Int J Adv Life Sci Res. Volume 9(2) 84-99
https://doi.org/10.31632/ijalsr.2026.v09i02.008

International Journal of Advancement in Life Sciences Research

Online ISSN: 2581-4877

Journal homepage http://ijalsr.org

Original Article

Multi-Stage Growth Parameter Correlation, Yield Prediction Models, and Sustainability Analysis for Soybean and Pigeon Pea

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Abstract

Enhancing crop productivity and sustainability is a critical priority in modern agriculture, particularly for leguminous crops such as soybean (*Glycine max L.*) and pigeon pea (*Cajanus cajan L.*), which play a vital role in global food security and soil fertility improvement. Accurate yield prediction models integrating multi-stage growth parameters can enable informed decision-making for crop management and resource optimisation. However, limited studies have simultaneously examined stage-wise parameter correlations, regression-based yield estimation, and sustainability metrics for these crops under varied treatments. This study aims to develop and evaluate multi-stage correlation matrices, regression models, and sustainability indices for soybean and pigeon pea yields using a comprehensive set of morphological and physiological parameters observed across key developmental stages. The parameters included seed yield (SY), dry matter (DM), plant height (PH), number of functional leaves (NFL), number of branches (NOB), leaf area (LA), number of pods (NOP), leaf area duration (LAD), pod weight (PW), number of seeds (NOS), seed weight (SW), test weight (TW), and harvest index (HI), with model performance evaluated using the coefficient of determination (R^2) and prediction error (PE). Results revealed strong positive correlations between LA, NOP, PW, and SY in soybean, and between DM, NOP, and SY in pigeon pea at later growth stages, with regression models achieving R^2 values exceeding 0.90 for the best-performing treatments. Sustainability yield index (SYI) analysis indicated that specific treatments consistently maintained high yield stability across seasons. The findings conclude that integrating multi-stage growth parameters into regression models significantly improves yield prediction accuracy and aids in identifying treatments that enhance sustainability. The developed models can serve as decision-support tools for optimising crop management practices, and future research may extend this approach to other legume species and integrate remote sensing data for real-time yield forecasting.

Keywords: *Benefit-Cost Ratio; Correlation; Plant Parameters; Regression; Soybean Equivalent Yield; Strip Cropping; Sustainability Yield Index*

Introduction

Soybean (*Glycine max*) is an essential crop due to its seeds' high oil and protein content, accounting for 56% of oilseed production worldwide. Globally, morethan340 million metric tonnes of soybeans were grown during 2016 (Cheng *et al*., 2018; Dreoni *et al*., 2022; Murithi *et al*., 2016; Wingeyer *et al*., 2015). In the USA, 33 million ha of soybeans were harvested and subsequently sold for $41 billion, with value derived from their seed composition, 38% protein, and 18% oil. During 1961-2013, the global area under soybeans increased at an annual compound rate of 2.97%, while production increased by 4.46%. Soybeans account for 37.4% of global oilseed area and contribute 28% of

Received on :10th August 2025; Revised version received on :21st February2026; Accepted: 2nd March 2026

vegetable oil production (Colussi *et al*., 2022; Jin *et al*., 2025; Li *et al*., 2020; Stojšin *et al*., 2014). The adaptability of crops to the diverse agro-ecological environments of the tropics, subtropics, and temperate regions was responsible for their rapid spread across the globe. Soybean is a high-value nutrient crop that is major in addressing food and nutritional security problems (Elmerich *et al*., 2023; Ngalamu *et al*., 2023; Tsegaw *et al*., 2025). Soybeans have been a leading oilseed crop in India for 4 decades since they were introduced for commercial cultivation. The crop share in total oilseed production increased from 5% in the 1980s to 37% recently. Soybean area increased from less than 0.5% in the 1980s to 5% of the country's gross cropped area in 2011 due to economic superiority over other crops (Morales *et al*., 2021; Ramappa *et al*., 2022). In Kharif 2018, the soybean area in India was 111.31 lakh ha and produced a total of 132.68 lakh tonnes, with an overall productivity of 1,192 kg ha-1. In this context, Maharashtra had a cultivation cover of 40.40 lakh ha and yielded 45.50 lakh tonnes, which corresponds to a productivity of 1,125 kg ha-1. (Nuthalapati *et al*., 2024; Prashnani *et al*., 2024).

Cajanus cajan L. (pigeon pea) is an economically important legume grown and utilised in vast areas of the tropical and subtropical belt, and India is a major producer that contributes close to 90% of the world's output. Pigeon pea now ranks second among pulses with 4.42 million ha, with two-thirds grown in India (14.5% of all pulse-growing land), and the other third in the Sudan (3.7 million ha). The crop is largely used as dry-split dal, although several additional uses make use of different components of the plant. Pigeon pea is nutritionally very high in protein (20-22%); hence, it is a complement to cereal-based diets common in vegetarian diets (Haji *et al*., 2024; Mashifane *et al*., 2024; Singh, 2016). It contains vital amino acids like lysine, tyrosine, and arginine, but cystine and methionine are present in a minimal form. Potassium, phosphorus, magnesium, calcium, and iodine are significant; iron and selenium are moderate, and zinc, copper, manganese, vitamin A, niacin, thiamine, and riboflavin are noted in small quantities in the seeds of pigeon pea. Pictorially, pigeon pea has a 23.3 per cent protein, 3.5 per cent minerals, and 57.6 per cent carbohydrate content to provide a total of about 335 kcal per 100 g of the consumable volume (Pranati *et al*., 2024; Saxena *et al*., 2020; Singh *et al*., 2020).

The area under pigeon pea so far in India during the 2018 Kharif was 47.80 lakh ha, and the total production was 33.20 lakh tonnes, with the average yield being 751 kg ha-1. At the level of the country, the highest planted area (12.61 lakh ha), production (8.34 lakh tonnes), and productivity (662 kg ha-1) were registered in Maharashtra. Increasing demand for agricultural products in the world necessitates intensification and improvement of techniques and better use of the input; hence it is becoming critical. One of the key factors of these efficiency improvements is mechanisation (Saxena *et al*., 2020). Strip intercropping, two or more crops each in parallel strips that allow each to be managed independently, although leaving them susceptible to agronomic interaction, offers another avenue (Awaad & El-Naggar, 2019; Juventia & van Apeldoorn, 2024; Te *et al*., 2023; Wang *et al*., 2020). Strip cropping enhances resource partitioning maximally by manipulating the width and arrangement of stripes which results in the mechanical cultivation of fields, thus lowering interspecific competition and increasing yield, especially at the boundaries of fields (Cuperus *et al*., 2024; Juventia & van Apeldoorn, 2024). Technology is in a position to aid such patterns commercially in large territories as the capabilities of machinery continue to enable it (Rakotomalala *et al*., 2023). Correctly managed strip systems prove to be more profitable and conserve more soil and water than monoculture (Alarcón-Segura *et al*., 2022). Zero tillage, residue retention, site-specific nutrient management, laser land levelling, rotation, rainwater harvesting, and off-season tillage, as well as contour farming and crop rotation, are generally observed integrated practices related to resource conservation, which are common to strip cropping. A mixture of plant species in neighbouring strips reduces wind and water erosion and neutralises nutrient leaching (Karas, 2020). Light dispersion modelling strategies of strip-cropping systems rely on the geometrical characteristics that include inter-row distance, row orientation, canopy height and width, solar angle, and leaf area distribution in the row to forecast the light variability that exists within the landscape (Oshunsanya *et al*., 2023; Siddoway & Barnett, 1976; Srivalai *et al*., 2025).

Verdelli *et al*. (2012) found that by utilising regular strip intercropping, a maize yield of 9765-11710 kg/ha and 1527-1538 kg/ha of soybean with a soil equivalent ratio of 1.4 were attained. Grain yields were 12750 kg/ha in maize and 1650 kg/ha in soybean under regular strip intercropping (Verdelli *et al*., 2012). In the maize-soybean strip system, the prevention of continuous soil cultivation barriers and improvement of sustainable farmland production are due to alternative rotation between maize-soybean strips compared with successive maize-soybean strip intercropping annually (Ali *et al*., 2022; Chen *et al*., 2023). Absorption of N, P, and K in maize yield increased by 7.5, 18.5, 9.1, and 14.2%, respectively, without significant changes in soybean yield of the maize-soybean strip alternative rotation (Guo *et al*., 2020). Additional soybean production was attained without affecting maize yield under intercropping, which adjusted high crop efficiency and sustainability (Raza *et al*., 2019). Strip-cropping has reduced the thickness and biomass of weeds in beans while decreasing the quantity of weeds in maize. In both beans and maize, the impact of strip-cropping was marked in conditions of mechanical weed control (Berdjour *et al*., 2020; Nolla *et al*., 2018). The growing legume plants would increase soil fertility and health, while crops would keep soil integrity intact due to strip-cropping. Straw mulch would cover the soil, since cover crops would improve soil fertility and water-holding capacity (Glowacka, 2013; Raza *et al*., 2024).

Recent advances highlight the value of integrative physiological, soil, and remote sensing approaches for yield prediction in legumes. Drone-derived NDVI at early lettuce heading explained 87% of yield variability and 77% of nitrogen status while effectively detecting flood-induced stress (Nakano *et al*., 2026). In soybean, exogenous 24-epibrassinolide significantly enhanced SPAD, Fv/Fm, antioxidant enzyme activity, and stress-responsive gene expression under combined salinity and drought (Khan *et al*., 2026). Soil amendments such as 4.5% gyttja-derived biochar improved soybean biomass by 84.9%, root length by 29.2%, and urease activity nearly twofold (Beyyavaş, 2025). Field studies in pigeon pea further demonstrated a 33.4% higher seed yield with transplanting and strong correlations between yield and pods per plant (r = 0.86) (Venkatesh *et al*., 2025), while multivariate soil analyses explained over 80% yield variability with robust regression fits ($R^2 \approx 0.68$) (N L *et al*., 2023). Collectively, these findings underscore the importance of multi-parameter, data-driven frameworks for improving yield forecasting and management in soybean–pigeon pea systems.

Murungu *et al*. (2011) indicated that strip intercropped crops attained lower biomass yields than single crops. The sole crop's highest biomass yield was achieved due to high crop density per unit area. The highest biomass was attained in the 3:2 strip pattern compared to 4:2 and 6:2 strip patterns. In strip intercropping, the biomass yield that would be realised if each system were used by farmers, compared to the sole crop cover crop biomass yield, was calculated based on the total crop biomass produced in the whole plot. Cover crop species affected final biomass yield when yield was compared on an equal area basis across strip-intercrop patterns. Less biomass yield under the 6:2 pattern may not make any meaningful contribution to the system's overall performance (Murungu *et al*., 2011).

Despite numerous studies on soybean and pigeon pea productivity, most existing research focuses on isolated growth stages, single parameter yields associations, or general agronomic evaluations, without integrating multi-stage morphological and physiological data into predictive frameworks. Additionally, the sustainability aspects of yield stability under different treatments remain underexplored. To address these gaps, the present study aims to (i) analyse stage-wise correlations among key growth parameters, (ii) develop regression-based yield prediction models for soybean and pigeon pea, and (iii) assess the sustainability of yields across treatments using the Sustainability Yield Index (SYI).

Materials and Methods

Experimental Details

An experiment was established in the kharif seasons of 2023 and 2024 at Parbhani, the soils of which were semi-arid vertisols, to study the effect of eight treatments based on different proportions of soybean (*Glycine max* L. cv. MAUS-162) and pigeon pea (*Cajanus cajan* L. cv. BDN-711) row ratios on crop productivity, plant-level characteristics, and monetary returns. It was a three-replication randomised block study whose treatments were assigned randomly within each replication. The treatments tested were: (i) T1: Soybean: Pigeon pea strip of 6:3 rows; (ii) T2: Soybean: Pigeon pea Strip of 6:6 rows; (iii) T3: Soybean: Pigeon pea strip of 12:9 rows; (iv) T4: Soybean: Pigeon pea Strip of 12:12 rows; (v) T5: Soybean: Pigeon pea strip of 18:12 rows; (vi) T6: Soybean + pigeon pea (4:2) intercropping system; (vii) T7: Sole soybean; (viii) T8: Sole pigeon pea. The arrangement of the experiment used 54 plots of variable size that were arranged in three replications.

Before sowing, a 15-20 cm deep ploughing was done with the use of a tractor-driven plough, followed by harrowing several times to get a fine tilth. Farmers ploughed down stubble left over by the previous crop. Seeds were sourced at the Seed Processing Plant, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, and inoculated with the volume of *Rhizobium* spp. (250 g per 10 kg of seeds). Basal fertilizer quantities applied to soybean and pigeon pea were 30:60:30 NPK kg ha^{-1} and 25:50 NP kg ha^{-1} using urea (46% N) and diammonium phosphate (18% N and 46% P_2O_5) and muriate of potash (60% K_2O) as sources of nutrients. It was sown using a ferti-cum-seed drill at row x row spacings of 45 x 5 cm in soybean and 90 x 20 cm in pigeon pea on 27 June 2023 and 5 July 2024, respectively.

One plot of five plants had been randomly tagged to observe biometric observations within the same crop development stage. Parameters sampled were plant height (cm), branches per $plant^{-1}$, functional leaves per $plant^{-1}$, leaf area per $plant^{-1}$ (dm^2), and total dry matter per $plant^{-1}$ (g). The height of the plants was recorded by taking a measurement of the height of the plant to the tip of the plant from the ground at15-day intervals between 30 and 75 days after sowing (DAS) and 30-day interval between 30 and 150 DAS in soybean and pigeon pea, respectively. At similar intervals starting 30 DAS in each crop, functional leaves that showed photosynthetic activity were counted.

An example is a phenotyping study of soybean (Glycine max) and pigeon pea (*Cajanus cajan*), of which the number of branches per plant on the main stem was counted on five representative plants at 30, 45, 60, and 75 days after sowing (DAS) and at harvest in soybean and at 30, 60, 90, 120, and 150 DAS and at harvest in pigeon pea. Components. To estimate the total dry matter per plant, one of the plants in the gross plot was chosen by a random method and pulled out, and each was separated into stem, leaves, and pods. These were air-dried first, then dry-oven at 60°C until a constant weight was attained; the dry weight of individual plants was recorded at the same respective times in the case of both soybean and pigeon pea. To estimate the leaf dry matter, leaves were removed from individuals of the uprooted sample plant and grouped into three sizes, namely small size, medium size, and large size. The count of the leaves of each category was taken. Each category of leaflet was identified, and one leaflet was randomly chosen and measured in cm in length and breadth. The leaf area was estimated by:

$$L_a = L x B x F x N$$

Where L_a= Leaf area (cm^2); L = Length of leaf (cm); B = Breadth of leaf (cm); F= Leaf area constant: 0.79 for Soybean and 0.81forpigeon pea (Krishnamurthy and Williams, 1974); N=Number of functional leaves.

Leaf area/leaflets were derived in each category and then summed up. The number of pods/plants was counted from 60 days to harvest for soybean and 120 days for pigeon pea. Leaf area duration is a measure of the ability of a plant to produce and maintain leaf area during the crop growth period and is given as

$$LAD = \{(LA_2 + LA_1)(t_2 - t_1)\}/2$$

Where $LA_1$and LA_2 are leaf are as at t_1 and t_2, respectively. From 5 plants, the number of filled pods/plant was counted at harvest, and the mean number of pods/plants was derived. The pods were dried, weighed, and expressed as pod weight/plant. Seeds were dried, weighed, and expressed as pod weight/plant. A sample of 1000 seeds was taken from the seeds produced from each net plot, counted, and the weighted. Plants from each plot were harvested, and seeds were separated by threshing. After sun drying, the seed yield obtained in each net plot was weighed in kg and converted to kg/ha. Harvest index was derived as

Harvest index = [Seed yield (kg/ha)] / [Biological yield (kg/ha)] x 100
where biological yield=seed yield + straw yield.

Pigeon pea and soybean yields were converted to soybean equivalent yields based on the prevailing market price of crops. Soybean equivalent yield was derived as

Soybean equivalent yield (kg/ha) = [Pigeon pea yield (kg/ha) x price (Rs/kg)] / [Soybean price (Rs/kg)]

The gross monetary returns (Rs/ha) accrued due to different treatments were derived by considering the market prices. Each treatment's cost of cultivation (Rs/ha) was derived by considering the price of inputs, output, and other charges. The net monetary returns (Rs/ha) of each treatment were derived by deducting the cost of cultivation (Rs/ha) of each treatment from gross monetary returns (Rs/ha) attained from the respective treatments. Each treatment's benefit: The cost ratio (B:C) was derived by dividing the gross monetary returns by the cost of cultivation.

Sustainability Yield Index (SYI): To assess yield stability and sustainability across treatments over the two experimental years (2023 and 2024), the Sustainability Yield Index (SYI) was calculated using the following formula:

$$\text{SYI} = \frac{\bar{Y} - \sigma}{Y_{\max}}$$

where:
$\bar{Y}$= mean yield (kg ha^{-1}) of a given treatment across years,
σ= standard deviation of yield (kg ha^{-1}) of the respective treatment across years,
$Y_{\max}$= maximum yield (kg ha^{-1}) recorded among all treatments during the study period.

The SYI value ranges between 0 and 1. Higher SYI values indicate greater yield stability and sustainability, as the index integrates both average productivity and inter-annual variability under different cropping systems.

Statistical Analysis

The experimental data were analysed using an analysis of variance (ANOVA) appropriate for a randomised block design. Treatment means were compared using the least significant difference (LSD) test at $P \leq 0.05$. Correlation analysis was performed using Pearson's correlation coefficient to examine relationships among growth and yield parameters. Regression analysis was conducted to develop predictive models for yield estimation. The significance of correlation coefficients was tested using the t-test, and regression models were evaluated through ANOVA. All statistical analyses were performed using SYSTAT Statistical Software, Version 13.2.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Results

Correlation between different parameters of Soybean observed on various days after sowing

The estimates of correlation between different parameters observed in soybeans when pooled over years are given in Table 1. Plant height had a significant correlation with (i) number of functional leaves (NFL), leaf area (LA), dry matter (DM) and leaf area duration (LAD) on 30, 45 and 60 DAS; (ii) LAD and number of branches (NOB) on 45, 60 and 75 DAS; (iii) number of pods (NOP) on 60 and 75 DAS; and (iv) DM, NOP, PW, NOS, SW, TW, seed yield and HI at harvest. NFL had a significant correlation with (i) LA, DM, and LAD on 30, 45, and 60 DAS; (ii) NOB on 45, 60, and 75 DAS; and (iii) NOP on 60 and 75 DAS. NOB had a significant correlation with (i) LA, DM, and LAD on 45, 60, and 75 DAS; and (ii) NOP on 60 and 75 DAS, while LA had a significant correlation with (i) DM and LAD on 30, 45, 60, and 75 DAS; and (ii) NOP on 60 and 75 DAS. DM had a significant correlation with (i) LAD on 30, 45 and 60 DAS; (ii) NOP on 60 and 75 DAS and at harvest; and (iii) PW, NOS, SW, TW, seed yield and HI at harvest, while NOP had a significant correlation with (i) LAD on 60 DAS, and (ii) PW, NOS, SW, TW, seed yield and HI at harvest. PW had a significant correlation with NOS, SW, TW, seed yield, and HI, while NOS had a significant correlation with SW, TW, seed yield, and HI at harvest. SW had a significant correlation with TW, seed yield, and HI at harvest, while TW had a significant correlation with seed yield and HI, and seed yield had a significant correlation with HI at harvest.

Table 1: *Correlation between Different Parameters of Soybean Over the Years*

Parameter-1	Parameter-2	30 DAS	45 DAS	60 DAS	75 DAS	Harvest
Plant Height	No. of functional leaves	0.916**	0.962**	0.941**	0.981**	
	Leaf area	0.955**	0.967**	0.965**	0.991**	
	Dry matter	0.956**	0.966**	0.960**	0.961**	0.978**
	Leaf area duration	0.949**	0.979**	0.932**		
	No. of branches		0.909**	0.949**	0.930**	
	No. of pods			0.959**	0.957**	0.970**
	Pod weight					0.950**
	No. of seeds					0.953**
	Seed weight					0.945**
	Test weight					0.795**
	Seed yield					0.942**
	Harvest index					0.824**
No. of Functional Leaves	Leaf area	0.939**	0.968**	0.988**	0.982**	
	Dry matter	0.856**	0.954**	0.963**	0.977**	
	Leaf area duration	0.915**	0.966**	0.949**		
	No. of branches		0.932**	0.975**	0.966**	
	No. of pods			0.972**	0.977**	
No. of Branches	Leaf area		0.928**	0.982**	0.940**	
	Dry matter		0.924**	0.970**	0.967**	
	Leaf area duration		0.936**	0.969**		
	No. of pods			0.969**	0.980**	
Leaf Area	Dry matter	0.901**	0.973**	0.977**	0.971**	
	Leaf area duration	0.989**	0.990**	0.952**		
	No. of pods			0.985**	0.963**	
Dry Matter	Leaf area duration	0.913**	0.979**	0.972**		
	No. of pods			0.984**	0.957**	0.956**
	Pod weight					0.948**
	No. of seeds					0.976**
	Seed weight					0.974**
	Test weight					0.861**
	Seed yield					0.906**
	Harvest index					0.798**
No. of Pods	Leaf area duration			0.964**		
	Pod weight					0.941**
	No. of seeds					0.908**
	Seed weight					0.905**
	Test weight					0.847**
	Seed yield					0.971**
	Harvest index					0.881**
Pod Weight	No. of seeds					0.928**
	Seed weight					0.912**
	Test weight					0.789**
	Seed yield					0.907**
	Harvest index					0.843**
No. of Seeds	Seed weight					0.996**
	Test weight					0.826**
	Seed yield					0.826**
	Harvest index					0.685**
Seed Weight	Test weight					0.850**
	Seed yield					0.818**
	Harvest index					0.682**
Test Weight	Seed yield					0.784**
	Harvest index					0.762**
Seed Yield	Harvest index					0.946**

*** indicates significance at 1% level*

Correlation between different parameters of pigeon pea observed on various days after sowing

The estimates of correlation between different parameters observed in pigeon pea when pooled over the years are given in Table 2. Plant height had a significant correlation with (i) number of functional leaves (NFL), leaf area (LA), dry matter (DM), and leaf area duration (LAD) on 30, 60, 90, 120, and 150 DAS and at harvest; (ii) Number of branches (NOB) on 60, 90, 120 and 150 DAS and at harvest; (iii) Number of pods (NOP) on 120 and 150 DAS and at harvest; and (iv) PW, NOS, SW, TW, seed yield and HI at harvest. NFL had a significant correlation with (i) LA, DM, and LAD on 30, 60, 90, 120 and 150 DAS and at harvest and 60 DAS; (ii) NOB on 60, 90, 120, 150 DAS and at harvest; (iii) NOP on 120 and 150 DAS and at harvest; (iv) PW, NOS, SW, TW, seed yield and HI at harvest. NOB had a significant correlation with (i) LA, DM, and LAD on 60, 90, 120, and 150 DAS and at harvest; (ii) NOP on 120, 150 DAS and at harvest; (iii) PW, NOS, SW, TW, seed yield, and HI at harvest. LA had a significant correlation with (i) DM and LAD on 30, 60, 90, 120, and 150 DAS and at harvest; (ii) NOP on 120 and 150 DAS and at harvest; and (iii) PW, NOS, SW, TW, seed yield, and HI at harvest. DM had a significant correlation with (i) LAD on 30, 60, 90, 120, and 150 DAS and at harvest; (ii) NOP on 120 and 150 DAS and at harvest; (iii) PW, NOS, SW, TW, seed yield, and HI at harvest. NOP significantly correlated with (i) LAD on 150 DAS and at harvest; (ii) PW, NOS, SW, TW, seed yield, and HI at harvest. LAD significantly correlated with PW, NOS, SW, TW, seed yield, and HI at harvest. PW significantly correlated with NOS, SW, TW, seed yield, and HI at harvest. NOS significantly correlated with SW, TW, seed yield, and HI. SW had a significant correlation with TW, seed yield, and HI; while TW had a significant correlation with seed yield and HI, seed yield had a significant correlation with HI.

***Table 2:** Correlation between Different Parameters of Pigeon Pea Over the Years*

Parameter-1	Parameter-2	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS	Harvest
Plant height	Number of functional leaves	0.928**	0.976**	0.987**	0.960**	0.986**	0.967**
	Leaf area	0.938**	0.928**	0.987**	0.934**	0.977**	0.976**
	Dry matter	0.894**	0.949**	0.987**	0.990**	0.979**	0.957**
	Leaf area duration	0.923**	0.937**	0.982**		0.942**	0.982**
	No. of branches		0.770**	0.956**	0.973**	0.965**	0.952**
	No. of pods				0.960**	0.958**	0.882**
	Pod weight						0.910**
	No. of seeds						0.909**
	Seed weight						0.913**
	Test weight						0.886**
	Seed yield						0.926**
	Harvest index						0.872**
Number of Functional Leaves	Leaf area	0.956**	0.944**	0.974**	0.912**	0.987**	0.960**
	Dry matter	0.974**	0.957**	0.978**	0.931**	0.986**	0.960**
	Leaf area duration	0.945**	0.963**	0.974**	0.942**	0.963**	0.974**
	No. of branches		0.832**	0.956**	0.949**	0.963**	0.966**
	No. of pods				0.929**	0.978**	0.882**
	Pod weight						0.906**
	No. of seeds						0.889**
	Seed weight						0.856**
	Test weight						0.789**
	Seed yield						0.959**
	Harvest index						0.905**
No. of Branches	Leaf area		0.908**	0.936**	0.952**	0.977**	0.976**
	Dry matter		0.840**	0.944**	0.961**	0.967**	0.973**
	Leaf area duration		0.893**	0.955**	0.978**	0.976**	0.981**
	No. of pods				0.985**	0.967**	0.917**
	Pod weight						0.932**
	No. of seeds						0.921**
	Seed weight						0.911**
	Test weight						0.853**

	Seed yield						0.915**
	Harvest index						0.913**
Leaf Area	Dry matter	0.907**	0.929**	0.982**	0.909**	0.987**	0.964**
	Leaf area duration	0.993**	0.987**	0.995**	0.989**	0.982**	0.994**
	No. of pods				0.973**	0.969**	0.912**
	Pod weight						0.914**
	No. of seeds						0.924**
	Seed weight						0.922**
	Test weight						0.879**
	Seed yield						0.918**
	Harvest index						0.889**
Dry Matter	Leaf area duration	0.900**	0.932**	0.978**	0.957**	0.955**	0.979**
	No. of pods				0.950**	0.953**	0.853**
	Pod weight						0.875**
	No. of seeds						0.863**
	Seed weight						0.864**
	Test weight						0.810**
	Seed yield						0.893**
	Harvest index						0.859**
No. of Pods	Leaf area duration					0.970**	0.895**
	Pod weight						0.982**
	No. of seeds						0.975**
	Seed weight						0.935**
	Test weight						0.886**
	Seed yield						0.887**
	Harvest index						0.891**
Leaf Area Duration	Pod weight						0.911**
	No. of seeds						0.915**
	Seed weight						0.915**
	Test weight						0.864**
	Seed yield						0.919**
	Harvest index						0.884**
Pod Weight	No. of seeds						0.978**
	Seed weight						0.938**
	Test weight						0.893**
	Seed yield						0.897**
	Harvest index						0.878**
No. of Seeds	Seed weight						0.948**
	Test weight						0.908**
	Seed yield						0.880**
	Harvest index						0.885**
Seed Weight	Test weight						0.982**
	Seed yield						0.818**
	Harvest index						0.844**
Test Weight	Seed yield						0.759**
	Harvest index						0.788**
Seed Yield	Harvest index						0.946**

*** indicates significance at 1% level*

Regression models of soybean yield through different parameters observed on various days after sowing

The multi-year treatment data were pooled together, and several regression models were then made to predict soybean seed yield on the basis of many of the parameters of plant growth. Table 3 shows the models, along with their coefficients of determination (R^2), prediction errors (PE), and yield indices of sustainability (SYI). SYI has been estimated in each model as a ratio of the average value of treatment yield over the years minus the PE, which can be developed in the specific model, while the maximum yield attained by any treatment in the study was divided. The model that included the heights of the plants at 30, 45, 60, and 75 DAS and the yields reported has an R^2 of 0.953, a PE of 52.31 kg/ha, and an SYI of 67.6%. An R^2 = 0.921, PE = 63.93 kg ha^{-1}, and SYI = 66.9% were produced with the model based on the number of functional leaves at 30, 45, 60, and 75 DAS. The model attains a similar performance in the case of the number of branches at 45, 60, and 75 DAS with an R^2 of 0.907, PE of 65.85 kg ha^{-1}, and SYI of 66.7%. The developed model exhibited the highest R^2 (0.974) and the lowest prediction error (36.46 kg ha^{-1}), with an SYI of 68.6%, based on leaf area measurements at 30, 45, 60, and 75 DAS. In this model, leaf area at 30 and 75 DAS showed a strong negative influence on yield, whereas leaf area at 45 and 60 DAS had positive effects.

At 30, 45, 60, and 75 DAS, harvest dry matter gives R^2 = 0.869, PE = 87.30 kg ha^{-1}, and SYI = 65.4 %, whereas for the model based on 60 and 75 DAS and, at harvest, pod numbers, R^2 = 0.946, PE = 50.20 kg ha^{-1}, and SYI = 67.8 %. In the latter model, there is a strong positive association between the pod counts during harvest and the yield. Throughout the calibration steps, the SYI was 65.4% (in dry matter) to 68.6% (leaf area), and the PE was 36.46 kg ha^{-1} (leaf area) to 87.30 kg ha^{-1} (dry matter). Table 4 contains model performance per growth stage, in values of R^2, PE, and SYI. At 30 DAS, the model with plant height and the number of functional leaves, leaf area, dry matter, and leaf area duration has an R^2 of 0.937%, PE of 60.66 kg $ha^{-1,}$ and SYI of 67.1%. An inclusion of a number of branches at 45 DAS results in an increase in the degree of predictability, R^2 = 0.987, lowest PE (28.93 kg ha^{-1}), and highest SYI (69.1%). Leaf area at 45 DAS makes a highly significant negative contribution, and the importance of leaf area duration is highly positive. The parameter set, including plant height, number of functional leaves, area of leaves, dry matter, area of leaves period, number of branches, and the amount of pods produced, had R^2 = 0.983, PE = 36.56 kg ha^{-1}, and SYI = 68.6% at 60 DAS. At 75 DAS, the same parameter set corresponds to R^2 = 0.951, PE = 62.02 kg ha^{-1}, and SYI = 67.0%, and plant height had a significant positive effect.

Table 3: *Regression Models of Seed Yield of Soybean Through Different Parameters*

Parameter	Regression Model	R^2	PE	SYI
Plant height on 30, 45, 60, 75 DAS and at harvest	SY = -1937.94** + 69.18 (PH 30) + 32.41 (PH 45) – 30.28 (PH 60) + 48.87 (PH 75) – 14.57 (PH AH)	0.953**	52.31	67.6
No. of functional leaves on 30, 45, 60, and 75 DAS	SY = -157.03 + 50.09 (NFL 30) + 71.39 (NFL 45) – 44.38 (NFL 60) + 55.22 (NFL 75)	0.921**	63.93	66.9
No. of branches on 45, 60, and 75 DAS	SY = 456.98** + 150.78* (NOB 45) – 12.75 (NOB 60) + 62.71 (NOB 75)	0.907**	65.85	66.7
Leaf area on 30, 45, 60, and 75 DAS	SY = 97.92 + 121.36** (LA 30) – 12.45 (LA 45) – 43.15 (LA 60) + 74.84** (LA 75)	0.974**	36.46	68.6
Dry matter on 30, 45, 60, 75 DAS and at harvest	SY = 289.31 + 35.74 (DM 30) + 36.55 (DM 45) + 45.11 (DM 60) – 53.96 (DM 75) + 40.82 (DM AH)	0.869**	87.30	65.4
No. of pods on 60, 75 DAS, and at harvest	SY = -811.94** + 20.08 (NOP 60) – 40.03 (NOP 75) + 89.20* (NOP AH)	0.946**	50.20	67.8
PH, NFL, LA, DM, LAD on 30 DAS	SY = -98.65 + 31.83 (PH 30) + 21.11 (NFL 30) + 100.01 (LA 30) – 18.89 (DM 30) + 1.57 (LAD 30)	0.937**	60.66	67.1
PH, NFL, NOB, LA, DM, LAD on 45 DAS	SY = 795.15* - 20.28 (PH 45) – 36.79 (NFL 45) + 47.32 (NOB 45) – 57.44* (LA 45) + 29.12 (DM 45) + 14.33** (LAD 45)	0.987**	28.93	69.1
PH, NFL, NOB, LA, DM, NOP, LAD on 60 DAS	SY = -1089.49* + 7.34 (PH 60) + 43.50 (NFL 60) + 9.49 (NOB 60) – 232.92** (LA 60) – 27.82 (DM 60) + 107.02 (NOP 60) + 13.61 (LAD 60)	0.983**	36.56	68.6
PH, NFL, NOB, LA, DM, NOP, LAD on 75 DAS	SY = -2567.01* + 71.82* (PH 75) – 64.42 (NFL 75) – 2.62 (NOB 75) – 111.85 (LA 75) – 3.82 (DM 75) + 68.01 (NOP 75) + 2.25 (LAD 75)	0.951**	62.02	67.0
PH, DM, NOP at harvest	SY = -1375.39** + 16.76 (PH AH) – 35.67 (DM AH) + 76.53** (NOP AH)	0.953**	46.68	68.0
PW, NOS, SW, TW, HI at harvest	SY = -2165.70 – 69.76 (PW) + 38.79 (NOS) – 77.47 (SW) – 37.67 (TW) + 132.86** (HI)	0.967**	43.65	68.2

*** indicates significance at 1% level. SYI: Sustainability yield (%)R2: Coefficient of determination; PE: Prediction error (kg/ha); SY: Seed yield (kg/ha); DM: Dry matter; PH: Plant height (cm) ; NFL: No. of functional leaves; NOB: No. of branches; LA: Leaf area; NOP: No. of pods; LAD: Leaf area duration; PW: Pod weight; NOS: No. of seeds; SW: Seed weight; TW: Test weight; HI: Harvest index (%); AH: At harvest*

During the harvest, the model using plant height, dry matter, and the number of pods captures R^2 = 0.953, PE = 46.68 kg ha^{-1}, and SYI = 68.0%. R (2) = 0.967, PE = 43.65 kg ha^{-1}, and SYI = 68.2% are obtained using the model that applies the pod weight, the number of seeds, seed weight, test weight, and harvest index. In this latter model, pod number and harvest index have a strong positive effect on yield. The highest SYI system value is 67.0% (75 DAS), and the lowest value is 69.1% (45 DAS) with corresponding values of 28.93 kg ha^{-1} (45 DAS) and 62.02 kg ha^{-1} (75 DAS), respectively, which results in an average of 52.90 kg ha^{-1} at all the calibrated models.

Regression models of pigeon pea yield through different parameters observed on various days after sowing

Based on the pooled multi-year treatment data, regression models were adjusted, and the models estimated the pigeon pea seed yield using some of the parameters related to plant growth. The efficacy of models was calculated as the coefficient of determination (R^2), prediction error (PE), and the sustainability yield index (SYI). Table 4 provides the evaluations.

A model that included plant height measured at 30, 60, 90, 120, and 150 DAS and at harvest had R = 0.922; the PE equation was 74.50 kg ha^{-1}, and the SYI equation was 62.7 per cent. The model that used the number of functional leaves measured at similar time intervals yielded R^2 = 0.949, PE = 60.46 kg ha^{-1}, and SYI = 63.7 per cent. Especially, the predictive power of the model based on the number of branches assessed at 60, 90, 120, and 150 DAS and at the harvest (R^2 = 0.904, PE = 77.47 kg ha^{-1}, SYI = 62.5%). Leaf area measured at the same times returned R^2 = 0.953, PE = 58.21 kg ha^{-1}, and SYI = 63.9%, respectively.

Single-parameter performance of DM measured at days 30, 60, 90, 120, and 150 DAS and harvest produced the biggest R^2 (= 0.979), PE (= 38.46 kg ha^{-1}), SYI (= 65.3%). A model, incorporating pod number measured at 120 and 150 DAS, and at harvest, resulted in intermediate predictive power (R^2 = 0.837, PE = 90.32 kg ha^{-1} number of pods per 1 extmentre^{-1}, SYI = 61.6%). In this model, DM t30 DAS and DM at harvest were the only measurements that had a significant positive influence on yield.

Additional advances came along with multiparameter modelling. Plant height, functional leaves, leaf area, DM, and leaf area duration (LAD) at 30 DAS explained 0.940 of the R^2, 61.29 kg ha^{-1} PE, and 63.7% SYI. The number of branches was subsequently added, leading to improvement of model performance results to R^2 = 0.976, PE = 41.10 kg ha^{-1}, and SYI = 65.1% with plant height at 30 and 60 DAS and their branches at 60 DAS showing significant positive influences.

High predictability was maintained at points in the midseason growth stages. The model with the number of functional leaves, leaf area, DM, LAD, branches, and the height of the plants had R^2 = 0.948, PE = 61.11 kg ha^{-1}. In a model that includes pods at 120 DAS, predictability was further supported (R^2 = 0.984, PE = 36.62 kg ha^{-1}, SYI = 65.4%). In this case, functional leaves and leaf areas indicated a significant negative relationship, whereas branches and LAD indicated a positive influence. The same set of parameters yielded 150 DAS and R^2 = 0.976, PE = 44.98 kg ha^{-1}, and SYI = 64.8 per cent.

Those based on harvest-stage values were found to be roughly the same; a series of functional leaves, leaf area, dry matter, LAD, branches, and pods provided R^2 = 0.950, PE = 64.72 kg ha^{-1}, and SYI = 63.4%. Pod weight, number of seeds, seed weight, test weight, and harvest index (HI) gave a model with R^2 = 0.927, PE = 67.67 kg ha^{-1}, and SYI = 63.2%; HI had a significant positive impact on the yield. The average PE was 59.61 kg ha^{-1} on all the calibrated models.

Given the high R^2 values observed in several models, possible interrelationships among growth variables were considered. As traits such as plant height, leaf area, and dry matter are biologically related, moderate correlation is expected. Stepwise regression was applied to reduce redundancy and retain only significant predictors. The models were developed primarily for yield prediction rather than interpretation of individual coefficients.

Table 4: *Regression Models of Seed Yield of Pigeon Pea Through Different Parameters*

Parameter	Regression Model	R^2	PE	SYI
Plant height on 30, 60, 90, 120, 150 DAS and at harvest	SY = -2101.59 + 50.09 (PH 30) + 38.30 (PH 60) + 50.29 (PH 90) – 12.32 (PH 120) + 87.93 (PH 150) – 118.97 (PH AH)	0.922**	74.50	62.7
No. of functional leaves on 30, 60, 90, 120, 150 DAS and at harvest	SY = -1007.97 + 83.61 (NFL 30) + 29.46 (NFL 60) – 29.74 (NFL 90) – 16.50 (NFL 120) + 33.97 (NFL 150) + 29.34 (NFL AH)	0.949**	60.46	63.7
No. of branches on 60, 90, 120, 150 DAS, and at harvest	SY = -347.05 + 119.83 (NOB 60) – 65.726 (NOB 90) + 43.99 (NOB 120) + 130.35 (NOB 150) – 67.05 (NOB AH)	0.904**	77.47	62.5
Leaf area on 30, 60, 90, 120, 150 DAS and at harvest	SY = -1366.79 – 0.27 (LA 30) + 92.89 (LA 60) + 39.43 (LA 90) – 9.55 (LA 120) – 3.03 (LA 150) + 4.04 (LA AH)	0.953**	58.21	63.9
Dry matter on 30, 60, 90, 120, 150 DAS and at harvest	SY = -582.23 + 145.59** (DM 30) – 45.78 (DM 60) + 29.77 (DM 90) + 34.28 (DM 120) + 9.34 (DM 150) – 21.19** (DM AH)	0.979**	38.46	65.3
No. of pods on 120, 150 DAS, and at harvest	SY = -1034.51** + 22.78 (NOP 120) – 9.84 (NOP 150) + 12.29 (NOP AH)	0.837**	90.32	61.6
Leaf area duration on 30, 60, 90, 120, 150 DAS and at harvest	SY = -1724.38 – 7.99 (LAD 30) + 4.51 (LAD 60) + 2.43 (LAD 90) – 0.113 (LAD 120) – 0.524 (LAD 150) + 0.65 (LAD AH)	0.954**	57.66	63.9
PH, NFL, LA, DM, LAD on 30 DAS	SY = -693.39 + 48.86* (PH 30) + 24.80 (NFL 30) + 43.57 (LA 30) + 74.20 (DM 30) – 5.70 (LAD 30)	0.940**	61.29	63.7
PH, NFL, NOB, LA, DM, LAD on 60 DAS	SY = -2272.90** + 62.58** (PH 60) – 14.63 (NFL 60) + 174.17** (NOB 60) + 45.36 (LA 60) – 17.84 (DM 60) – 3.73 (LAD 60)	0.976**	41.10	65.1
PH, NFL, NOB, LA, DM, LAD on 90 DAS	SY = -1092.10 + 1.77 (PH 90) – 18.65 (NFL 90) + 4.53 (NOB 90) – 47.46 (LA 90) + 31.86 (DM 90) + 5.10 (LAD 90)	0.948**	61.11	63.7
PH, NFL, NOB, LA, DM, NOP, LAD on 120 DAS	SY = -1228.90 + 42.07 (PH 120) – 18.95** (NFL 120) + 176.52* (NOB 120) – 83.18** (LA 120) – 49.54 (DM 120) – 7.87 (NOP 120) + 4.62* (LAD 120)	0.984**	36.62	65.4
PH, NFL, NOB, LA, DM, NOP, LAD on 150 DAS	SY = -788.17 + 5.38 (PH 150) – 16.43 (NFL 150) + 125.62* (NOB 150) + 29.64 (LA 150) + 34.78 (DM 150) – 7.95 (NOP 150) – 1.38 (LAD 150)	0.976**	44.98	64.8
PH, NFL, NOB, LA, DM, NOP, LAD at harvest	SY = -1335.30 + 3.15 (PH AH) + 53.87* (NFL AH) – 22.30 (NOB AH) + 57.07 (LA AH) + 1.34 (DM AH) + 3.99 (NOP AH) – 2.82 (LAD AH)	0.950**	64.72	63.4
PW, NOS, SW, TW, HI at harvest	SY = -2820.81 + 41.08 (PW) – 0.92 (NOS) – 15.09 (SW) + 2.82 (TW) + 96.47** (HI)	0.927**	67.67	63.2

*** indicates significance at 1% level. SYI: Sustainability yield (%);R^2: Coefficient of determination;PE: Prediction error (kg/ha); SY: Seed yield (kg/ha); DM: Dry matter; PH: Plant height (cm); NFL: No. of functional leaves ; NOB: No. of branches; LA: Leaf area; NOP: No. of pods; LAD: Leaf area duration; PW: Pod weight; NOS: No. of seeds; SW: Seed weight;TW: Test weight; HI: Harvest index (%); AH: At harvest*

Sustainability of yield attained by different treatments

The sustainability yield index (SYI) values of soybean and pigeon pea were derived using the mean yield of soybean and pigeon pea attained by each treatment, the maximum soybean yield of 1550 kg/ha, the pigeon pea yield of 1420 kg/ha, and a mean prediction error of 52.90 kg/ha of soybean and 59.61 kg/ha of pigeon pea. Similarly, using the mean soybean equivalent yield (SEY) attained by each treatment, a maximum SEY of 2991 kg/ha attained by T5 in 2019 and a prediction error of 23.57 kg ha^{-1}, SYI values of treatments were derived and are presented in Figure 1. The regression model of soybean equivalent yield through rainwater use efficiency attained by different treatments over the years gave a predictability of 0.997 with a prediction error of 23.57 kg/ha. The model is presented as

$$SEY = -24.368 + 572.703^{**} (RWUE)$$

The SYI of soybean ranged from 55.4% attained by T6: soybean + pigeon pea (4:2) to 91.9% attained by T7: sole soybean with a mean of 67.6% (CV of 17.9%), while the SYI of pigeon pea ranged from 50.2% attained by T6: soybean + pigeon pea (4:2) to 88.9% attained by T8: sole pigeon pea with a mean of 63.8% (CV of 19.8%). Compared to this, the SYI of soybean equivalent yield ranged from

71.5% attained by T6: soybean + pigeon pea (4:2) to 94.1% attained by T5: soybean: pigeon pea (18:12), with a mean SYI of 83.0% (CV of 10.0%). Among treatments with different row ratios, T5: soybean: pigeon pea (18:12) gave a maximum mean soybean yield of 1163 kg/ha and pigeon pea yield of 1033 kg/ha over the years. T5: soybean: pigeon pea (18:12) incurred the maximum mean cost of cultivation of Rs 35812/ha and gave maximum mean gross returns of Rs 100494/ha over the years. The study indicated that T5: soybean: pigeon pea (18:12) was superior, with a maximum SYI of 94.1% and a soybean equivalent yield of 2839 kg/ha, rainwater use efficiency of 5.01 kg/ha/mm, net returns of Rs 64682/ha, and a BC ratio of 1.81. T4: soybean: pigeon pea (12:12) was found to be the 2nd best treatment with SYI of 88.7% and gave a soybean equivalent yield of 2677 kg/ha, rainwater use efficiency of 4.73 kg/ha/mm, net returns of Rs 60341/ha, and BC ratio of 1.76.

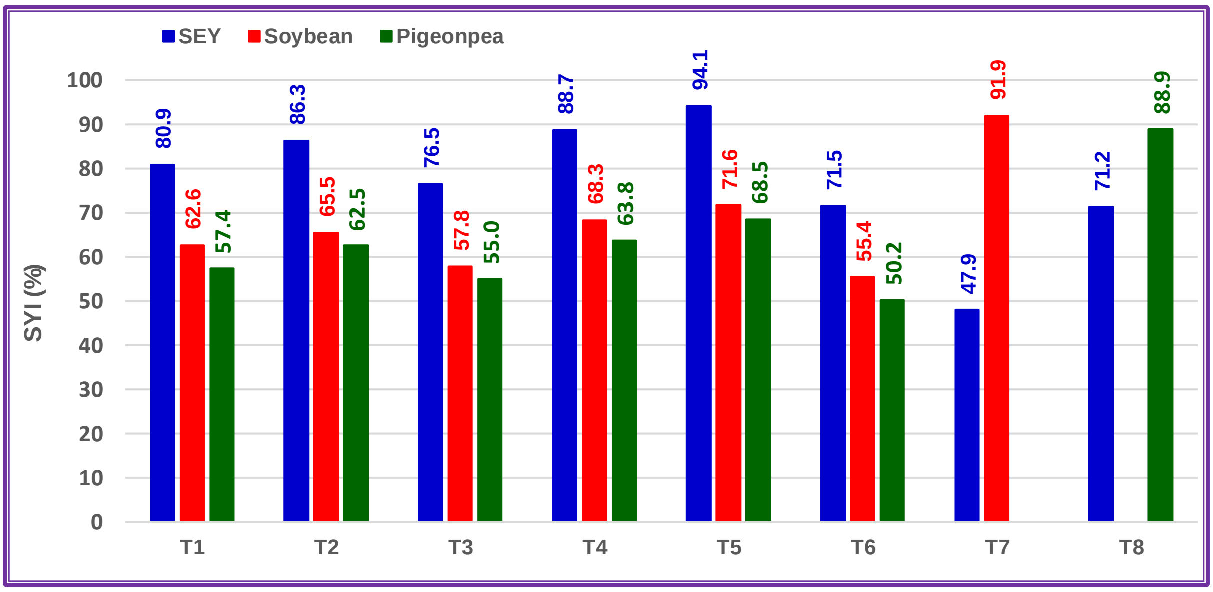

Figure 1: *Sustainability Yield Index of Treatments for Attaining Maximum Soybean, Pigeon Pea, and Soybean Equivalent Yield at Parbhani*

Discussion

The strong and consistent correlations observed among growth attributes and yield components in both soybean and pigeon pea indicate that early and mid-season vegetative development plays a decisive role in final productivity. In soybean, plant height, leaf area, and dry matter accumulation showed highly significant associations with seed yield and harvest index, with correlation coefficients frequently exceeding 0.95 at 60 and 75 DAS. This confirms that canopy expansion and assimilate accumulation during the reproductive transition stage are critical determinants of pod formation and seed filling. Similar physiological relationships between assimilate competition and seed growth have been reported by Ali *et al*. (2022), who demonstrated that early assimilating dynamics significantly influence pod and seed development in soybean.

The regression analyses further strengthened these findings. In soybeans, leaf area-based models achieved the highest predictive accuracy (R^2 = 0.974; PE = 36.46 kg ha^{-1}; SYI = 68.6%), indicating that canopy development is a robust integrative indicator of yield potential. Mid-season models incorporating plant height, branches, leaf area, and pods at 45–60 DAS yielded R^2 values up to 0.987 with minimal prediction error (28.93 kg ha^{-1}), underscoring the importance of vegetative–reproductive balance during this stage. Comparable findings have been reported in strip intercropping systems, where an optimised canopy architecture improved radiation interception and yield stability (Verdelli *et al*., 2012; Wang *et al*., 2020).

In pigeon pea, dry matter accumulation emerged as the most reliable single predictor (R^2 = 0.979; PE = 38.46 kg ha^{-1}; SYI = 65.3%), suggesting that biomass partitioning efficiency is central to yield realisation. Multi-parameter models at 120 DAS achieved R^2 = 0.984 with PE = 36.62 kg ha^{-1}, highlighting the relevance of branch development and leaf area duration in supporting sustained reproductive growth. These observations align with multivariate analyses of pigeon pea yield variability, where soil–plant interactions and biomass traits were shown to strongly influence productivity (N L*et al*., 2023).

The sustainability yield index (SYI) analysis revealed clear treatment advantages. The soybean–pigeon pea strip ratio of 18:12 (T5) achieved the highest SYI of 94.1% for soybean equivalent yield, with a mean SEY of 2839 kg ha^{-1} and rainwater use efficiency of 5.01 kg ha^{-1} mm^{-1}. This demonstrates the complementarity effect often reported in legume-based intercropping systems (Raza *et al*., 2019; Rakotomalala *et al*., 2023). Intercropping configurations can enhance resource use efficiency, stabilise yields, and improve economic returns, as also evidenced by multi-year strip cropping analyses (Juventia & van Apeldoorn, 2024).

Overall, the high R^2 values across models reflect strong biological coherence among growth parameters. While interrelationships among variables are expected due to shared physiological pathways, stepwise regression effectively minimised redundancy and retained predictive efficiency. The integration of growth-stage–specific modelling with sustainability metrics provides a practical framework for yield forecasting and agronomic optimisation under rainfed conditions.

Limitations

The study is limited by its reliance on data collected from a single geographical location and a restricted set of treatment combinations, which may constrain the generalizability of the developed models across diverse agro-climatic conditions. Additionally, the regression-based approach does not fully account for complex non-linear interactions among growth parameters, potentially limiting predictive robustness under variable environmental scenarios.

Future Scope

Future research should focus on validating the developed models across multiple locations, seasons, and crop varieties to enhance their robustness and applicability under diverse field conditions. Furthermore, integrating advanced data-driven techniques such as machine learning and remote sensing could improve real-time yield prediction and enable more precise, scalable decision-support systems.

Conclusion

This study investigates soybean and pigeon pea productivity by integrating multi-stage morphological and physiological data into predictive models and assessing yield sustainability across various treatments. The findings revealed robust correlations among growth parameters across days after sowing (DAS), highlighting key relationships influencing yield. For soybeans, parameters such as plant height, leaf area, dry matter, and the number of pods showed strong correlations with seed yield ($r \geq 0.90$). Similarly, for pigeon pea, correlations between plant height, leaf area, dry matter, and harvest index were significant across multiple stages ($r \geq 0.90$). Regression models developed for yield prediction revealed high predictability ($R^2 \geq 0.95$) for both crops using key parameters. Notably, the regression model for soybean, including parameters like plant height, leaf area, and number of pods, exhibited a coefficient of determination of 0.987 and a sustainability yield index (SYI) of 69.1%. For pigeon pea, the best model had an R^2 of 0.984 and an SYI of 65.4%, suggesting that multi-parameter models effectively predict yields with minimal prediction errors (PE ≤ 77.47 kg/ha). The sustainability of yields across treatments was quantified using the Sustainability Yield Index (SYI). Soybean treatments ranged from an SYI of 55.4% to 91.9%, while pigeon pea treatments exhibited a range of 50.2% to 88.9%. The soybean-pigeon pea intercropping treatment (18:12) demonstrated the highest SYI (94.1%) and soybean equivalent yield (2839 kg/ha), highlighting its superior sustainability and economic returns. This study underscores the importance of integrated multi-stage data and sustainability metrics for optimising yield prediction and stability across diverse agronomic practices.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Acknowledgment

Authors would like to thank Manipal Institute of Technology, MAHE, Manipal, for providing the time of a staff member to collaborate with researchers from VNMKV Parbhani as a part of the networking project "Support to Society".

References

Alarcón-Segura, V., Grass, I., Breustedt, G., Rohlfs, M., & Tscharntke, T. (2022). Strip intercropping of wheat and oilseed rape enhances biodiversity and biological pest control in a conventionally managed farm scenario. *Journal of Applied Ecology*, *59*(6), 1513-1523. https://doi.org/10.1111/1365-2664.14161

Ali, M. F., Brown, P., Thomas, J., Salmerón, M., & Kawashima, T. (2022). Effect of assimilate competition during early seed development on the pod and seed growth traits in soybean. *Plant Reproduction*, *35*(3), 179-188. https://doi.org/10.1007/S00497-022-00439-2

Awaad, H., & El-Naggar, N. (2018). Potential Role of Intercropping in Maintaining and Facilitating Environmental Sustainability. In: Negm, A.M., Abu-hashim, M. (eds) Sustainability of Agricultural Environment in Egypt: Part I. The Handbook of Environmental Chemistry, vol 76. Springer, Cham. https://doi.org/10.1007/698_2017_163

Berdjour, A., Dugje, I. Y., Dzomeku, I. K., & Rahman, N. A. (2020). Maize–soybean intercropping effect on yield productivity, weed control and diversity in northern Ghana. *Weed Biology and Management, 20*, 69–81. https://doi.org/10.1111/wbm.12198

Beyyavaş, V. (2025). Improving soybean (Glycine max (L.) Merr.) growth and soil health with Gyttja biochar: insights into plant biochemical attributes and soil chemical properties. *BMC Plant Biology*, *25*(1), 974. https://doi.org/10.1186/s12870-025-07081-w

Chen, K., Zhang, J., Han, K., Luo, H., Ma, Q., & Wu, L. (2023). Suitability screening of soybean varieties at seedling stage under photovoltaic panels. Zhejiang Daxue Xuebao (Nongye Yu Shengming Kexue Ban)/*Journal of the Zhejiang University - Agriculture and Life Science*, 49(4), 535–546. https://doi.org/10.3785/J.ISSN.1008-9209.2023.02.212

Cheng, M. H., Sekhon, J. J., Rosentrater, K. A., Wang, T., Jung, S., & Johnson, L. A. (2018). Environmental impact assessment of soybean oil production: Extruding-expelling process, hexane extraction and aqueous extraction. *Food and Bioproducts Processing*, *108*, 58-68. https://doi.org/10.1016/j.fbp.2018.01.001

Colussi, J., Morgan, E. L., Schnitkey, G. D., & Padula, A. D. (2022). How communication affects the adoption of digital technologies in soybean production: A survey in Brazil. *Agriculture*, *12*(5), 611. https://doi.org/10.3390/agriculture12050611

Cuperus, F., Allema, B., Bianchi, F. J., Rossing, W. A., & van Apeldoorn, D. F. (2024). Cauliflower strip cropping promotes ground-dwelling arthropod richness and spider abundance. *Agriculture, Ecosystems & Environment*, *374*, 109137. https://doi.org/10.1016/J.AGEE.2024.109137

Dreoni, I., Matthews, Z., & Schaafsma, M. (2022). The impacts of soy production on multi-dimensional well-being and ecosystem services: A systematic review. *Journal of Cleaner Production*, *335*, 130182. https://doi.org/10.1016/j.jclepro.2021.130182

Elmerich, C., Faucon, M. P., Garcia, M., Jeanson, P., Boulch, G., & Lange, B. (2023). Envirotyping to control genotype x environment interactions for efficient soybean breeding. *Field Crops Research*, *303*, 109113. https://doi.org/10.1016/j.fcr.2023.109113

Glowacka, A. (2013). The influence of strip cropping and weed control methods on weed diversity in dent maize (Zea mays L.), narrow-leafed lupin (Lupinus angustifolius L.) and oats (Avena sativa L.). *Acta agrobotanica*, *66*(4). https://doi.org/10.5586/aa.2013.065

Guo, S. Q., Cui, Z. T., Weijie, S. H. I., Cheng, H. Y., Xiao, R., Xiao, Z. W., ... & Cao, J. Z. (2020). Effects of nitrogen, phosphorus, potassium and their combined application on nutrient absorption and utilization of seed maize. *Agricultural Research in the Arid Areas, 38*(2), 221-226. https://doi.org/10.7606/J.ISSN.1000-7601.2020.02.31

Haji, A., Teka, T. A., Yirga Bereka, T., Negasa Andersa, K., Desalegn Nekera, K., Geleta Abdi, G., ... & Makiso Urugo, M. (2024). Nutritional composition, bioactive compounds, food applications, and health benefits of pigeon pea (Cajanus cajan L. Millsp.): A review. *Legume Science*, *6*(2), e233. https://doi.org/10.1002/LEG3.233

Jin, S. S., Sun, Z. Y., Deng, F., Yan, C. Z., & Zhu, R. N. (2025). Impact of technological innovation on global crop export trade: the example of innovation in GM technology. *Food and Energy Security*, *14*(1), e70031. https://doi.org/10.1002/FES3.70031

Juventia, S. D., & Van Apeldoorn, D. F. (2024). Strip cropping increases yield and revenue: multi-year analysis of an organic system in the Netherlands. *Frontiers in Sustainable Food Systems*, *8*, 1452779. https://doi.org/10.3389/fsufs.2024.1452779

Karas, E. (2020). Evaluation of a sustainable land use planning model in the Elmalı basin. *Environmental monitoring and assessment*, *192*(4), 255. https://doi.org/10.1007/s10661-020-8203-8

Khan, T. A., Saeed, T., Tran, L. S. P., & Gururani, M. A. (2026). Coordinated physiological and molecular reprogramming by brassinosteroids improves soybean tolerance to combined salt and drought stress. *Plant Signaling & Behavior*, *21*(1), 2616539. https://doi.org/10.1080/15592324.2026.2616539

Krishnamurthy, L., & Williams, F. A. (1974). A flame sheet in the stagnation-point boundary layer of a condensed fuel. *Acta Astronautica*, *1*(5-6), 711-736.https://doi.org/10.1016/0094-5765(74)90029-0

Li, M. W., Wang, Z., Jiang, B., Kaga, A., Wong, F. L., Zhang, G., ... & Lam, H. M. (2020). Impacts of genomic research on soybean improvement in East Asia. *Theoretical and Applied Genetics*, *133*(5), 1655-1678. https://doi.org/10.1007/S00122-019-03462-6

Mashifane, D. C., Chiulele, R. M., & Gwata, E. T. (2024). Diversity in selected grain mineral and protein among Pigeonpea Landraces. *Applied Sciences*, *14*(2), 573. https://doi.org/10.3390/APP14020573

Morales, L. E., Balié, J., & Magrini, E. (2021). How has the minimum support price policy of India affected cross-commodity price linkages? *International Food and Agribusiness Management Review*, *24*(2), 179-196. https://doi.org/10.22434/IFAMR2020.0035

Murithi, H. M., Beed, F., Tukamuhabwa, P., Thomma, B. P., & Joosten, M. H. (2016). Soybean production in eastern and southern Africa and threat of yield loss due to soybean rust caused by Phakopsora pachyrhizi. *Plant Pathology*, *65*(2), 176-188. https://doi.org/10.1111/ppa.12457

Murungu, F. S., Chiduza, C., & Muchaonyerwa, P. (2011). Productivity of maize after strip intercropping with leguminous crops under warm-temperate climate. *African Journal of Agricultural Research*, *6*(24), 5405-5413. https://doi.org/10.5897/AJAR11.507

N L, R., K, N. R., U, S., V B, W., K, B., H V, R., & B K, D. (2023). Variability in soil properties influencing pigeonpea (Cajanus *cajana L.*) yield: A multivariate statistical analysis. *F1000Research*, *10*, 944. https://doi.org/10.12688/f1000research.53095.3

Nakano, S., Hama, A., Koyama, R., & Uno, Y. (2026). Growth Diagnosis and Yield Prediction in Lettuce Using a Drone Equipped with a Multispectral Camera. *The Horticulture Journal*, *95*(1), 30-39. https://doi.org/10.2503/hortj.SZD-046

Ngalamu, T., Bulli, P., & Meseka, S. (2023). Yield Performance and Stability Analysis of Promising Soybean Genotypes under Contrasting Environments in the Semi-arid Zone of Sudan. *Legume Research: An International Journal*, *46*(7), 822 - 829. https://doi.org/10.18805/LRF-722

Nolla, A., Jucksh, I., Castaldo, J. H., Alvarenga, R. C., & Albrecht, L. P. (2018). Growth and accumulation of nutrients by weeds, in maize and legumes intercrops. *Planta Daninha*, *36*, e018175433.https://doi.org/10.1590/S0100-83582018360100096

Nuthalapati, C. S., Kumar, A., Birthal, P. S., & Sonkar, V. K. (2024). Demand-side and supply-side factors for accelerating varietal turnover in smallholder soybean farms. *Journal of Cleaner Production*, *447*, 141372.https://doi.org/10.1016/J.JCLEPRO.2024.141372

Oshunsanya, S. O., Yu, H., Opara, C. C., Odebode, A. M., Oluwatuyi, T. S., & Babalola, O. (2023). Integration effect of vetiver grass strips with maize population density on soil erosion under two contrasting slopes of rainforest agroecology. *Catena*, *221*, Part A, 106768.https://doi.org/10.1016/J.CATENA.2022.106768

Pranati, J., Chilakamarri, V., Kalyan, A., Shruthi, H. B., Bomma, N., Yogendra, K., & Gangashetty, P. (2024). Strategizing pigeonpea for enhancing health-benefitting traits: A path to nutritional advancements. *Crop Design*, *3*(4), 100068.https://doi.org/10.1016/J.CROPD.2024.100068

Prashnani, M., Dupare, B., Vadrevu, K. P., & Justice, C. (2024). Towards food security: Exploring the spatio-temporal dynamics of soybean in India. *PloS One*, *19*(5), e0292005.https://doi.org/10.1371/journal.pone.0292005

Rakotomalala, A. A., Ficiciyan, A. M., & Tscharntke, T. (2023). Intercropping enhances beneficial arthropods and controls pests: A systematic review and meta-analysis. *Agriculture, Ecosystems & Environment*, *356*, 108617.https://doi.org/10.1016/J.AGEE.2023.108617

Ramappa, K. B., Jadhav, V., & Manjunatha, A. V. (2022). A benchmark study on economic impact of Neem Coated Urea on Indian agriculture. *Scientific Reports*, *12*(1), 9082.https://doi.org/10.1038/s41598-022-12708-1

Raza, M. A., Bin Khalid, M. H., Zhang, X., Feng, L. Y., Khan, I., Hassan, M. J., ... & Yang, W. (2019). Effect of planting patterns on yield, nutrient accumulation and distribution in maize and soybean under relay intercropping systems. *Scientific Reports*, *9*(1), 4947.https://doi.org/10.1038/S41598-019-41364-1

Raza, M. A., Din, A. M. U., Shah, G. A., Zhiqi, W., Feng, L. Y., Gul, H., ... & Zhongming, M. (2024). Legume choice and planting configuration influence intercrop nutrient and yield gains through complementarity and selection effects in legume-based wheat intercropping systems. *Agricultural Systems*, *220*, 104081.https://doi.org/https://doi.org/10.1016/j.agsy.2024.104081

Saxena, R. K., Hake, A., Hingane, A. J., Kumar, C. S., Bohra, A., Sonnappa, M., ... & Varshney, R. K. (2020). Translational pigeonpea genomics consortium for accelerating genetic gains in pigeonpea (Cajanus cajan L.). *Agronomy*, *10*(9), 1289.https://doi.org/10.3390/AGRONOMY10091289

Siddoway, F. H., & Barnett, A. P. (1976). Water and wind erosion control aspects of multiple cropping. *Multiple cropping*, *27*, 317-335.https://doi.org/10.2134/ASASPECPUB27.C16

Singh, I. P. (2016). Nutritional benefits of pigeonpea. In *Biofortification of food crops* (pp. 73-81). New Delhi: Springer India.https://doi.org/10.1007/978-81-322-2716-8_7

Singh, N., Rai, V., & Singh, N. K. (2020). Multi-omics strategies and prospects to enhance seed quality and nutritional traits in pigeonpea. *The Nucleus*, *63*(3), 249-256.https://doi.org/10.1007/S13237-020-00341-0

Srivalai, T., Pattanasri, S., Jaikla, P., & Smittakorn, S. (2025). Impact of Crop Cover on Soil Erosion. In: Yuan, C. (eds) Proceedings of 6th International Conference on Resources and Environmental Research - ICRER 2024. ICRER 2024. Environmental Science and Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-93295-3_6

Stojšin, D., Matson, K. W., & Leitz, R. A. (2014). Sustainable Agriculture and Soybean Breeding: Contribution of Soybean Yield Increase to Sustainable Agriculture. In: Songstad, D., Hatfield, J., Tomes, D. (eds) Convergence of Food Security, Energy Security and Sustainable Agriculture. Biotechnology in Agriculture and Forestry, vol 67. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-55262-5_9

Te, X., Din, A. M. U., Cui, K., Raza, M. A., Ali, M. F., & Xiao, J. (2023). Inter-specific root interactions and water use efficiency of maize/soybean relay strip intercropping. *Field Crops Research*, *291*, 108793.https://doi.org/10.1016/j.fcr.2022.108793

Tsegaw, M., Wu, T., Xu, M., Naser, M., Xiong, G., Jiang, B., ... & Han, T. (2025). Screening of adaptive cultivars and identification of QTNs associated with flowering time and related traits of diverse soybean cultivars grown in low-latitude, high-altitude regions. *Plant, Cell & Environment*.https://doi.org/10.1111/PCE.15663

Venkatesh, B., Reddy, M. M., Sarada, C., Vijayakumar, S., Kumar, N. V., Yakadri, M., & Padmaja, B. (2025). Integrated agronomic practices and their impact on hybrid pigeonpea productivity. *Plant Science Today, 12*(2). https://doi.org/10.14719/pst.6861

Verdelli, D., Acciaresi, H. A., & Leguizamón, E. S. (2012). Corn and soybeans in a strip intercropping system: crop growth rates, radiation interception, and grain yield components. *International Journal of Agronomy*, *2012*(1), 980284.https://doi.org/10.1155/2012/980284

Wang, R., Sun, Z., Zhang, L., Yang, N., Feng, L., Bai, W., ... & van der Werf, W. (2020). Border-row proportion determines strength of interspecific interactions and crop yields in maize/peanut strip intercropping. *Field Crops Research*, *253*, 107819.https://doi.org/10.1016/J.FCR.2020.107819

Wingeyer, A. B., Amado, T. J., Pérez-Bidegain, M., Studdert, G. A., Perdomo Varela, C. H., Garcia, F. O., & Karlen, D. L. (2015). Soil quality impacts of current South American agricultural practices. *Sustainability*, *7*(2), 2213-2242.https://doi.org/10.3390/su7022213