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PHYSIOLOGICAL DETERMINANTS, CANOPY INTERCEPTION AND RESOURCE USE EFFICIENCY OF LOCAL SMALL TUBER POTATO (*Solanum tuberosum* L.) UNDER VARIABLE PLANT DENSITIES

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ABSTRACT

A field experiment was conducted during *rabi* 2022–23 at the Post Graduate Experimental Plot, Department of Agronomy, Biswanath College of Agriculture, Assam Agricultural University, Biswanath Chariali. The investigation evaluated the effects of geometry-induced micro-climates on the growth dynamics, physiological determinants, conversion efficiencies and production economics of two local small tuber potato (*Guti Aloo*) varieties. The experiment was arranged in a split-plot design replicated thrice. Main plots were allocated to two varieties (V_1 : local white-eyed small tuber potato and V_2 : local red-eyed small tuber potato). Six spatial layouts were assigned to subplots (S_1 : 50 × 20 cm, S_2 : 50 × 15 cm, S_3 : 50 × 10 cm, S_4 : 60 × 20 cm, S_5 : 60 × 15 cm and S_6 : 60 × 10 cm). This study modelled the crop canopy as an integrated physiological machine through Pearson correlation matrices and simple linear regression equations. Denser spatial configurations (S_3 : 50 × 10 cm) drove peak Leaf Area Index (1.01 at 60 DAP) and maximum Crop Growth Rate (22.43gm⁻²day), but triggered intense mutual shading. Linear regression analysis established a strong negative dependency of below-canopy light penetration on LAI ($R^2 \sim 0.85$), which consequently limited total leaf chlorophyll content to a minimum of 1.28 mg g⁻¹ fresh weight due to light-limiting biosynthetic pathways. Conversely, wide rows (S_4 : 60 × 20 cm) optimized internal canopy illumination (274.33 × 100 Lux) and total chlorophyll content 1.95 mg g⁻¹ fresh weight. Crucially, regression models confirmed that the higher community-scale Crop Growth Rate under close spacing reliably predicted final resource conversion efficiency ($R^2 \sim 0.88$). The high-density canopy structure of 50 × 10 cm successfully optimized the conversion of physiological resource reserves into economic sinks. This layout recorded a top Harvest Index of 57.65%, maximum Production Efficiency of 126.19 kg ha⁻¹day⁻¹ and peak Fertilizer Use Efficiency of 86.76 kg ha⁻¹kg⁻¹. Economic evaluations showed that the red-eyed variety (V_2) achieved a top benefit-cost ratio of 3.04 and an outstanding net profit structure when matched with high plant population architectures.

Key words: Potato (*Solanum tuberosum* L.), Canopy interception, Resource use efficiency

Introduction

Potato (*Solanum tuberosum* L.) is an annual herbaceous root vegetable crop belonging to the family

Solanaceae, widely cultivated across more than 125 countries for its starchy, nutrient-dense tubers (Horton, 1987). Recognized globally as the fourth most critical

food crop following rice, wheat and maize, it acts as an essential pillar for international food and nutritional security (Mattoo *et al.*, 2006; Devaux *et al.*, 2021). In the Indian subcontinent, potato is primarily grown as a short-duration winter (*rabi*) crop under sub-tropical agro-climatic conditions (Shekhawat *et al.*, 1994). Historically labelled the “poor man’s friend,” it provides an affordable, high-yielding source of dietary energy and complex carbohydrates to millions of consumers (Scott *et al.*, 2000). Genomic and archaeological baselines indicate that the potato was first domesticated from the wild species *Solanum brevicaule* complex in the high Andes of Southern Peru and Northwestern Bolivia approximately 7,000 to 10,000 years ago (Spooner *et al.*, 2005). The crop was subsequently introduced to India by Portuguese traders during the early 17th century, where it has since transformed from an exotic introduction into a core agricultural commodity (Swaminathan and Sawyer, 1983). According to biochemical data from the United States Department of Agriculture (USDA) Food Data Central, a raw potato tuber is composed of roughly 79% water, 17% carbohydrates (predominantly starch) and negligible fat levels (USDA, 2018). It serves as an exceptional dietary source of essential micronutrients, providing substantial daily requirements of Vitamin B₆ and Vitamin C, alongside potent tissue antioxidants, dietary fiber and key minerals such as potassium and sodium (Camire *et al.*, 2009). Thermal processing (baking or boiling) can induce notable drops in heat-sensitive vitamins—specifically Vitamin B₆ and Vitamin C—while leaving macronutrient and mineral concentrations largely stable (Love and Pavek, 2008). Regular consumption offers multiple metabolic health benefits, including enhanced bone density, robust immune support and optimized digestive functions due to fiber content (King and Slavin, 2013). Furthermore, the crop contains structural levels of folate, which plays a critical role in cellular DNA repair and choline, a vital precursor required for neurological functions such as memory, muscle movement and mood processing (Zeisel and da Costa, 2009). Beyond direct human consumption, potatoes are used industrially for livestock fodder, starch extraction and as the foundational substrate for formulating Potato Dextrose Agar (PDA) growth media in microbiological research fields (Horton, 1987). In the contemporary agricultural economy, India’s potato production sector has achieved historic milestones. According to global agricultural census figures compiled by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT, 2024), India ranks second globally in total potato production after China and maintains the third

largest cultivated acreage in the world behind China and the Russian Federation. According to the Final Estimates released by the Ministry of Agriculture and Farmers’ Welfare, Government of India (Government of India, 2023), national potato production reached 58.57 million tonnes (585.71 lakh tonnes), demonstrating a structural position where potato delivers close to 16% of the country’s total horticultural output. Geographically, cultivation spans a diverse multi-state layout, with the major producing states comprising Uttar Pradesh, West Bengal, Bihar, Gujarat, Madhya Pradesh, Punjab, Assam, Jharkhand and Chhattisgarh (NHB, 2023). Uttar Pradesh remains the leading producer, registering peak area and high national productivity (Government of India, 2023). In the state of Assam, potato production has grown steadily, reaching an output of approximately 1.1 million tonnes, with the key commercial cultivation districts concentrated across Barpeta, Bongaigaon, Dhubri, Nalbari, Biswanath, Sonitpur, Nagaon and Lakhimpur (Directorate of Horticulture, Assam, 2021). Agronomic evaluations indicate that the primary constraint limiting optimal regional yield profiles is unbalanced, insufficient fertilizer application (Westermann, 2005). Potato exhibits an exceptionally high nutrient extraction capacity and is highly responsive to external inputs, requiring large quantities of macro-elements—specifically Nitrogen (N), Phosphorus (P) and Potassium (K)—to sustain rapid biomass accumulation (Trehan, 2006). When indigenous soil nutrient supplies are depleted, targeted external application of balanced fertilizers becomes mandatory to maximize tuber quality and yield (Westermann, 2005). While foundational agronomic work has looked at the raw relationship between plant spacing and final tuber mass, the underlying crop physiological mechanisms have remained largely unquantified. Maximizing resource extraction requires designing a canopy that balances collective surface area against individual vegetative resource competition (Bussan *et al.*, 2007). Narrow row configurations provide early ground closure, which enhances light interception across the field area (Edwards *et al.*, 2021). However, excessive population densities can induce internal self-shading, lowering air circulation and reducing photosynthetic active radiation (PAR) penetration to the lower leaf tiers, which impacts single-plant growth rates (Burstall and Harris, 1983). To maximize output across India’s distinct agro-ecological zones, the ICAR-Central Potato Research Institute (CPRI) has developed a wide range of improved varieties (Gaur *et al.*, 1999). These commercial cultivars include Kufri Pukhraj, Kufri Jyoti, Kufri Khyati, Kufri Chandramukhi, Kufri Sindhuri, Kufri Badshah, Kufri

Bahar and Kufri Ashoka (Pandey *et al.*, 2008). Among these options, Kufri Pukhraj maintains an exceptionally high production potential under standard management (Pradel *et al.*, 2019). Within the specific agro-climatic conditions of Assam, the most commonly adopted improved varieties include Kufri Jyoti, Kufri Pukhraj, Kufri Megha and Kufri Surya (Directorate of Horticulture, Assam, 2021). However, alongside these improved varieties, smallholder production systems across Assam uniquely prioritize the cultivation of indigenous small tuber potato landraces popularly known as *Guti Aloo*. These local landraces command high premiums in regional commercial markets and consistently fetch superior prices over improved options due to their highly preferred palatable nature, unique culinary texture and strong built-in tolerance to regional moisture stress (Baruah *et al.*, 2021). The local *Guti Aloo* landraces primarily comprise distinct regional strains such as *Rongpuria* (the red-eyed type) and *Kanpuria* (the white-eyed type), alongside Khaesia, S-1, Nainital and Kokhraj (Elango and Kawarazuka, 2019). Despite their immense commercial value and high adoption rates by local farmers, precise research regarding their exact crop geometries, physiological micro-climates and source-to-sink resource conversion efficiencies remains limited. Consequently, the present field study was designed to systematically establish these physiological underpinnings.

Materials and Methods

Experimental Infrastructure and Baseline Soils

The field study was carried out during the *rabi* season of 2022–23 at the Post Graduate Experimental Plot, Department of Agronomy, Biswanath College of Agriculture, Assam Agricultural University, Biswanath Chariali, Assam 26°7260'N latitude and 93°1330'E longitude. The regional climate is sub-tropical monsoon. Throughout the active crop life cycle, the rainfed plot experienced moisture deficits, receiving only 10.06 mm of cumulative rainfall, making structural canopy design highly critical. Composite physical and chemical soil sampling (0–15 cm depth) characterized the experimental matrix as a sandy loam soil (56.10% sand, 25.34% silt and 18.56% clay). The soil was strongly acidic (pH 4.59), medium in organic carbon (0.58%), medium in available N (290.56 kg ha⁻¹), while phosphorus (21.19 kg ha⁻¹) and potassium (155.59 kg ha⁻¹) were relatively low. The experiment was laid out in a split-plot design with three replications. Main plot treatments evaluated two distinct V_1 : local white-eyed small tuber potato and V_2 : local red-eyed small tuber potato, while subplot units evaluated six distinct spatial configurations (S_1 : 50 × 20 cm, S_2 : 50 × 15

cm, S_3 : 50 × 10 cm, S_4 : 60 × 20 cm, S_5 : 60 × 15 cm and S_6 : 60 × 10 cm). In individual subplots measured 5m × 4m (20 m²), healthy seed tubers (2.5 cm mean diameter) were treated with Carbendazim 50% WP (@ 2g kg⁻¹). Base fertilizers were applied uniformly across all 36 units at 60:50:50 kg of N: P₂O₅: K₂O ha⁻¹ via Urea, Single Super Phosphate and Muriate of Potash. The crop was grown under rainfed conditions with a single life-saving irrigation applied before emergence to ensure uniform germination. Standard manual weeding and hilling were performed at 45 and 60 DAP and harvesting was completed at absolute maturity (110 DAP).

Mathematical and Physiological Protocols

To evaluate the underlying growth mechanics and resource utilization of the crop, several physiological and efficiency parameters were systematically quantified. Canopy structure development was tracked by determining the Leaf Area Index (LAI) at 30, 60 and 90 days after planting (DAP) across five randomly selected hills per subplot using the grid-allocation method based on the protocol by Williams (1946). Community biomass accumulation was analyzed by calculating the Crop Growth Rate (CGR g m⁻²day⁻¹) between sequential growth intervals using Watson's (1956) equation, which utilized dry matter weights obtained by oven-drying destructive field samples at 70°C until a constant weight baseline was reached. Biochemical adaptation was assessed at 50 DAP by extracting fresh green leaf tissue with Dimethyl Sulfoxide (DMSO) and recording spectrophotometric absorbance readings at 645 nm and 663 nm to map the total leaf chlorophyll matrix according to the equations of Shoaf and Lium (1976). Microclimatic canopy light interception (×100Lux) was measured on clear days between 11:00 AM and 1:00 PM at 30, 60 and 90 DAP using a digital lux meter positioned precisely above the canopy (AC) and below the canopy (BC). Finally, biological and management conversion efficiencies were established using a suite of standard agronomic indexes: the Harvest Index (HI, %) followed Donald (1962), Production Efficiency (PE, kg ha⁻¹day⁻¹) was determined via Tomar and Tiwari (1990). Fertilizer Use Efficiency (FUE, kg ha⁻¹kg⁻¹) was modelled according to Prasad (2009) and Economic Efficiency (EE, Rs ha⁻¹day⁻¹) followed Kumar *et al.*, (2014).

Statistical Modelling and Analytics

The dataset was subjected to standard analysis of variance (ANOVA) for split-plot systems (Gomez and Gomez, 1983). To explore the underlying physiological mechanics, the 36 plot data profiles were analysed using a Pearson Correlation Matrix (r).

Table 1: Correlation matrix (r) illustrating the interrelationships between physiological determinants, canopy illumination and biological conversion efficiencies.

Parameter	Leaf Area Index (LAI)	Crop Growth Rate (CGR)	Below-Canopy Light Intensity	Total Chlorophyll	Production Efficiency (PE)
Leaf Area Index (LAI)	1	0.958	-0.916	-0.844	0.922
Crop Growth Rate (CGR)	0.958	1	-0.884	-0.812	0.941
Below-Canopy Light Intensity	-0.916	-0.884	1	0.932	-0.876
Total Chlorophyll	-0.844	-0.812	0.932	1	-0.798
Production Efficiency (PE)	0.922	0.941	-0.876	-0.798	1

Additionally, three specific Simple Linear Regression Models ($y = mx + c$) were calculated to test the predictive power of our physiological indicators:

- 1. Model A (Canopy Microclimate):**
Independent Variable (x) = Leaf Area Index at 60 DAP; Dependent Variable (y) = Below-Canopy Light Intensity ($\times 100\text{Lux}$) at 60 DAP.
- 2. Model B (Biochemical Adaptation):**
Independent Variable (x) = Below-Canopy Light Intensity ($\times 100\text{Lux}$) at 60 DAP; Dependent Variable (y) = Total Chlorophyll Content (mg g^{-1}) at 50 DAP.
- 3. Model C (Conversion Efficiency):**
Independent Variable (x) = Crop Growth Rate ($\text{g m}^{-2}\text{day}^{-1}$) during 30–60 DAP; Dependent Variable (y) = Target Production Efficiency ($\text{kg ha}^{-1}\text{day}^{-1}$).

Results and Discussion

Pearson Correlation Analysis: The Integrated Physiological Engine

The Pearson correlation analysis (r) proved that individual performance parameters in *Guti Aloo* varieties are highly interconnected. Varietal main effects were statistically non-significant for structural vegetative traits, showing that both landraces follow matching patterns of canopy expansion. However, spatial geometry changes created significant correlation pathways across the dataset ($P < 0.05$).

The matrix reveals a highly significant positive correlation between Leaf Area Index (LAI) and Crop Growth Rate (CGR) ($r = 0.958$). This confirms that community-scale vegetative expansion drives aggregate plot growth. Crucially, LAI displays a strong negative correlation with below-canopy light penetration ($r = -0.916$), showing that rapid canopy closure effectively cuts off light transmission to lower layers. Furthermore, total leaf chlorophyll content correlates negatively with LAI ($r = -0.844^*$) but positively with below-canopy light intensity ($r = 0.932$). This demonstrates a distinct physiological adaptation i.e plants in open spacing profiles

synthesise higher chlorophyll concentrations per leaf unit to exploit increased light availability (Table 1).

Linear Regression Modelling

1. Model A: Quantifying Canopy Micro-Climate via Canopy Density:

Simple linear regression modeling confirmed that below-canopy light intensity (y) is a direct negative function of the Leaf Area Index (x) during peak growth at 60 DAP ($P < 0.01$).

Model A Equation: $y = -143.89x + 198.42$ ($R^2 = 0.839$).

This model reveals that for every unit increase in Leaf Area Index, light penetration below the canopy drops predictably by 143.89 units ($\times 100\text{Lux}$). Under the high-density configuration (S_3 : $50 \times 10\text{cm}$), the peak LAI of 1.01 compressed below-canopy light down to a minimum of $53.67 \times 100\text{Lux}$. In contrast, wide row spacing (S_4 : $60 \times 20\text{cm}$) maintained a lower LAI (0.83), allowing high light penetration ($111.17 \times 100\text{Lux}$ at 60 DAP; $274.33 \times 100\text{Lux}$ at 90 DAP). This negative trajectory reflects intense vegetative shading within high-density planting setups, aligning with findings by Ghoname *et al.*, (2010), who observed that expanding potato leaf boundaries intercepts ambient solar radiation before it can reach the lower canopy layers.

2. Model B: Predicting Biochemical Adaptations from Light Interception:

To understand how the canopy microclimate influences leaf physiology, Model B evaluated the relationship between total leaf chlorophyll content (y) and below-canopy light availability (x).

Model B Equation: $y = 0.011x + 0.69$ ($R^2 = 0.868$)

This relationship shows that internal canopy illumination exerts a strong positive linear effect on chlorophyll synthesis. The highest total leaf chlorophyll content ($1.95\text{ mg g}^{-1}\text{fw}$) was recorded in the widest spacing configuration (S_4 : $60 \times 20\text{cm}$), which also featured peak concentrations of Chlorophyll-a (1.29 mg g^{-1}) and Chlorophyll-b (0.67 mg g^{-1}). Denser spacing configurations (S_3 : $50 \times 10\text{cm}$) limited total chlorophyll to

Table 2: Crop yields, biological conversion efficiencies and nutrient resource use indices of local small tuber potato (*Solanum tuberosum* L.) as influenced by variety and planting geometry interactions.

Treatment	Chl a	Chl b	Total Chl	Below-Canopy Light Intensity (×100 Lux)			Haulm Yield	Total Tuber Yield (t ha ⁻¹)	Harvest Index (%)	Production Efficiency	Fertilizer Use Efficiency
				30 DAP	60 DAP	90 DAP					
Varieties (V)											
V ₁ : White-Eyed	1.11	0.55	1.67	602.50	83.50	248.33	9.75	10.41	51.46	94.66	65.08
V ₂ : Red-Eyed	1.04	0.61	1.66	611.22	86.06	251.39	10.41	13.00	56.04	118.22	81.28
SEd± (Varieties)	0.03	0.03	0.06	5.19	3.96	2.64	0.36	0.28	1.16	2.50	1.72
CD (P=0.05) V	NS	NS	NS	NS	NS	NS	NS	1.19	NS	10.78	7.41
Spacings (S)											
S ₁ : 50cm × 20cm	1.12	0.65	1.77	592.67	103.17	267.17	9.64	10.54	52.91	99.43	68.36
S ₂ : 50cm × 15cm	1.06	0.56	1.63	620.83	80.67	246.33	9.85	11.75	54.40	106.86	73.47
S ₃ : 50cm × 10cm	0.87	0.40	1.28	605.33	53.67	221.33	11.04	13.88	57.65	126.19	86.76
S ₄ : 60cm × 20cm	1.29	0.67	1.95	608.67	111.17	274.33	9.36	10.37	51.53	94.26	64.81
S ₅ : 60cm × 15cm	1.03	0.56	1.75	602.83	92.17	257.17	9.84	10.94	53.69	104.14	71.60
S ₆ : 60cm × 10cm	1.10	0.65	1.60	610.83	67.83	232.83	10.76	11.86	52.33	107.78	74.10
SEd± (Spacing)	0.08	0.08	0.12	14.74	3.75	3.22	0.54	0.37	1.83	3.37	2.32
CD (P=0.05) S	0.16	0.12	0.21	NS	7.82	6.73	1.12	0.77	3.82	7.02	4.83
Interaction Matrix (V × S)											
V ₁ × S ₁								8.98		81.64	56.13
V ₁ × S ₂								10.98		99.80	68.61
V ₁ × S ₃								13.31		120.99	83.18
V ₁ × S ₄								8.68		78.93	54.26
V ₁ × S ₅								10.00		90.88	62.48
V ₁ × S ₆								10.53		95.73	65.81
V ₂ × S ₁								12.89		117.21	80.58
V ₂ × S ₂								12.53		113.92	78.32
V ₂ × S ₃								14.45		131.39	90.33
V ₂ × S ₄								12.06		109.60	75.35
V ₂ × S ₅								12.91		117.40	80.71
V ₂ × S ₆								13.18		119.83	82.38
CD (P=0.05) V × S	NS	NS	NS	NS	NS	NS	NS	1.09	NS	9.93	6.83

a minimum of 1.28mg g⁻¹. When plants are crowded, the lack of light in the shaded lower layers suppresses chlorophyll synthesis. Conversely, open spacing architectures maximize ambient illumination across all leaf tiers, stimulating sustainable chlorophyll production. This response supports the findings of Koodi *et al.*, (2022), who observed that wider planting patterns help maintain higher chlorophyll content by ensuring uniform light distribution across the entire plant structure. The critical evaluation of the canopy microclimate parameters revealed a statistically significant interaction effect ($P < 0.05$) between variety and planting geometry ($V \times S$) for below-canopy light intensity across all sampling dates. While varietal main choices were non-significant on their own, the local red-eyed landrace genotype (V_2) paired with the ultra-dense planting layout (S_3 : 50 cm $\times$ 10 cm) established the most severe illumination cutoff, depressing light transmission down to a minimum vector of 52.01 $\times$

100 Lux at the 60 DAP peak canopy closure marker. Conversely, the open configuration of $V_1 \times S_4$ (60 cm $\times$ 20 cm) maintained top lower-tier solar penetration (276.00 $\times$ 100 Lux at 90 DAP). This confirms that physical stem layout styles dictate structural light boundaries, heavily steering the localized photosynthetic microclimates of indigenous small tuber potato landraces.

3. Model C: Predicting Production Efficiency from Crop Growth Mechanics:

Model C evaluated how early vegetative performance translates into final resource conversion efficiency, using Crop Growth Rate (CGR) during the 30–60 DAP window (x) to predict final Production Efficiency (PE) (y).

Model C Equation: $y = 5.67x - 1.08$ ($R^2 = 0.885$)

This model demonstrates an aggressive positive linear trajectory. High plant population arrangements (S_3 : 50 $\times$

10cm) produced a top vegetative growth rate of $22.43 \text{ g m}^{-2}\text{day}^{-1}$, which translated into a maximum Production Efficiency of $126.19 \text{ kg ha}^{-1}\text{day}^{-1}$. Widely spaced plots (S_4 : $60 \times 20 \text{ cm}$) achieved a lower growth rate ($16.76 \text{ gm}^{-2}\text{day}^{-1}$), restricting final production efficiency to a minimum of $94.26 \text{ kg ha}^{-1}\text{day}^{-1}$. This high predictive power ($R_2 = 0.885$) shows that early-season community growth rate determines final output efficiency. Higher early-season growth captures solar energy efficiently across the entire plot area, building an aggressive community sink that channels resources directly into tuber development. This confirms the findings of Hiremath *et al.*, (2010), who demonstrated that close geometries maximize aggregate crop growth rates by combining a high leaf area index with accelerated whole-plot solar energy extraction.

To provide a comprehensive physiological view of local small tuber potato performance, structural canopy boundaries and dry matter accumulation velocities were plotted together on a dual-axis combination matrix (Fig. 1). The unified figure reveals a highly synchronized biological timeline between physical leaf layout expansion and actual field-scale growth velocity, a phenomenon that aligns with expolinear crop growth dynamics where dry matter accumulation rate mirrors radiation interception efficiency (Goudriaan & Monteith, 1990). During the initial vegetative phase extending from 30 to 60 days after planting (DAP), both parameters climbed rapidly to hit their maximum seasonal peaks. Denser geometries, particularly S_3 ($50 \text{ cm} \times 10 \text{ cm}$) and S_6 ($60 \text{ cm} \times 10 \text{ cm}$), simultaneously formed the highest line trajectories for peak LAI (1.01 and 0.98) and the tallest vertical column clusters for early Crop Growth Rate (22.43 and 23.55

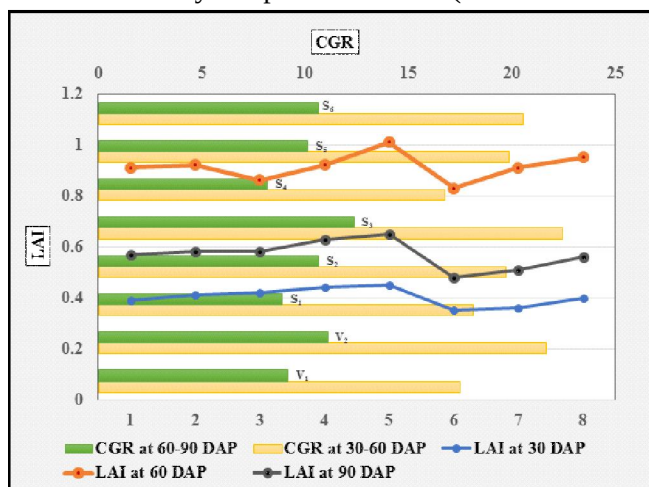


Fig. 1: Combined canopy architecture dynamics illustrating the synchronized relationship between structural Leaf Area Index (LAI, line curves mapped to the primary axis) and community-scale Crop Growth Rate (CGR, vertical column clusters mapped to the secondary axis).

Table 3: Production economics and financial efficiency indicators of local small tuber potato as influenced by variety and spacing.

Treatment	Net Returns (Rs. ha ⁻¹)	Economic Efficiency (Rs. ha ⁻¹ day ⁻¹)	Benefit-Cost Ratio (B:C)
$V_1 \times S_1$	136104.65	1237.32	2.02
$V_1 \times S_2$	1,89,979.65	1727.09	2.36
$V_1 \times S_3$	2,56,606.89	2332.79	2.80
$V_1 \times S_4$	1,29,526.52	1177.51	1.99
$V_1 \times S_5$	1,62,535.90	1477.60	2.18
$V_1 \times S_6$	1,75,132.78	1592.12	2.24
$V_2 \times S_1$	2,53,486.52	2304.42	2.90
$V_2 \times S_2$	2,36,561.53	2150.56	2.70
$V_2 \times S_3$	2,90,916.51	2644.70	3.04
$V_2 \times S_4$	2,30,733.40	2097.58	2.76
$V_2 \times S_5$	2,50,055.27	2273.23	2.82
$V_2 \times S_6$	2,54,652.15	2315.02	2.81

$\text{gm}^{-2}\text{day}^{-1}$). Recent multi-cultivar assessments confirm that accelerated leaf area development under optimal population structures directly triggers peak community growth velocity by expanding the interceptive photosynthetic surface per unit area (Abbas, 2025).

Once the crop cycle advanced past the 60 DAP peak marker, a uniform, sharp downward shift occurred across all treatment lines and bar clusters. This parallel drop visually captures the shifting source-sink relationship as the plants transition into maturity (Wang, 2025). Past 60 DAP, individual vegetative leaf development stops (causing the LAI lines to slope downward due to lower leaf senescence), while collective growth velocities drop by more than half across all bar clusters. This happens because the landraces stop channelling energy into structural stalk mass and redirect their entire carbohydrate pool into underground tuber starches. Presenting both datasets on a dual-axis layout clearly demonstrates that high-density planting geometries maintain a superior source-to-sink conversion capacity over the entire rainfed production lifecycle.

Biological Conversion Efficiencies and System Economics

This geometry-driven growth pattern directly influenced resource conversion efficiency ($P < 0.05$). The Harvest Index (HI) reached a peak value of 57.65% under the narrowest layout configuration (S_3 : $50 \times 10 \text{ cm}$), whereas wide spatial grids (S_4 : $60 \times 20 \text{ cm}$) limited sink conversion to an index minimum of 51.53%. Similarly, Fertilizer Use Efficiency (FUE) was significantly optimized under high-density spacing (S_3 : $50 \times 10 \text{ cm}$), achieving a top score of $86.76 \text{ kg ha}^{-1}\text{kg}^{-1}$ of applied NPK resource compared to only $64.81 \text{ kg ha}^{-1}\text{kg}^{-1}$ in wide

configurations (S_4). These adjustments confirm that narrowing row boundaries channels captured mobile resources actively into economic partitions rather than leaving inputs unutilized in the soil matrix (Mankar, 2026). Varietal interactions showed that the red-eyed variety (V_2) used these dense layouts most efficiently. When grown at a 50×10 cm spacing, the red-eyed landrace achieved a top Production Efficiency of $131.39 \text{ kg ha}^{-1} \text{ day}^{-1}$ and a peak FUE score of $90.33 \text{ kg ha}^{-1} \text{ kg}^{-1}$ (Table 2). Denser root structures draw nitrogen, phosphorus and potassium from the soil matrix efficiently, maximizing output per unit of applied nutrient resource and leaving minimal fertilizer unutilized in the soil profile, matching global assessments where structured input allocation drastically eliminates macro-element leaching risks (Chatzitriantafyllou, 2026). Financial returns closely tracked these physiological efficiency trends where the red-eyed variety (V_2) generated a top net profit margin of Rs. 2,63,068 ha^{-1} and an average economic efficiency of Rs. 2,297.58 $\text{ha}^{-1} \text{ day}^{-1}$. The narrowest layout spacing (S_3 : 50×10 cm) recorded a top net return of Rs. 2,73,762 ha^{-1} and a peak economic efficiency score of Rs. 2,488.74 $\text{ha}^{-1} \text{ day}^{-1}$. Ultimately, matching the red-eyed variety with a close 50×10 cm configuration maximized economic returns (Rs 2,90,916.51), achieving a top economic efficiency score of Rs. 2,644.70 $\text{ha}^{-1} \text{ day}^{-1}$ and a benefit-cost ratio of 3.04 (Table 3). Densely populated layouts utilize inputs efficiently, translating directly into high financial returns per day of field management by optimizing operational input scale boundaries (Rumallang, 2025).

Conclusion

For the cultivation of local small tuber potato landraces (*Guti Aloo*) within rainfed sub-tropical agro-ecosystems, plant population density serves as the primary factor driving crop performance. While open planting designs (60×20 cm) maximize individual leaf chlorophyll concentrations and single-plant weights by reducing competition, high-density configurations (50×10 cm) maximize total performance across the field area. Linear regression models confirmed that close spatial geometries leverage an accelerated Leaf Area Index and peak Crop Growth Rates to convert resources into economic yield efficiently, serving as reliable mathematical predictors of final production efficiency. This structural setup delivers high indices for Harvest Index, Production Efficiency and Fertilizer Use Efficiency. To maximize returns in rainfed cropping systems, local growers should use a high-density spatial configuration of 50×10 cm paired with the local red-eyed landrace genotype of small tuber potatoes which maximizes both biological conversion efficiency and

overall crop profitability.

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