (Beagley *et al*. (2024), further supporting the interpretation that Sambaiba's superior late-season height growth rate at Kubwa imposed a yield penalty through enhanced vegetative competition during seed filling.

The contrasting pattern at Samaru where CGR at 9–12 WAS was the only growth index significantly and positively correlated with grain yield ($r = 0.978$, $P \leq 0.05$), and where IPAR at 6 WAS was significantly negatively correlated with yield reflects a strong genotype × environment interaction rather than a true inverse physiological relationship between radiation capture and yield. This divergence between early canopy traits and final yield at Samaru highlights that the relationship between growth indices and yield is not fixed but is mediated by genotype adaptation to local edaphic and climatic conditions. Genotype × environment interactions have been shown to account for a substantial proportion of variation in soybean grain yield across locations (Abebe *et al*., 2024), with environmental effects and GEI collectively explaining the predominant portion of yield variation, underscoring the importance of location specific interpretation of growth index to yield relationships (Abebe *et al*., 2024)). The positive correlation between CGR at 9–12 WAS and grain yield at Samaru is consistent with the findings of Shiraiwa *et al*. (2004), who demonstrated that CGR during the initial seed-filling period was closely associated with high seed yield in soybean, and that the critical stage during which yield potential is determined is the initial seed-filling period.

CONCLUSION

Rhizobium inoculation, sowing date and genotype significantly influenced soybean growth dynamics and seed yield across the Guinea Savanna of Nigeria. Inoculation improved grain yield at both locations, affirming its value as a low-cost input for enhancing productivity. Late-June sowing optimized canopy development and radiation interception, translating into superior grain yield at Samaru, and is recommended as the preferred planting window. Marked genotype × environment interaction underscored the necessity of site-specific variety selection: Sambaiba is recommended for the Northern Guinea Savanna, while TGx 1951-3F is the preferred variety for the Southern Guinea Savanna. Location specific management integrating appropriate variety, optimum sowing date and rhizobium inoculation is essential for closing the yield gap in Nigerian soybean production. Multi-season validation of these findings is recommended before wider adoption.

Table 1: Physical and chemical properties of soil of the experimental sites at 0 – 30 cm depth for 2018 Rainy Season.

Location	KUBWA	SAMARU
Soil depth (cm)	0-30	0-30
Soil characteristics		
Textural class	Sandy loam	Loam
Chemical composition		
pH in H_2O (1:2.5)	4.9	5.6
Organic carbon (g kg^{-1})	2.2	13.6
Available phosphorus (mg kg^{-1})	15.7	19.2
Total nitrogen (g kg^{-1})	0.15	0.95
Exchangeable bases (c mol kg^{-1})		
Calcium	0.44	2.13
Magnesium	0.06	0.31
Potassium	0.01	0.13
Sodium	0.10	0.21
Exchangeable acidity	0.45	0.29
ECEC	1.07	3.07

Soil analyzed in the Analytical laboratory of agronomy, International Institute of Tropical Agriculture (IITA) Ibadan for Kubwa location and Analytical Laboratory of Agronomy Department, Ahmadu Bello University, Samaru Zaria for Samaru location (2018).

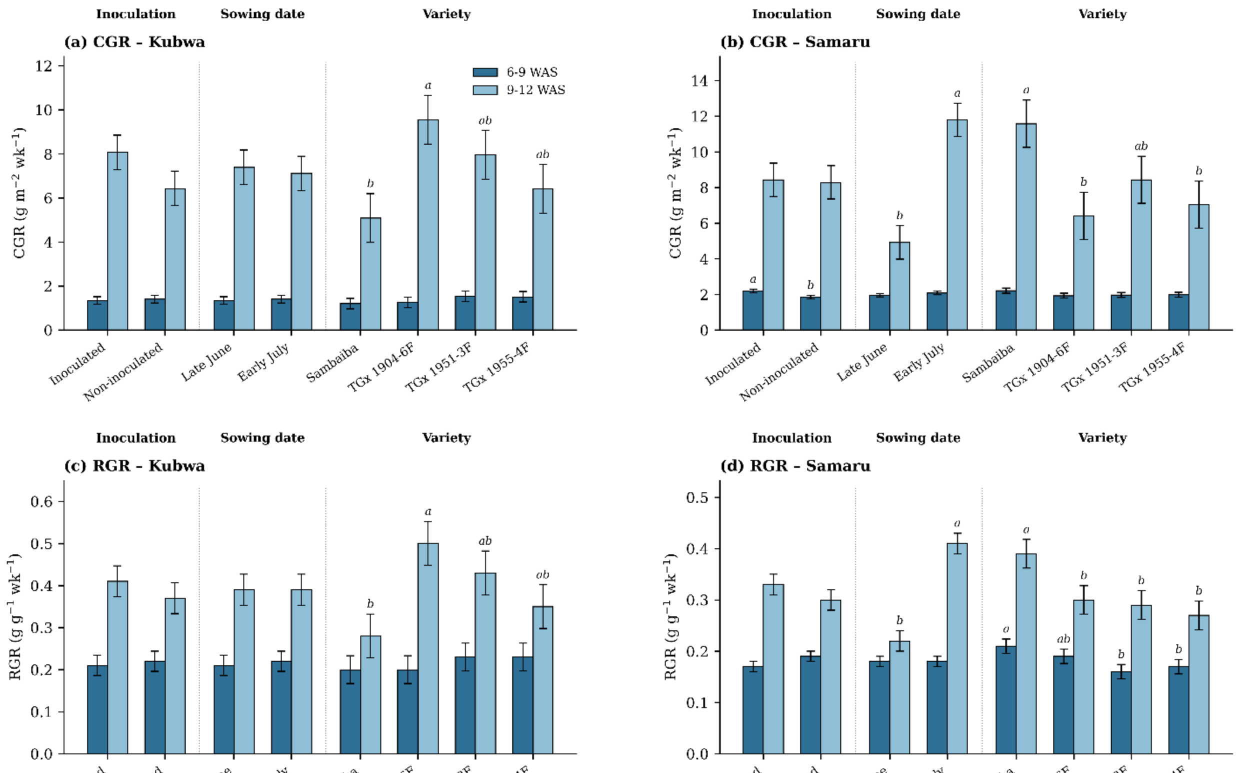

Figure 1: Crop Growth Rate (CGR, g m^{-2} wk^{-1}) and Relative Growth Rate (RGR, g g^{-1} wk^{-1}) of soybean varieties as influenced by Inoculation, Sowing date, and Variety at Kubwa and Samaru in the 2018 Rainy Season. Bars topped with the same letter within a treatment group are not significantly different at the 5% level of probability using DMRT (P≤0.05). Error bars represent the standard error of the mean (SE±), as follows — CGR at Kubwa: Inoculation/Sowing date SE± = 0.168 (6–9 WAS), 0.782 (9–12 WAS); Variety SE± = 0.238, 1.106. CGR at Samaru: Inoculation/Sowing date SE± = 0.099, 0.937; Variety SE± = 0.140, 1.325. RGR at Kubwa: Inoculation/Sowing date SE± = 0.024, 0.037; Variety SE± = 0.033, 0.052. RGR at Samaru: Inoculation/Sowing date SE± = 0.010, 0.020; Variety SE± = 0.014, 0.028. WAS = Week after sowing.

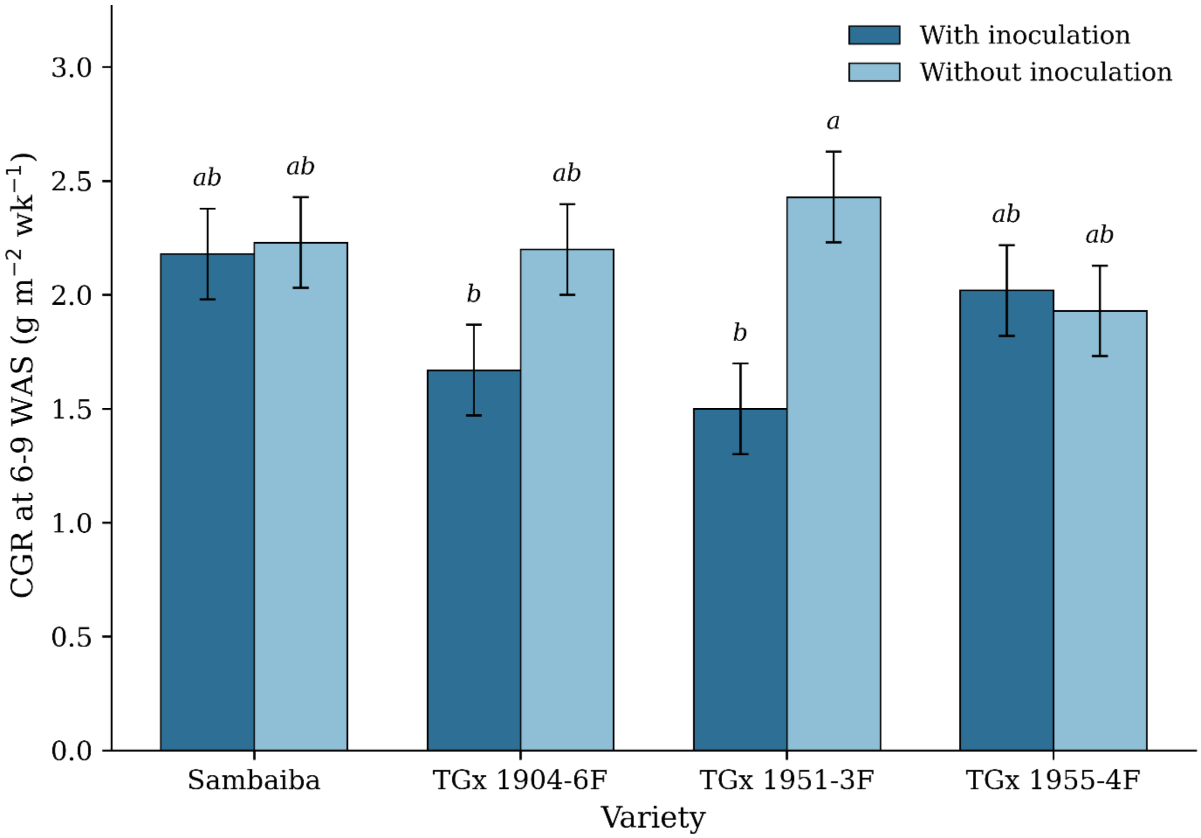

Figure 2: Interaction between Variety and Inoculation on Crop Growth Rate (CGR, g m^{-2} wk^{-1}) at 6–9 WAS in Samaru. Bars topped with the same letter are not significantly different at the 5% level of probability using DMRT ($P \leq 0.05$). Error bars represent the standard error of the mean (SE± = 0.199, pooled across all variety × inoculation means).

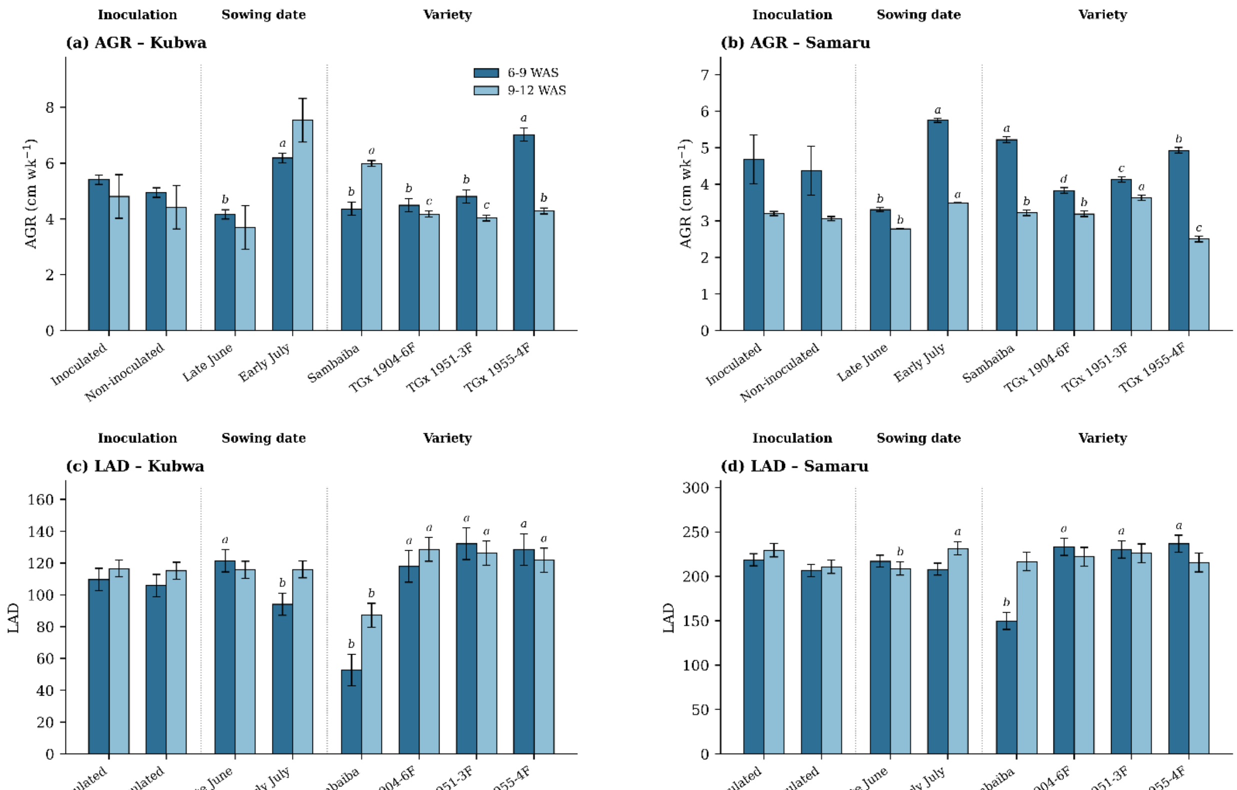

Figure 3: Absolute Growth Rate (AGR; cm wk⁻¹) and Leaf Area Duration (LAD) of soybean varieties as influenced by Inoculation, Sowing date, and Variety at Kubwa and Samaru in the 2018 Rainy Season. Bars topped with the same letter within a treatment group are not significantly different at the 5% level of probability using DMRT (P≤0.05). Error bars represent the standard error of the mean (SE±), as follows — AGR at Kubwa: Inoculation/Sowing date SE± = 0.168 (6–9 WAS), 0.782 (9–12 WAS); Variety SE± = 0.238, 0.106. AGR at Samaru: Inoculation SE± = 0.667, 0.0567; Sowing date SE± = 0.0537, 0.00567; Variety SE± = 0.0760, 0.0767. LAD at Kubwa: Inoculation/Sowing date SE± = 7.014, 5.334; Variety SE± = 9.933, 7.518. LAD at Samaru: Inoculation/Sowing date SE± = 6.762, 7.455; Variety SE± = 9.576, 10.542. WAS = Week after sowing.

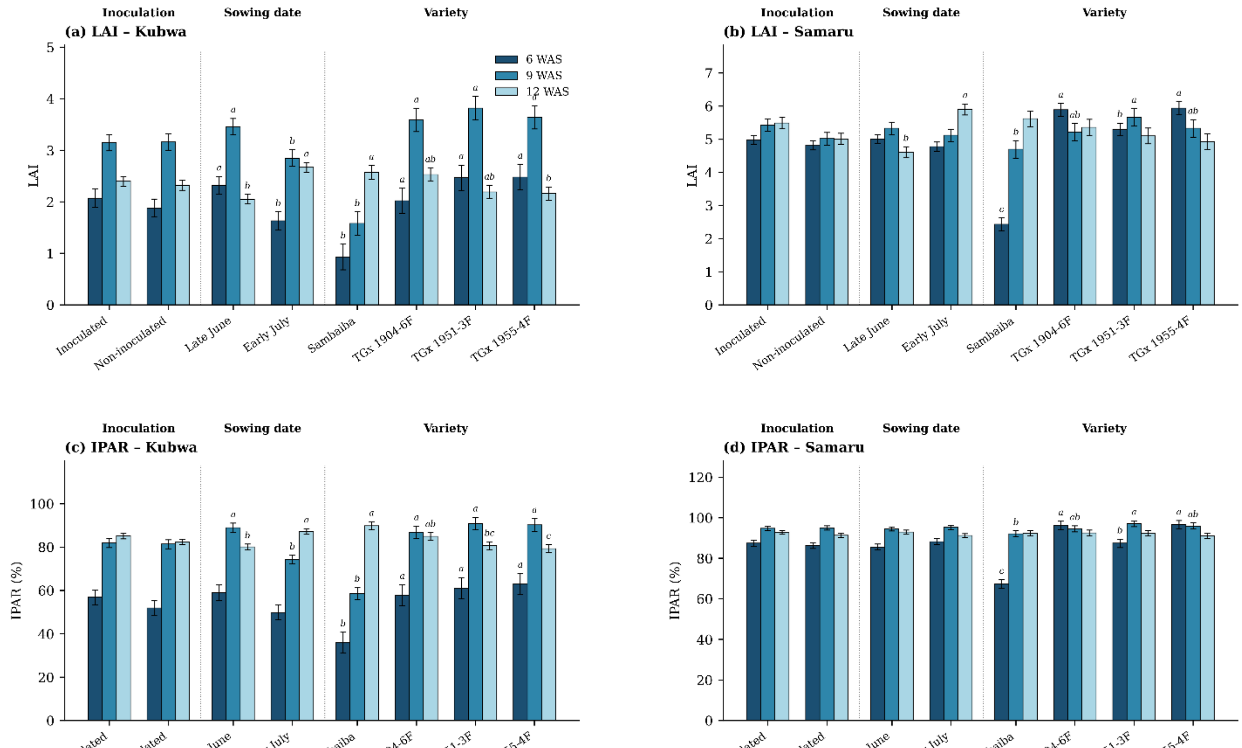

Figure 4: Leaf Area Index (LAI) and Intercepted Photosynthetically Active Radiation (IPAR, %) of soybean varieties as influenced by Inoculation, Sowing date, and Variety at Kubwa and Samaru in the 2018 Rainy Season. Bars topped with the same letter within a treatment group are not significantly different at the 5% level of probability using DMRT ($P \leq 0.05$). Error bars represent the standard error of the mean (SE±), as follows — LAI at Kubwa: Inoculation/Sowing date SE± = 0.174 (6 WAS), 0.160 (9 WAS), 0.094 (12 WAS); Variety SE± = 0.247, 0.226, 0.132. LAI at Samaru: Inoculation/Sowing date SE± = 0.135, 0.187, 0.168; Variety SE± = 0.192, 0.264, 0.238. IPAR at Kubwa: Inoculation/Sowing date SE± = 3.464, 2.051, 1.282; Variety SE± = 4.899, 2.900, 1.813. IPAR at Samaru: Inoculation/Sowing date SE± = 1.468, 1.061, 0.924; Variety SE± = 2.076, 1.500, 1.306. WAS = Week after sowing.

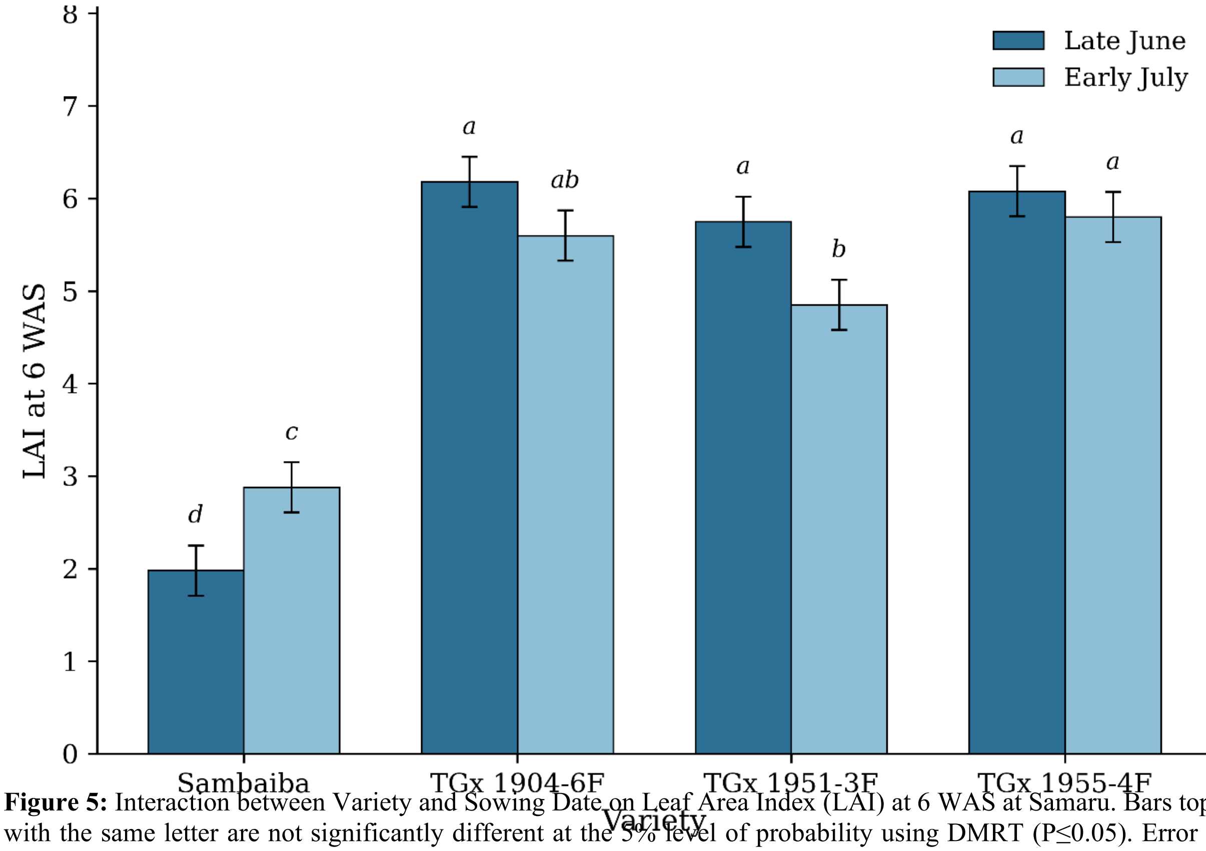

Figure 5: Interaction between Variety and Sowing Date on Leaf Area Index (LAI) at 6 WAS at Samaru. Bars topped with the same letter are not significantly different at the 5% level of probability using DMRT ($P \leq 0.05$). Error bars represent the standard error of the mean (SE± = 0.271, pooled across all variety × sowing date means).

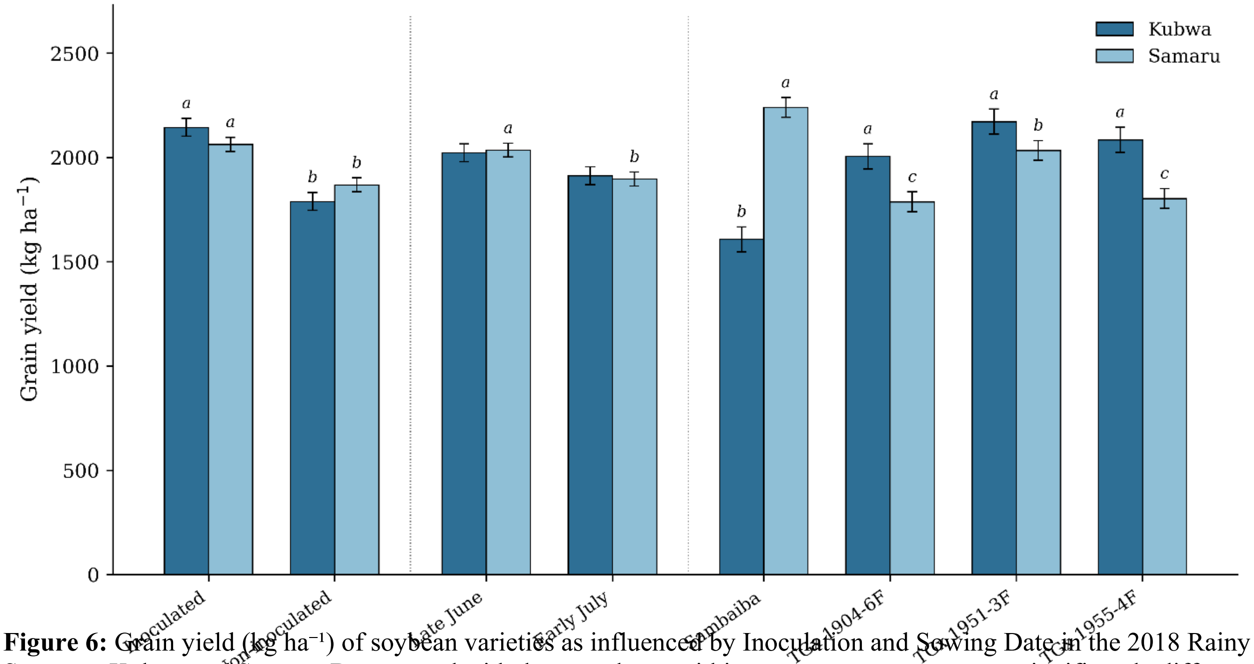

Figure 6: Grain yield (kg ha^{-1}) of soybean varieties as influenced by Inoculation and Sowing Date in the 2018 Rainy Season at Kubwa and Samaru. Bars topped with the same letter within a treatment group are not significantly different at the 5% level of probability using DMRT ($P \leq 0.05$). Error bars represent the standard error of the mean (SE±), as follows — Inoculation/Sowing date SE± = 42.502 (Kubwa), 33.583 (Samaru); Variety SE± = 60.107 (Kubwa), 47.493 (Samaru).

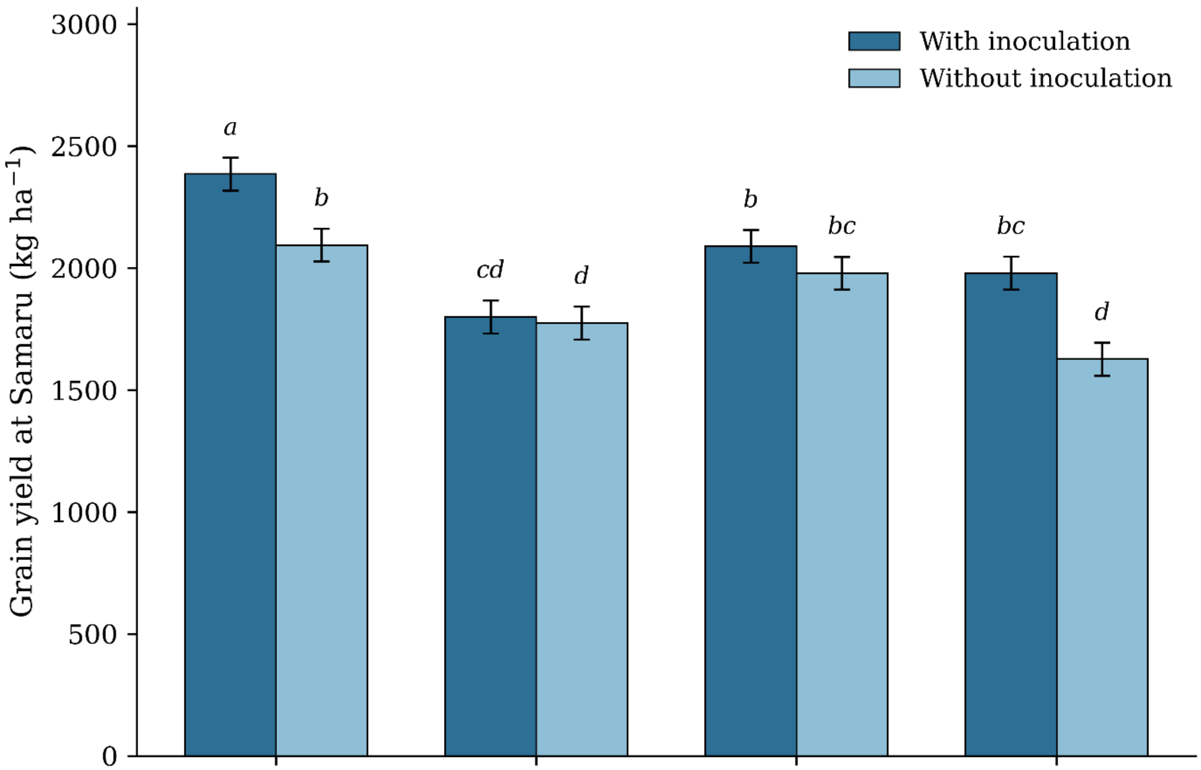

Figure 7: Interaction between Variety and Inoculation on Grain Yield (kg ha^{-1}) at Samaru. Bars topped with the same letter are not significantly different at the 5% level of probability using DMRT ($P \leq 0.05$). Error bars represent the standard error of the mean (SE± = 67.165, pooled across all variety × inoculation means).

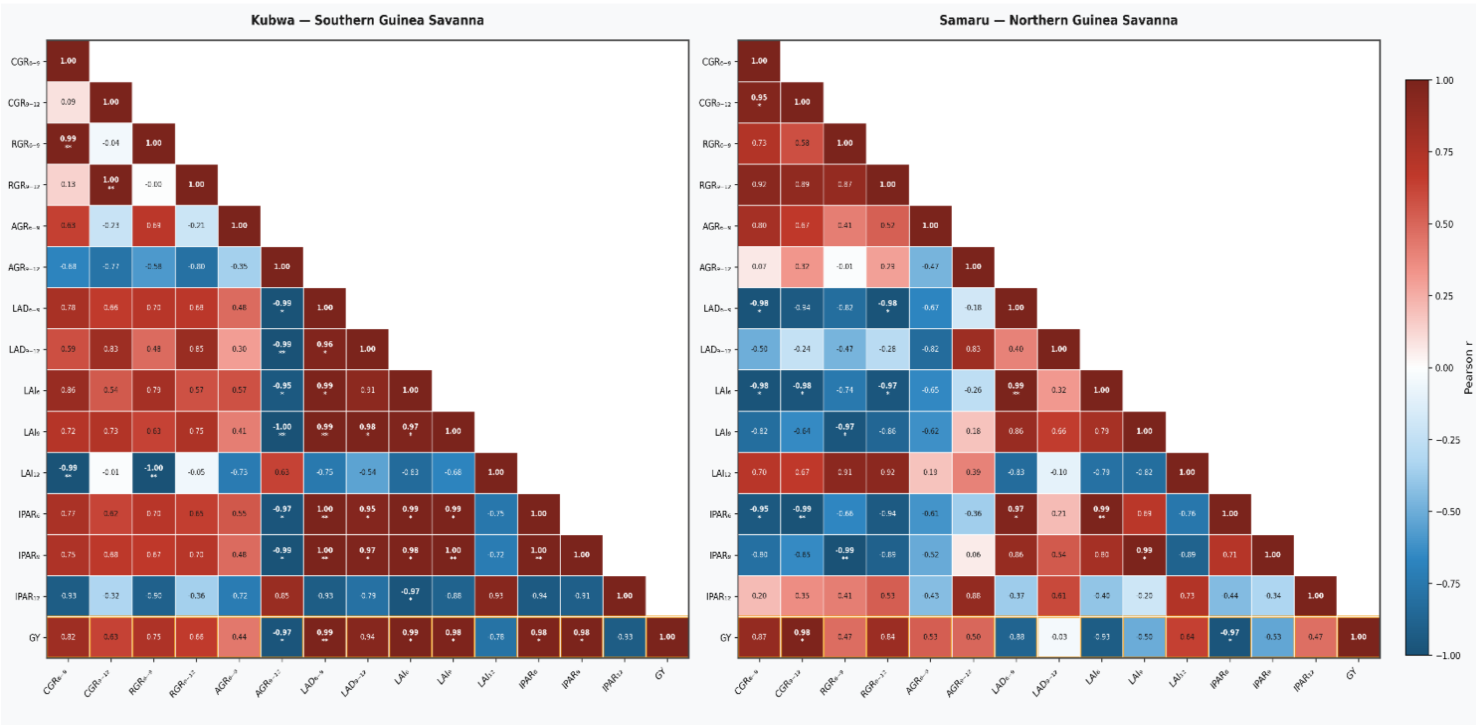

Figure 8: Pearson correlation matrices displaying the relationships between crop growth parameters and final grain yield (GY) at Kubwa (Southern Guinea Savanna, left) and Samaru (Northern Guinea Savanna, right). Color gradients indicate the strength and direction of the Pearson correlation coefficient (r), ranging from strong negative (dark blue, r ≤ -0.75) to strong positive (dark red, r ≥ 0.75).

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