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Variety, plant geometry and NPK nutrition jointly govern growth, green-pod yield, nutritional quality and profitability of French bean (*Phaseolus vulgaris* L.)

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Abstract

French bean (*Phaseolus vulgaris* L.) is a nutritionally dense vegetable legume whose productivity is jointly constrained by genotype, plant geometry and mineral nutrition, yet these three levers are seldom optimised together under Indian semi-arid conditions. Here we quantified the response of French bean to three varieties (Arka Suvidha, Arka Komal and Phule Varun), three plant spacings (45×10 , 45×20 and 45×30 cm) and three NPK levels (140:70:70, 120:60:60 and 100:50:50 kg ha⁻¹) in a split-split-plot design with two replications, over the Rabi seasons of 2023-24 and 2024-25 at Parbhani, Maharashtra, India. Arka Suvidha was superior for every trait examined, combining the highest green-pod yield (117.0 q ha⁻¹), the highest pod protein (26.8%) and the highest benefit-cost ratio (2.44). Plant geometry, by contrast, separated performance at the two scales of organisation. The widest spacing (45×30 cm) maximised branching, leaf area, dry matter, pod number, pod size and pod quality per plant, yet returned the lowest yield per hectare (103.6 q ha⁻¹); the closest spacing (45×10 cm), whose plants were taller but sparsely branched and bore fewer and smaller pods, gave the highest yield per hectare (114.8 q ha⁻¹) because its roughly threefold greater plant population outweighed its poorer individual plants. Nutrition acted without such a conflict: 140:70:70 kg NPK ha⁻¹ maximised growth, yield (119.1 q ha⁻¹), protein (27.4%) and mineral content while lowering crude fibre, at the cost of delaying 50% flowering by 2.6 d and maturity by 4.4 d. Soil reaction and salinity were stable and available N, P and K declined by only 3-7%, the largest residual pools remaining under the highest fertiliser dose. Profitability tracked yield per hectare, so the highest net return and benefit-cost ratio were obtained with Arka Suvidha, 45×10 cm spacing and 140:70:70 kg NPK ha⁻¹. This combination is recommended where marketable yield and monetary return are the objective, and 45×30 cm where large, tender, premium-grade pods command a price advantage. The two-replication, single-location design is acknowledged as a limitation warranting multi-location confirmation.

Keywords: French bean, *Phaseolus vulgaris*, plant density, NPK fertilisation, green-pod yield, pod quality, benefit-cost ratio

Introduction

French bean (*Phaseolus vulgaris* L., $2n = 2x = 22$) is the most widely cultivated food legume for direct human consumption worldwide and is grown both as a dry pulse and as a fresh green vegetable. Domesticated in the Americas and subsequently diversified across two major gene pools, it is now a staple component of cropping systems across Latin America, Africa and South Asia (Gepts, 1998; Blair *et al.*, 2010; Broughton *et al.*, 2003) [15, 7, 3]. As a vegetable, the immature green pods are valued for their tender texture and for their contribution of protein, fibre, minerals and vitamins to predominantly cereal-based diets, while the capacity of the crop for symbiotic nitrogen fixation supports the sustainability of the systems in which it is grown (Graham & Ranalli, 1997; Hardarson & Atkins, 2003) [17, 19]. Green pods are a particularly valuable dietary source of protein and micronutrients in cereal-dominated diets (Celmeli *et al.*, 2018; Petry *et al.*, 2015) [10, 28], and pod protein and mineral concentrations vary widely among genotypes (Guzmán-Maldonado *et al.*, 2000) [18], a variation that is partly under identifiable genetic control (Blair *et al.*, 2011) [6].

In India, French bean is an important cool-season vegetable of the Rabi and spring seasons, and demand for fresh green pods continues to rise with urbanisation and growing awareness of plant-based nutrition. Productivity at the farm level nevertheless remains well below the genetic potential of the crop, largely because the three most tractable management levers—choice of variety, plant geometry and mineral nutrition—are rarely optimised in combination for a given agro-ecology. Genotypes differ markedly in canopy architecture, phenology, pod characteristics and nutrient responsiveness, so that the ranking of varieties is strongly environment dependent (Beebe *et al.*, 2013; Miklas *et al.*, 2006; Graham & Ranalli, 1997) [4, 24, 17]. Indian evaluations of released French bean cultivars have repeatedly shown large genotypic differences in growth, phenology and pod yield under local conditions (Bharti *et al.*, 2024; Sharma *et al.*, 2013) [5, 31]. Establishing which released varieties perform best under local semi-arid subtropical conditions is therefore a prerequisite for any production recommendation, and multi-trait evaluation remains central to bean improvement (Broughton *et al.*, 2003; Checa & Blair, 2012) [9, 11], particularly because pod quality and pod yield are themselves quantitatively inherited and partly co-localised in the genome (Njau *et al.*, 2024) [25].

Plant geometry governs the capture of light, water and nutrients and sets the balance between growth of the individual plant and productivity of the crop community. Narrow spacing raises plant population and can increase yield per unit area, but it intensifies inter-plant competition, encourages etiolation and may reduce the size and quality of individual pods; wider spacing favours branching, canopy expansion and pod development per plant, but at a lower population (Board & Harville, 1994; Egli, 1988; Loomis & Williams, 1963) [8, 13, 22]. In common bean specifically, changes in population are buffered by compensation among yield components, so that pods per plant, seeds per pod and seed mass adjust in opposing directions as density changes (Adams, 1967; Duarte & Adams, 1972; Westermann & Crothers, 1977; Sundar & Lal, 2022) [1, 12, 34, 33]. Because green pods are marketed both by weight and, increasingly, by grade, the net effect on the value of the crop depends on how the resulting yield and quality responses are weighted, and must be resolved empirically for each variety and environment.

Mineral nutrition, and in particular the supply of nitrogen, phosphorus and potassium, is the third decisive lever. Nitrogen drives vegetative growth and leaf-area development, phosphorus underpins root development, energy metabolism and pod set, and potassium regulates water relations, assimilate translocation and pod filling; together they influence not only yield but also the protein, mineral and fibre composition of the pods (Marschner, 2012; Fageria *et al.*, 2011; Guzmán-Maldonado *et al.*, 2000) [18, 14, 18]. Because French bean fixes only part of its nitrogen requirement and is frequently grown on soils of moderate fertility, judicious external NPK supply is essential, yet excessive or poorly balanced fertilisation can delay maturity, depress quality and erode profitability (Marschner, 2012; Sharma *et al.*, 2013) [23, 31]. Defining the NPK level that maximises yield and quality without compromising earliness or economics is therefore of direct practical value. Although the individual effects of variety, spacing and fertilisation on French bean have each been examined, integrated multi-factor studies that resolve their combined

effects on growth, green-pod yield, nutritional quality and profitability under Indian semi-arid Rabi conditions remain limited (Sharma *et al.*, 2013; Sabale *et al.*, 2024) [31, 30]. In this study we evaluated three French bean varieties under three plant spacings and three NPK levels over two consecutive Rabi seasons, with the objectives of (i) characterising the growth, yield and quality response of the three varieties; (ii) determining the optimum plant spacing and NPK level; (iii) describing the trade-offs among yield, earliness and quality; and (iv) identifying the most productive and profitable agronomic package for the region.

Materials and Methods

Experimental site and season

The field experiment was carried out during the Rabi (post-monsoon winter) seasons of 2023-24 and 2024-25 at the experimental farm of the Department of Horticulture, Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani, Maharashtra, India. The site lies in the semi-arid subtropical zone of the Marathwada region, which is characterised by hot dry summers and mild winters suited to cool-season vegetable legumes. The soil of the experimental field was a well-drained clayey Vertisol, slightly alkaline in reaction, medium in available nitrogen, low in available phosphorus and high in available potassium (Table 5).

Treatments and experimental design

Twenty-seven treatment combinations were generated from three factors, each at three levels. The three varieties were V₁ (Arka Suvidha), V₂ (Arka Komal) and V₃ (Phule Varun); the three plant spacings were S₁ (45 × 10 cm), S₂ (45 × 20 cm) and S₃ (45 × 30 cm), equivalent to calculated plant populations of about 2.22, 1.11 and 0.74 lakh plants ha⁻¹, respectively; and the three nutrient levels were F₁ (140:70:70), F₂ (120:60:60) and F₃ (100:50:50 kg N:P₂O₅:K₂O ha⁻¹), bracketing the range shown to be responsive in comparable Indian trials (Sharma *et al.*, 2013; Sabale *et al.*, 2024) [31, 30]. The experiment was laid out in a split-split-plot design with two replications, with variety assigned to main plots, spacing to sub-plots and nutrient level to sub-sub-plots. Gross and net plot sizes were 3.60 × 2.70 m² and 3.00 × 1.80 m², respectively.

Crop establishment and management

The field was prepared to a fine tilth and laid out into plots according to the design. Seeds of each variety were dibbled at the assigned spacing at a uniform depth to ensure even establishment. The full dose of phosphorus and potassium and half of the nitrogen were applied basally at sowing, and the remaining nitrogen was top-dressed at the active vegetative stage, the quantities differing by nutrient treatment. Recommended cultural operations, comprising gap filling, weeding, earthing up, need-based irrigation and plant-protection measures, were carried out uniformly across all plots. Green pods were harvested at the marketable, tender stage in successive pickings, and observations were recorded on five randomly tagged plants per net plot.

Growth, phenology and yield observations

Growth attributes, comprising plant height (cm), number of functional leaves per plant, number of branches per plant, leaf area per plant (cm²) and dry-matter accumulation per plant (g), were recorded at 30, 45 and 60 days after sowing

(DAS) and at final harvest. Leaf area was measured as the total assimilatory area per plant and is reported as such rather than as a dimensionless leaf-area index, because the two are not interchangeable when plant population differs among treatments (Loomis & Williams, 1963) [22]. Phenological events were recorded as the number of days to 50% flowering and the number of days to first marketable maturity. Yield-attributing characters comprised the number of flowers per plant (recorded at 30, 45 and 60 DAS), number of green pods per plant, weight of green pods per plant (g), pod length (cm), pod diameter (cm), number of seeds per pod and weight of 100 seeds (g). Marketable green-pod yield was recorded on a net-plot basis and expressed in quintals per hectare (q ha^{-1}).

Pod quality analysis

Representative green-pod samples from each treatment were analysed for nutritional quality following standard procedures (AOAC, 2019). Crude protein content (%) was estimated from total nitrogen determined by the micro-Kjeldahl method, using a nitrogen-to-protein conversion factor of 6.25; crude fibre (%) was determined by the acid-alkali digestion method; and total ash (%), representing the mineral fraction, was determined by dry ashing in a muffle furnace.

Soil sampling and analysis

Composite soil samples (0-15 cm) were drawn before sowing and after harvest and analysed for reaction and available nutrients. Soil pH and electrical conductivity were measured in 1:2.5 and 1:5 soil-water suspensions, respectively; available nitrogen by the alkaline potassium permanganate method (Subbiah & Asija, 1956) [32]; available phosphorus by the sodium bicarbonate extraction method (Olsen *et al.*, 1954) [26]; and available potassium by neutral normal ammonium acetate extraction followed by flame photometry (Jackson, 1973) [20].

Economic analysis

The economics of each treatment were worked out from prevailing input costs and the market price of green pods, taken as ₹ 3000 q^{-1} . Cost of cultivation was computed on a per-hectare basis from the cost of seed, fertiliser, labour, irrigation and plant protection; gross income was obtained as marketable yield multiplied by price, net income as gross income less cost of cultivation, and the benefit-cost (B:C) ratio as the quotient of gross income and total cost of cultivation.

Statistical analysis

Data were subjected to analysis of variance appropriate to the split-split-plot design (Panse & Sukhatme, 1985; Gomez & Gomez, 1984) [27, 16]. Treatment effects were tested by the F-test, and the standard error of the mean ($\text{SEm} \pm$) and the critical difference (CD) at $p \leq 0.05$ were computed for the comparison of means; where the F-test was non-significant, differences are reported as non-significant. Because the experiment comprised two replications, the residual degrees of freedom were correspondingly limited; results are reported faithfully on this basis and the design is acknowledged as a study limitation. Treatment effects were resolved at the level of main effects, and two-year pooled means are presented and discussed unless otherwise stated.

Results

Variety, plant spacing and nutrient level each exerted significant main effects on all growth, phenological, yield, quality and economic traits at every stage of observation. Results are presented as two-year pooled main-effect means, with season-wise means additionally reported for green-pod yield; treatment means are compared throughout against the critical difference (CD) at $p \leq 0.05$. Complete stage-wise data for every character are provided in the accompanying data workbook (Supplementary Tables S1-S20).

Growth attributes

Table 1: Growth attributes of French bean at harvest as influenced by variety, plant spacing and NPK level (pooled over 2023-24 and 2024-25).

Treatment	Plant height (cm)	Leaves plant ⁻¹	Branches plant ⁻¹	Leaf area plant ⁻¹ (cm ²)	Dry weight plant ⁻¹ (g)
Varieties (main plots)					
Arka Suvidha	68.4	34.1	9.9	1226	45.7
Arka Komal	66.0	32.5	9.3	1176	44.3
Phule Varun	63.5	31.1	8.7	1153	43.2
SEm $\pm$	0.52	0.48	0.21	11.0	0.36
CD ($p \leq 0.05$)	1.52	1.39	0.58	29.9	1.03
Plant spacing (sub-plots)					
45 × 10 cm	69.9	31.9	8.5	1168	43.5
45 × 20 cm	66.8	33.5	9.5	1181	44.5
45 × 30 cm	64.4	34.9	10.3	1222	45.6
SEm $\pm$	0.46	0.44	0.20	10.5	0.34
CD ($p \leq 0.05$)	1.42	1.25	0.54	27.4	0.96
NPK level, kg ha⁻¹ (sub-sub-plots)					
140:70:70	70.5	36.2	10.5	1245	46.6
120:60:60	66.8	33.2	9.6	1192	44.4
100:50:50	63.3	30.8	8.6	1145	43.1
SEm $\pm$	0.48	0.46	0.21	10.9	0.35
CD ($p \leq 0.05$)	1.47	1.33	0.56	28.7	0.99

Values are two-year pooled means. SEm $\pm$, standard error of the mean; CD, critical difference at $p \leq 0.05$. Stage-wise means at 30, 45 and 60 days after sowing are given in Supplementary Tables S1-S5.

Plant height increased progressively from 30 days after sowing (DAS) to harvest under every treatment (Fig. 1), following the sigmoidal pattern typical of determinate bean cultivars (Robitaille, 1978) ^[29]. At harvest, Arka Suvidha was the tallest variety (68.4 cm), exceeding Arka Komal (66.0 cm) and Phule Varun (63.5 cm) by margins greater

than the critical difference (CD = 1.52 cm). Height responded inversely to plant spacing: the closest spacing produced the tallest plants (69.9 cm) and the widest the shortest (64.4 cm). Height rose with fertility, from 63.3 cm at 100:50:50 to 70.5 cm at 140:70:70 kg NPK ha⁻¹ (Table 1).

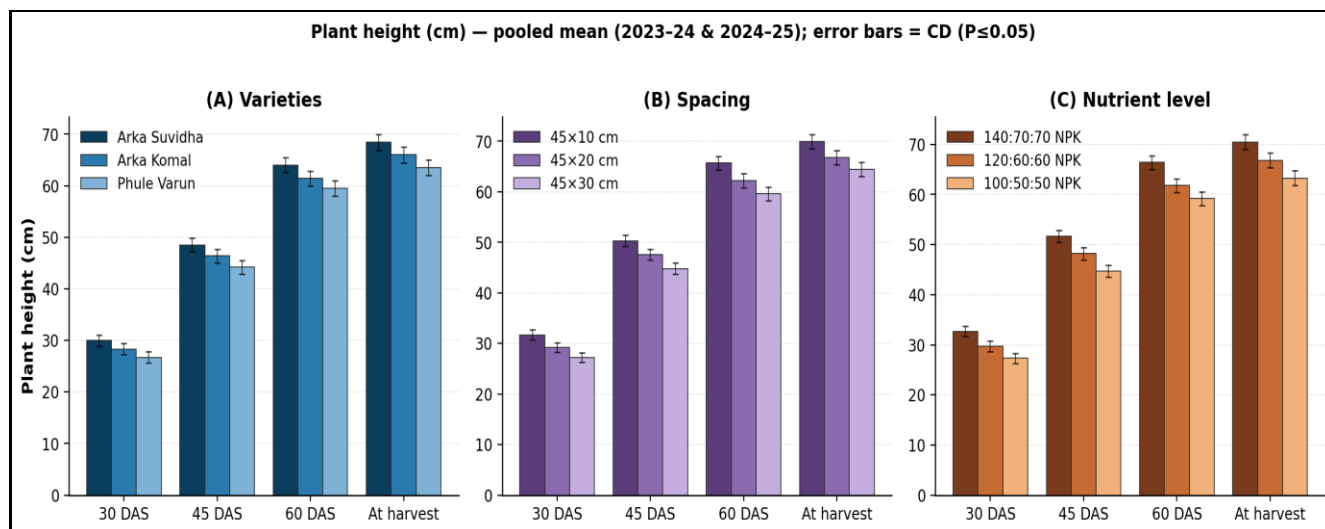


Fig 1: Plant height of French bean across crop age. Plant height at 30, 45 and 60 days after sowing (DAS) and at harvest as influenced by (A) variety, (B) plant spacing and (C) nutrient level. Bars are two-year pooled means; error bars on the at-harvest means denote the critical difference (CD) at $p \leq 0.05$.

Every other growth attribute responded to spacing in the direction opposite to height. Leaf number, branch number, leaf area and dry-matter accumulation per plant were all greatest at the widest spacing and least at the closest: at harvest the 45 × 30 cm treatment carried 34.9 leaves and 10.3 branches plant⁻¹, with 1222 cm² of leaf area and 45.6 g

of dry matter, against 31.9 leaves, 8.5 branches, 1168 cm² and 43.5 g at 45 × 10 cm (Table 1; Figs 2 and 3). Plants that were simultaneously taller, less branched and lighter under dense stands are the signature of a shade-avoidance response to competition for light rather than of superior growth (Kretschmer *et al.*, 1977; Yang & Li, 2017) ^[21, 35].

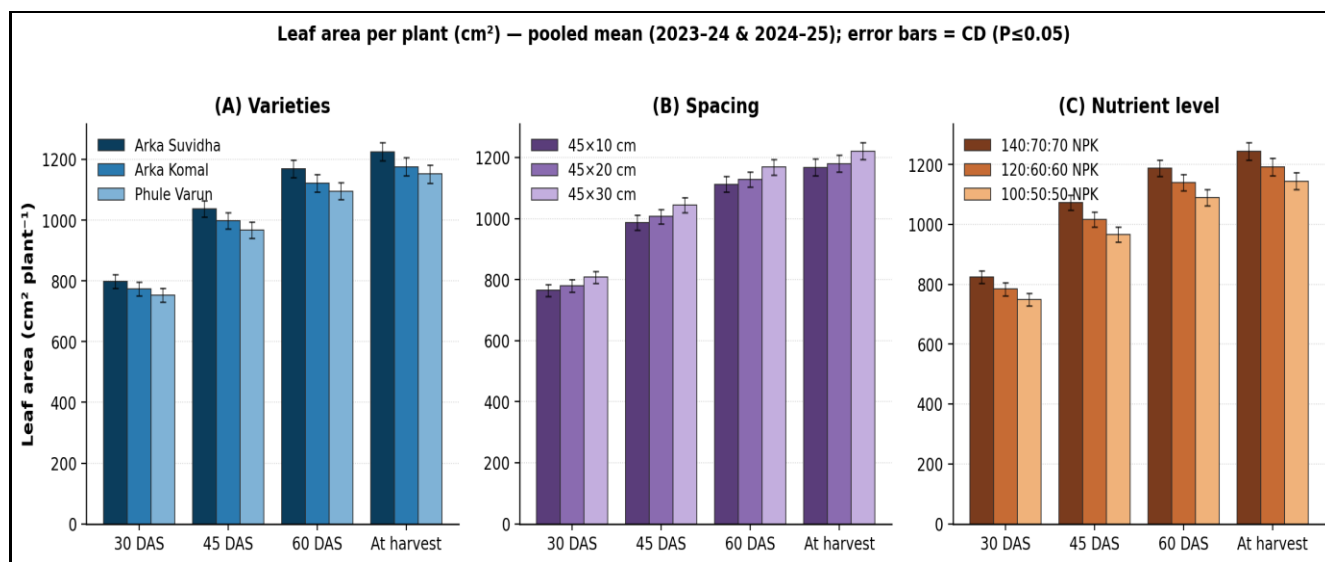


Fig 2: Leaf area per plant of French bean across crop age. Leaf area per plant as influenced by (A) variety, (B) plant spacing and (C) nutrient level. Error bars on the at-harvest means denote CD ($p \leq 0.05$).

Variety and nutrition, in contrast, acted consistently across all five growth attributes. Arka Suvidha ranked first for each, recording 34.1 leaves, 9.9 branches, 1226 cm² of leaf area and 45.7 g of dry matter plant⁻¹ at harvest, and every attribute increased with fertility, the 140:70:70 treatment giving 36.2 leaves, 10.5 branches, 1245 cm² and 46.6 g plant⁻¹ against 30.8, 8.6, 1145 cm² and 43.1 g at 100:50:50

kg NPK ha⁻¹ (Table 1). Dry weight per plant rose steeply after 45 DAS under all treatments, indicating that the period of most rapid biomass gain coincided with canopy expansion and the onset of reproductive growth (Fig. 3), in agreement with the dry-matter accumulation patterns described for the crop by Robitaille (1978) ^[29].

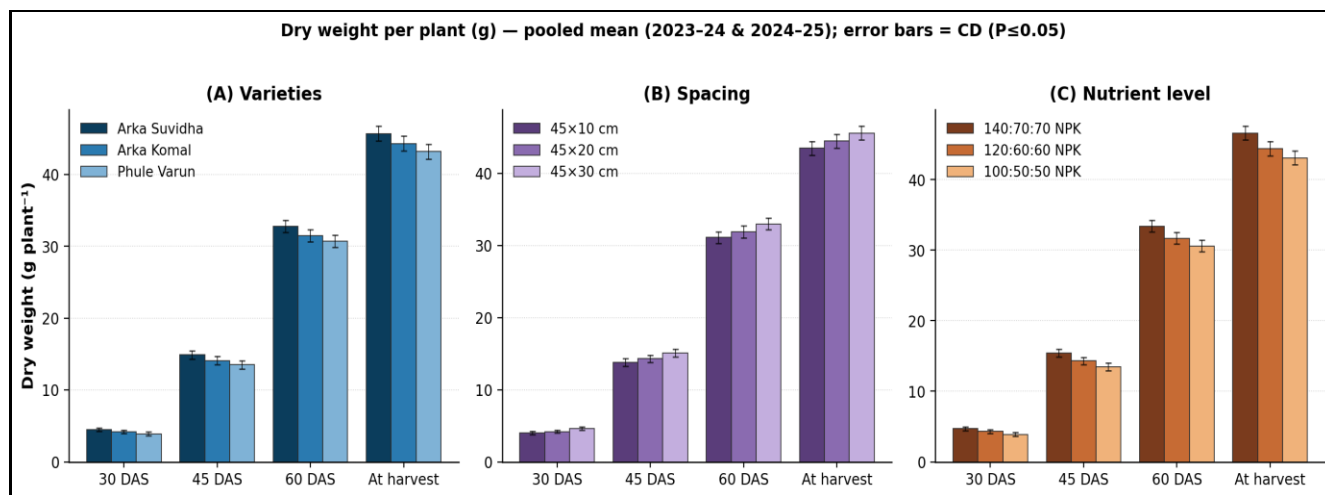


Fig 3: Dry-matter accumulation per plant of French bean across crop age. Dry weight per plant as influenced by (A) variety, (B) plant spacing and (C) nutrient level. Error bars on the at-harvest means denote CD ($p \leq 0.05$).

Phenology

Both phenological events responded significantly to all three factors, and in every case flowering and maturity moved together (Table 2, Fig. 4). Arka Suvidha was the earliest variety, reaching 50% flowering in 43.5 d and maturity in 78.9 d, against 45.6 d and 81.7 d in Phule Varun. Closely spaced plants were the earliest of the spacing treatments, flowering in 43.4 d and maturing in 78.7 d, whereas the widest spacing delayed both events to 45.4 d and 81.6 d. Increasing fertility likewise delayed development: 50% flowering was postponed from 43.2 d at 100:50:50 to 45.8 d

at 140:70:70 kg NPK ha^{-1} , and maturity from 78.1 to 82.5 d. The interval between 50% flowering and maturity nevertheless remained close to 35 d in every treatment (34.9-36.7 d), indicating that treatments shifted the timing of the reproductive transition rather than the duration of pod development itself. Phenology was thus the one respect in which both the widest spacing and the highest nutrient dose were unfavourable. A delay in flowering of comparable magnitude under raised fertility has been reported previously in French bean (Sharma *et al.*, 2013)^[31].

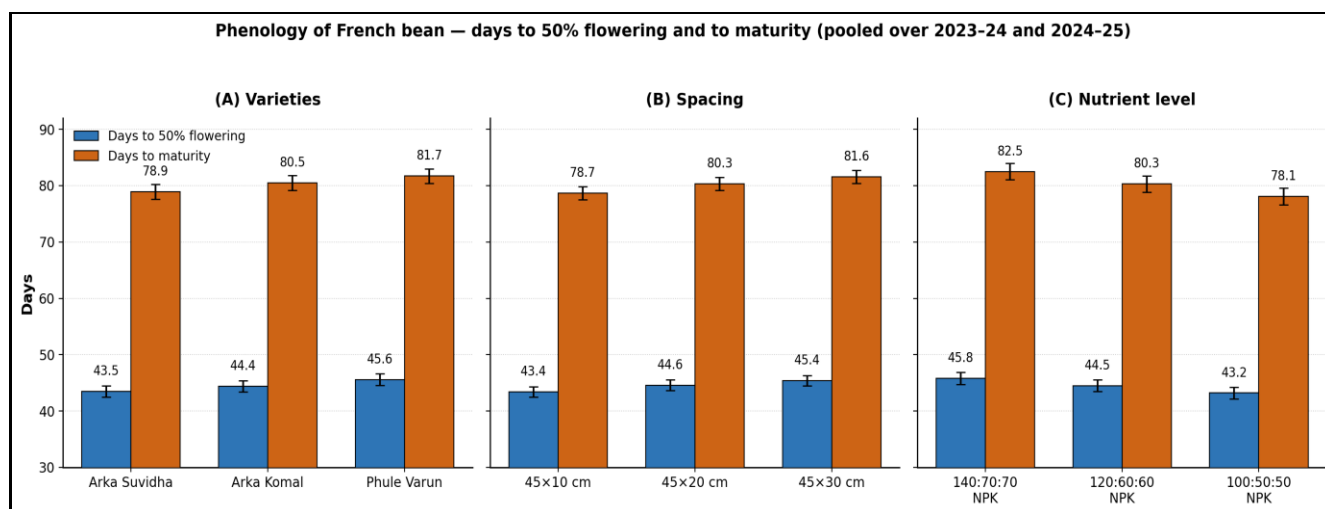


Fig 4: Phenology of French bean. Days to 50% flowering and days to maturity as influenced by (A) variety, (B) plant spacing and (C) nutrient level (two-year pooled means). Error bars denote CD ($p \leq 0.05$).

Yield-attributing characters

Table 2: Phenology and yield-attributing characters of French bean as influenced by variety, plant spacing and NPK level (pooled over two years).

Treatment	Days to 50% flowering	Days to maturity	Flowers plant ⁻¹ (60 DAS)	Pods plant ⁻¹	Pod weight plant ⁻¹ (g)	Seeds pod ⁻¹	100-seed weight (g)	Pod length (cm)	Pod diameter (cm)
Varieties (main plots)									
Arka Suvidha	43.5	78.9	38.7	28.1	261.9	7.0	32.7	14.4	0.98
Arka Komal	44.4	80.5	35.6	26.5	248.9	6.5	31.0	13.7	0.90
Phule Varun	45.6	81.7	34.4	25.2	235.1	6.0	29.8	12.9	0.84
SEm±	0.33	0.43	0.28	0.55	3.36	0.10	0.43	0.12	0.02
CD ($p \leq 0.05$)	1.01	1.31	0.83	1.65	9.7	0.31	1.24	0.35	0.04
Plant spacing (sub-plots)									
45 × 10 cm	43.4	78.7	34.4	25.3	236.1	6.1	30.4	13.2	0.85
45 × 20 cm	44.6	80.3	36.2	27.1	248.8	6.5	31.7	13.7	0.92
45 × 30 cm	45.4	81.6	37.8	28.3	261.0	6.9	32.4	14.4	1.03
SEm±	0.31	0.37	0.28	0.47	2.78	0.09	0.37	0.11	0.01
CD ($p \leq 0.05$)	0.92	1.15	0.83	1.40	8.0	0.27	1.07	0.31	0.03
NPK level, kg ha⁻¹ (sub-sub-plots)									
140:70:70	45.8	82.5	38.8	28.6	267.7	7.2	33.1	14.8	1.08
120:60:60	44.5	80.3	36.6	26.6	249.3	6.6	31.3	13.9	0.97
100:50:50	43.2	78.1	34.1	25.1	229.1	6.1	29.9	13.0	0.86
SEm±	0.36	0.50	0.28	0.51	3.10	0.09	0.39	0.11	0.02
CD ($p \leq 0.05$)	1.05	1.46	0.83	1.52	9.3	0.28	1.13	0.33	0.04

Values are two-year pooled means. SEm±, standard error of the mean; CD, critical difference at $p \leq 0.05$. Flower counts at 30 and 45 DAS are given in Supplementary Table S8.

Every yield component measured on an individual-plant basis responded in the same direction to each of the three factors (Table 2, Fig. 5). Flower number at 60 DAS was greatest in Arka Suvidha (38.7 plant⁻¹), at the widest spacing (37.8) and at the highest NPK level (38.8), and this ranking carried through to pod set: green pods per plant reached 28.1 in Arka Suvidha, 28.3 at 45 × 30 cm and 28.6 at 140:70:70 kg NPK ha⁻¹, against 25.2, 25.3 and 25.1 respectively in the corresponding poorest treatments. The weight of green pods per plant, which integrates pod number with pod size, followed the same pattern, rising from 229.1 g at the lowest

NPK dose to 267.7 g at the highest and from 236.1 g at 45 × 10 cm to 261.0 g at 45 × 30 cm.

Pod length, pod diameter, seeds per pod and 100-seed weight were likewise maximal in Arka Suvidha, at the widest spacing and at the highest nutrient level; the widest spacing produced pods 14.4 cm long and 1.03 cm in diameter against 13.2 cm and 0.85 cm at the closest spacing (Table 2). Individual-plant productivity was therefore highest under precisely the geometry that carried the fewest plants per unit area, the pattern of component compensation described for the crop by Adams (1967)^[1] and Westermann & Crothers (1977)^[34].

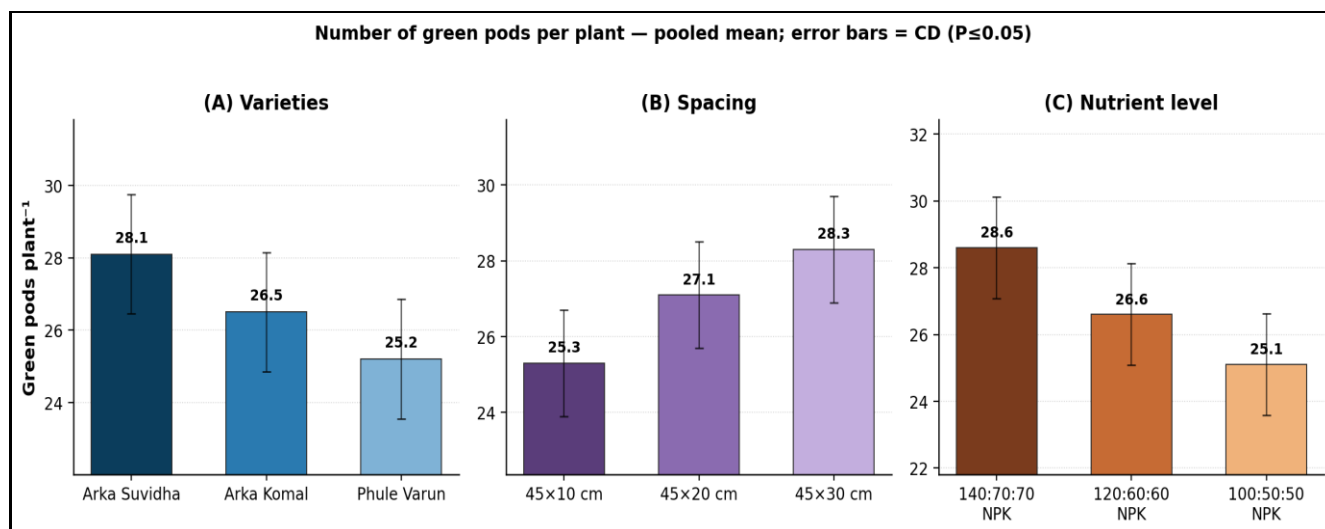


Fig 5: Number of green pods per plant of French bean. Green pods per plant as influenced by (A) variety, (B) plant spacing and (C) nutrient level (two-year pooled means). Error bars denote CD ($p \leq 0.05$).

Green-pod yield

Table 3: Green-pod yield (q ha⁻¹) of French bean as influenced by variety, plant spacing and NPK level in 2023-24, 2024-25 and pooled over years.

Treatment	2023-24	2024-25	Pooled
Varieties (main plots)			
Arka Suvidha	115.7	118.3	117.0
Arka Komal	108.9	110.5	109.7
Phule Varun	101.5	103.1	102.3
SEm±	1.82	1.67	1.58
CD ($p \leq 0.05$)	5.32	4.86	4.59
Plant spacing (sub-plots)			
45 × 10 cm	113.6	115.9	114.8
45 × 20 cm	109.8	111.2	110.5
45 × 30 cm	102.7	104.5	103.6
SEm±	1.55	1.47	1.39
CD ($p \leq 0.05$)	4.56	4.31	4.08
NPK level, kg ha⁻¹ (sub-sub-plots)			
140:70:70	117.8	120.4	119.1
120:60:60	109.9	111.5	110.7
100:50:50	98.8	100.9	99.9
SEm±	1.68	1.59	1.48
CD ($p \leq 0.05$)	4.91	4.78	4.44

SEm±, standard error of the mean; CD, critical difference at $p \leq 0.05$.

Marketable green-pod yield responded significantly to all three factors, and the ranking of treatments was identical in both seasons, yields being marginally higher in 2024-25 than in 2023-24 (Table 3, Fig. 6). Among varieties, Arka Suvidha recorded the highest pooled yield (117.0 q ha⁻¹), exceeding Arka Komal (109.7 q ha⁻¹) by 6.7% and Phule Varun (102.3 q ha⁻¹) by 14.4%. Yield rose steeply with fertility, the 140:70:70 treatment giving the greatest yield of any main-effect level (119.1 q ha⁻¹), 19.2% above the 99.9 q ha⁻¹ recorded at 100:50:50 kg NPK ha⁻¹. The spacing response ran counter to that of every per-plant attribute. The closest spacing of 45 × 10 cm gave the highest yield per hectare (114.8 q ha⁻¹) and the widest spacing the lowest (103.6 q ha⁻¹), a difference of 10.8% against a critical difference of 4.08 q ha⁻¹. Although plants at 45 × 10 cm bore fewer and smaller pods and accumulated less dry matter than those at 45 × 30 cm (Tables 1 and 2), the approximately threefold greater plant population at the closest spacing (2.22 against 0.74 lakh plants ha⁻¹) more than compensated for their lower individual productivity (Adams, 1967; Westermann & Crothers, 1977; Sundar & Lal, 2022) [1, 34, 33]. Taken together, the main-effect data identify Arka Suvidha grown at 45 × 10 cm with 140:70:70 kg NPK ha⁻¹ as the highest-yielding package of those tested.

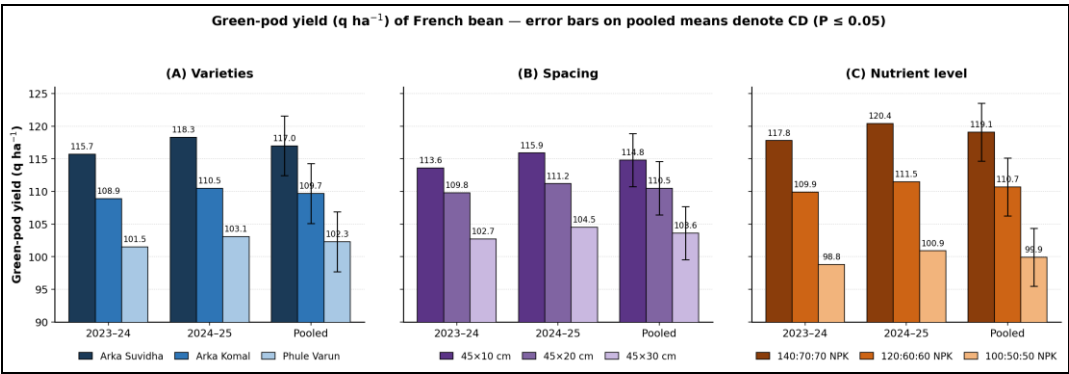


Fig 6: Green-pod yield of French bean. Yield (q ha⁻¹) in 2023-24, 2024-25 and pooled over years as influenced by (A) variety, (B) plant spacing and (C) nutrient level. Error bars on the pooled means denote CD ($p \leq 0.05$).

Pod nutritional quality

Table 4: Nutritional quality of French bean green pods as influenced by variety, plant spacing and NPK level (pooled over two years).

Treatment	Crude protein (%)	Crude fibre (%)	Total ash (%)
Varieties (main plots)			
Arka Suvidha	26.8	5.8	8.4
Arka Komal	25.2	6.2	7.9
Phule Varun	24.1	6.5	7.5
SEm±	0.35	0.18	0.22
CD ($p \leq 0.05$)	1.03	0.52	0.65
Plant spacing (sub-plots)			
45 × 10 cm	24.9	6.4	7.6
45 × 20 cm	25.6	6.1	7.9
45 × 30 cm	26.2	5.9	8.2
SEm±	0.31	0.16	0.20
CD ($p \leq 0.05$)	0.91	0.48	0.59
NPK level, kg ha⁻¹ (sub-sub-plots)			
140:70:70	27.4	5.6	8.6
120:60:60	25.6	6.1	7.9
100:50:50	24.2	6.6	7.4
SEm±	0.33	0.17	0.21
CD ($p \leq 0.05$)	0.98	0.51	0.63

Values are two-year pooled means. SEm±, standard error of the mean; CD, critical difference at $p \leq 0.05$. Higher protein and ash, and lower crude fibre, indicate superior pod quality.

Pod quality responded to variety and nutrition in the same direction as yield, but to spacing in the direction opposite to yield per hectare (Table 4, Fig. 7). Crude protein was highest in Arka Suvidha (26.8%) and rose with fertility from 24.2% at 100:50:50 to 27.4% at 140:70:70 kg NPK ha⁻¹. Total ash, an index of mineral richness, followed the same ranking, increasing from 7.4% to 8.6% across the nutrient range. Crude fibre, for which lower values denote greater tenderness, fell from 6.6% at the lowest NPK dose to 5.6%

at the highest and was lowest in Arka Suvidha (5.8%). Across spacings, however, the widest treatment produced the most protein (26.2%), the most ash (8.2%) and the least fibre (5.9%), against 24.9%, 7.6% and 6.4% respectively at the closest spacing. The geometry that maximised yield per hectare therefore produced the least tender and least nutritionally concentrated pods, a divergence consistent with the co-localisation of pod-quality and pod-yield determinants reported by Njau *et al.* (2024) [25].

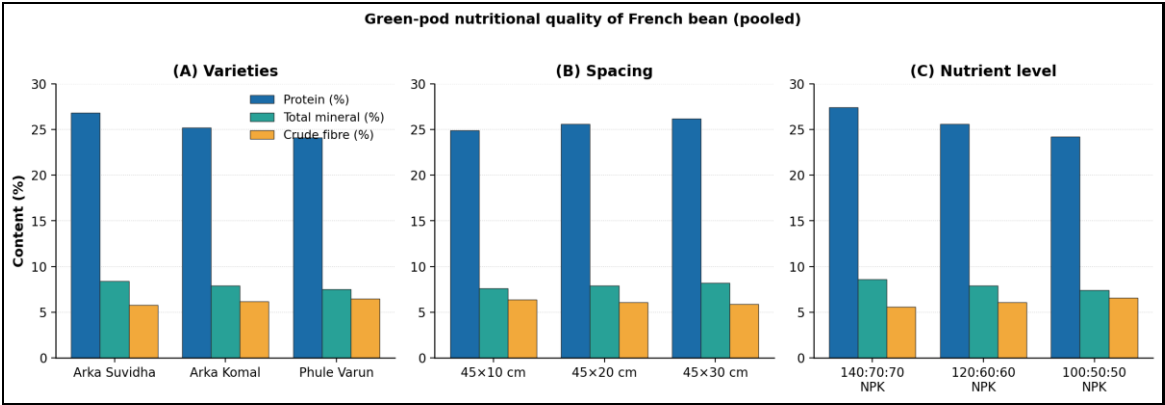


Fig 7: Nutritional quality of French bean green pods. Crude protein, total ash and crude fibre as influenced by (A) variety, (B) plant spacing and (C) nutrient level (two-year pooled means).

Soil reaction and available nutrients

Table 5: Soil reaction, electrical conductivity and available N, P and K before sowing and after harvest under three varieties, three plant spacings and three NPK levels (pooled over two years).

Treatment	Stage	pH (1:2.5)	EC (dS m ⁻¹)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
Varieties (main plots)						
Arka Suvidha	Initial	7.8	0.72	65	7.1	430
	Post-harvest	7.8	0.72	60	6.8	415
Arka Komal	Initial	7.8	0.71	62	6.9	420
	Post-harvest	7.8	0.71	57	6.6	405
Phule Varun	Initial	7.8	0.70	60	6.5	415
	Post-harvest	7.8	0.70	55	6.2	400
Plant spacing (sub-plots)						
45 × 10 cm	Initial	7.8	0.68	63	6.8	428
	Post-harvest	7.8	0.68	58	6.5	414
45 × 20 cm	Initial	7.8	0.70	64	7.0	432
	Post-harvest	7.8	0.70	59	6.7	418
45 × 30 cm	Initial	7.8	0.73	66	7.3	436
	Post-harvest	7.8	0.73	61	7.0	422
NPK level, kg ha⁻¹ (sub-sub-plots)						
140:70:70	Initial	7.8	0.75	70	8.0	440
	Post-harvest	7.8	0.75	65	7.7	426
120:60:60	Initial	7.8	0.72	65	7.2	430
	Post-harvest	7.8	0.72	60	6.9	416
100:50:50	Initial	7.8	0.70	60	6.8	425
	Post-harvest	7.8	0.70	55	6.5	410

Post-harvest rows are shown in italics.

Soil reaction was unchanged at pH 7.8 in every treatment both before sowing and after harvest, and electrical conductivity remained between 0.68 and 0.75 dS m⁻¹, far below the salinity threshold of 4.0 dS m⁻¹ (Table 5). The highest conductivity was recorded under 140:70:70 kg NPK ha⁻¹ (0.75 dS m⁻¹), consistent with a modest contribution of fertiliser salts, and the lowest under the closest spacing (0.68 dS m⁻¹). Available nitrogen, phosphorus and potassium all declined between sowing and harvest, by approximately 5-7%, 5-6% and 3-4% respectively (Table 5, Fig. 8). The absolute

depletion of available nitrogen was similar across nutrient levels (5 kg ha⁻¹), so that the highest dose left the largest residual pool (65 against 55 kg ha⁻¹ at the lowest dose); the same ordering held for phosphorus (7.7 against 6.5 kg ha⁻¹) and potassium (426 against 410 kg ha⁻¹). Available phosphorus remained low in absolute terms under every treatment (6.2-7.7 kg ha⁻¹ after harvest), whereas potassium reserves stayed high (400-426 kg ha⁻¹), a pattern expected of a legume grown for a single short season (Graham & Ranalli, 1997) [17].

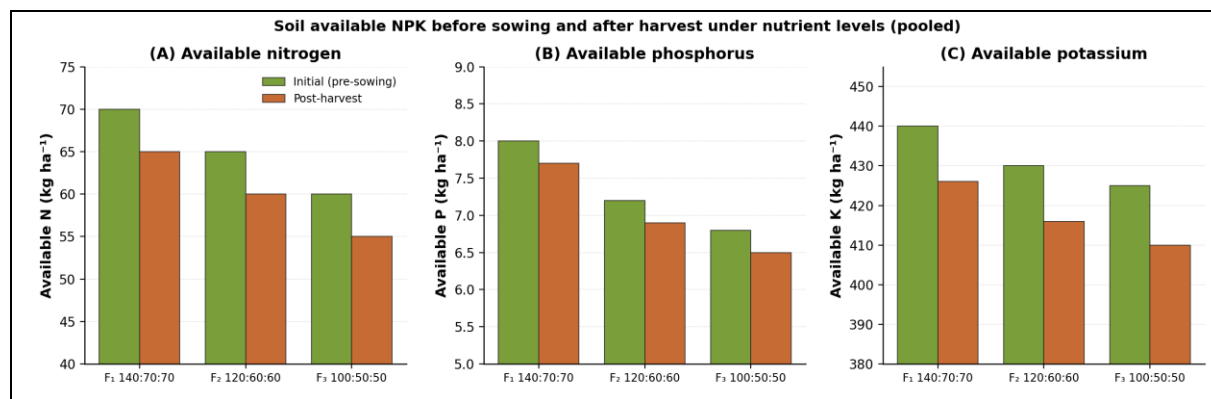


Fig 8: Soil available nitrogen, phosphorus and potassium before sowing and after harvest. (A) Available nitrogen, (B) available phosphorus and (C) available potassium under the three nutrient levels, before sowing (initial) and after harvest.

Economics

Table 6. Economics of French bean cultivation as influenced by variety, plant spacing and NPK level (pooled over two years).

Treatment	Cost of cultivation (₹ ha ⁻¹)	Green-pod yield (q ha ⁻¹)	Gross income (₹ ha ⁻¹)	Net income (₹ ha ⁻¹)	B:C ratio
Varieties (main plots)					
Arka Suvidha	1,43,600	117.0	3,51,000	2,07,400	2.44
Arka Komal	1,42,100	109.7	3,29,100	1,87,000	2.32
Phule Varun	1,40,600	102.3	3,06,900	1,66,300	2.18
Plant spacing (sub-plots)					
45 × 10 cm	1,46,100	114.8	3,44,400	1,98,300	2.36
45 × 20 cm	1,41,900	110.5	3,31,500	1,89,600	2.34
45 × 30 cm	1,38,500	103.6	3,10,800	1,72,300	2.24
NPK level, kg ha⁻¹ (sub-sub-plots)					
140:70:70	1,50,300	119.1	3,57,300	2,07,000	2.38
120:60:60	1,41,300	110.7	3,32,100	1,90,800	2.35
100:50:50	1,34,100	99.9	2,99,700	1,65,600	2.23

Computed at prevailing input costs and a green-pod price of ₹ 3000 q⁻¹. Gross income = yield × price; net income = gross income – cost of cultivation; B:C ratio = gross income/cost of cultivation. Component costs are given in Supplementary Table S19.

All treatments were profitable, with benefit-cost (B:C) ratios between 2.18 and 2.44 (Table 6, Fig. 9). Cost of cultivation varied with treatment in a manner determined by the inputs concerned. Fertiliser, applied on an area basis, differed only among nutrient levels (₹ 32,400-45,800 ha⁻¹) and generated the widest cost range (₹ 1,34,100-1,50,300 ha⁻¹); seed cost varied with plant population, making the closest spacing the most expensive geometry (₹ 1,46,100 ha⁻¹) and the widest the cheapest (₹ 1,38,500 ha⁻¹); and harvest labour varied with the quantity of produce, making Arka Suvidha marginally the most costly variety (₹ 1,43,600 ha⁻¹).

Because gross income is a direct function of marketable yield at a fixed price, net income and B:C ratio tracked yield per hectare in every case. Arka Suvidha returned the highest net income (₹ 2,07,400 ha⁻¹) and B:C ratio (2.44) among varieties; 140:70:70 kg NPK ha⁻¹ the highest among nutrient levels (₹ 2,07,000 ha⁻¹; B:C 2.38); and the closest spacing the highest among geometries (₹ 1,98,300 ha⁻¹; B:C 2.36) despite carrying the greatest cost. In each case the additional expenditure was more than recovered in the value of the extra produce, so that the treatments maximising yield were also the most remunerative.

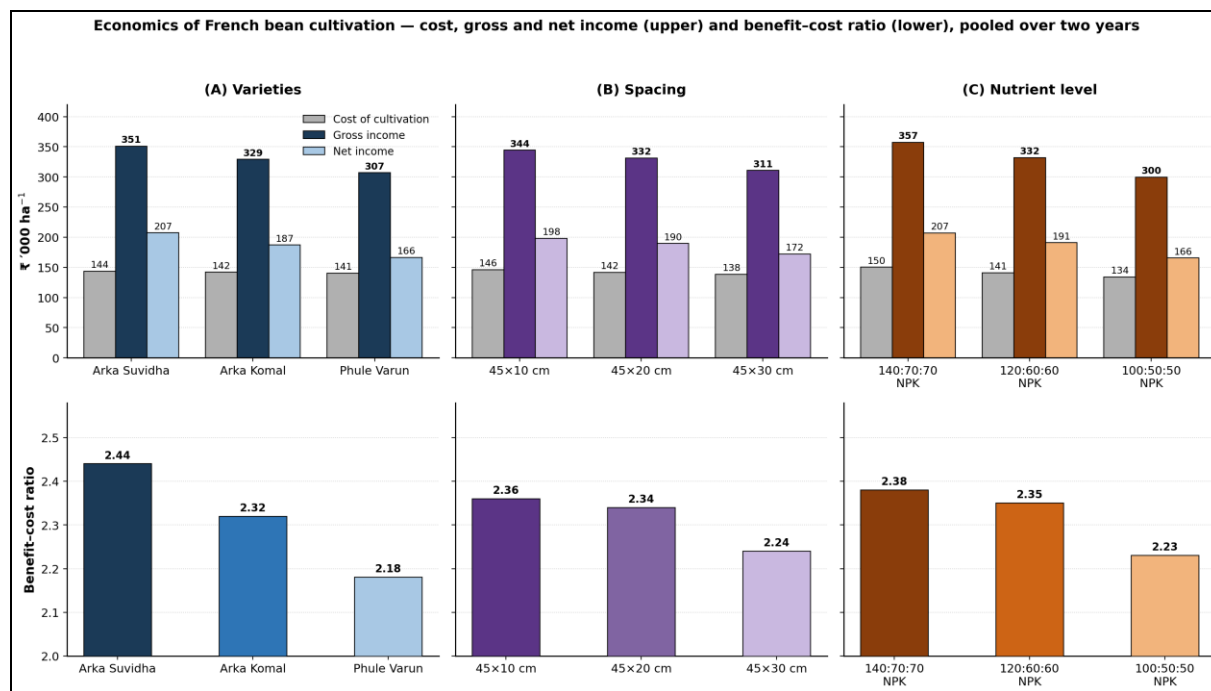


Fig 9: Economics of French bean cultivation. Cost of cultivation, gross income and net income (upper panels) and benefit-cost ratio (lower panels) as influenced by (A) variety, (B) plant spacing and (C) nutrient level (two-year pooled means).

Discussion

French bean is grown across a wide range of Indian environments, but recommendations for the crop are commonly built on one management factor at a time. By varying variety, plant geometry and NPK supply together over two seasons, the present study shows that the three levers act through distinct physiological routes and that their optimum levels are not uniformly compatible. Variety and nutrition improved growth, yield, quality and profitability in concert; plant geometry did not, and instead separated the yield-maximising treatment from the quality-maximising one.

The consistent superiority of Arka Suvidha across growth, phenology, yield, quality and economic traits identifies it as the best adapted of the three genotypes for this region. Its advantage was expressed simultaneously in canopy traits, in yield components, in pod composition and in earliness, which is the signature of a genotype with generally superior resource capture rather than one with a single favourable component. Because the ranking of common-bean varieties is known to be strongly environment dependent (Graham & Ranalli, 1997; Beebe *et al.*, 2013; Miklas *et al.*, 2006) [17, 4, 24], this ranking should be regarded as specific to the semi-arid subtropical conditions tested here rather than as a general ordering of the three varieties.

The spacing response is the clearest illustration in these data of the distinction between the individual plant and the crop community, and it resolves in opposite directions at the two scales. Close spacing increased plant height but reduced branching, leaf number, leaf area, per-plant biomass, pod number, pod size and seed filling. Plants that are taller yet simultaneously less branched and lighter are most plausibly expressing shade avoidance under competition for light rather than superior growth, and the concurrent advance of flowering and maturity under dense stands is consistent with that interpretation. Low red-to-far-red ratios within a dense canopy are perceived by phytochromes and elicit a coordinated syndrome of internode elongation, suppressed branching and accelerated flowering (Kretschmer *et al.*,

1977; Yang & Li, 2017) [21, 35], which is precisely the combination of responses recorded here at 45 × 10 cm. At the scale of the crop community, however, these individual-plant penalties were outweighed: the roughly threefold greater population at 45 × 10 cm converted markedly poorer plants into the highest marketable yield per hectare. Such dominance of population over individual-plant performance is the classical expression of yield-component compensation, first formalised for *Phaseolus vulgaris* by Adams (1967) [1] and subsequently demonstrated across a wide range of bean populations (Duarte & Adams, 1972; Westermann & Crothers, 1977; Adams, 1982; Sundar & Lal, 2022) [12, 34, 2, 33] and of the density-yield relationship documented more generally in grain legumes (Board & Harville, 1994; Egli, 1988; Loomis & Williams, 1963) [8, 13, 22]. The practical implication is that the yield-maximising geometry cannot be inferred from per-plant observations, which in this experiment pointed unambiguously the wrong way.

Because pod quality followed the per-plant traits rather than yield per hectare, plant geometry generates a genuine yield-quality trade-off. The widest spacing produced the longest, thickest, most protein- and mineral-rich and least fibrous pods, yet the lowest yield and the lowest B:C ratio; the closest spacing reversed all of these. The choice between them is therefore not purely agronomic but depends on the market being served. Where green pods are sold by weight into an undifferentiated market, 45 × 10 cm is the rational geometry. Where a premium is paid for large, tender, uniform pods, as is increasingly the case in urban retail and export channels, the 10.8% yield penalty at 45 × 30 cm may be recovered through price, and the wider geometry becomes preferable. Quantifying the price differential at which the two geometries break even is a natural next step and requires grade-wise market data that the present agronomic experiment did not collect. That pod size and pod fibre are under partly independent genetic control from pod yield (Njau *et al.*, 2024) [25] suggests the trade-off may also be tractable by breeding rather than by agronomy alone.

The nutrient response, by contrast, involved no such conflict. The highest dose of 140:70:70 kg ha⁻¹ maximised vegetative growth, leaf area and dry-matter accumulation, consistent with the role of nitrogen in canopy expansion, and enhanced pod set, seed filling and pod size, consistent with the roles of phosphorus and potassium in reproductive development and assimilate translocation (Marschner, 2012; Fageria *et al.*, 2011) [18, 14]. Comparable gains in growth and pod yield with rising NPK supply have been reported for French bean in India (Sharma *et al.*, 2013) [31] and for snap bean elsewhere (Sundar & Lal, 2022) [33]. It simultaneously raised crude protein and total ash and lowered crude fibre, so that within the nutrient factor the most productive treatment also produced the most tender and most nutritionally concentrated pods, consistent with the dependence of pod protein and mineral concentration on nitrogen and cation supply (Marschner, 2012; Guzmán-Maldonado *et al.*, 2000) [23, 18]. The response was still rising at the highest dose tested, so the true optimum was not bracketed by this experiment; the yield plateau, and the point at which additional fertiliser ceases to pay, remain to be established by a dose-response trial extending beyond 140:70:70 kg ha⁻¹.

The single cost of high fertility was phenological. Flowering was delayed by 2.6 d and maturity by 4.4 d between the lowest and highest doses, a well-recognised consequence of prolonged nitrogen-driven vegetative growth (Marschner, 2012; Fageria *et al.*, 2011) [23, 14] and one already documented in French bean at raised fertiliser levels (Sharma *et al.*, 2013) [31]. That the flowering-to-maturity interval remained nearly constant across treatments indicates that fertility shifted the timing of the reproductive transition rather than lengthening pod development itself. Where the crop is grown for an early market window, a delay of some four days in first picking is a real consideration and may justify accepting the slightly lower yield of the intermediate dose. It is worth noting that wide spacing delays harvest by a similar margin, so the two treatments that most improve pod quality are also the two that most postpone marketing. Soil reaction and salinity were unchanged over the study, and although available N, P and K all declined between sowing and harvest, the depletion was modest and the highest fertiliser dose left the largest residual pools. The recommended fertility level therefore appears compatible with the maintenance of soil fertility over the two seasons observed. This inference is necessarily short-term: two seasons cannot establish a nutrient balance, and the residual pools reported here describe the direction of change rather than a long-term equilibrium (Graham & Ranalli, 1997; Hardarson & Atkins, 2003) [17, 19]. The persistently low available phosphorus under every treatment further suggests that continued phosphorus supplementation will be required on this soil whichever geometry is adopted.

The economic analysis reinforces the agronomic conclusion without altering it, because gross income is a linear function of marketable yield at a fixed price. The closest spacing was the most expensive geometry, owing chiefly to a threefold higher seed requirement, and the highest nutrient dose the most expensive fertility level; in both cases the additional cost was more than recovered in the value of the extra produce. As all treatments returned a B:C ratio above 2.1, the choice among them is a matter of optimisation rather than of risk. These margins depend on the input costs and the green-pod price of ₹ 3000 q⁻¹ prevailing during the

study, and the ranking of treatments is more robust than the absolute returns, which will move with fertiliser prices and market rates. In particular, the economic case for close spacing rests on an undifferentiated pod price and would weaken under any pricing structure that rewards pod size.

Study limitations

Three features of the design temper the strength of these inferences. First, the experiment carried two replications; although the design was a fully specified split-split-plot and pooling over two seasons adds temporal robustness, the limited residual degrees of freedom reduce the precision of the error estimate. Second, treatment effects were resolved at the level of main effects, so the possibility that the optimum spacing differs between varieties or between nutrient levels was not tested; because the spacing response is the pivotal finding reported here, a variety × spacing interaction would be of particular interest, the more so as cultivars of contrasting growth habit are known to differ in their compensatory response to density (Westermann & Crothers, 1977; Adams, 1982; Checa & Blair, 2012) [34, 2, 11]. Third, the study was conducted at a single location, so the transferability of the recommended package across the wider Marathwada region and comparable semi-arid zones remains to be confirmed. Future work with additional replications and sites, explicit tests of interaction, a wider range of nutrient doses, and direct measurement of nitrogen fixation and nutrient-use efficiency (Hardarson & Atkins, 2003) [19] would strengthen and extend these findings.

Conclusion

Over two Rabi seasons, the productivity, quality and profitability of French bean in a semi-arid subtropical environment were jointly governed by variety, plant geometry and NPK nutrition, but the three factors did not converge on a single optimum. Arka Suvidha was the superior variety for every trait examined, and 140:70:70 kg NPK ha⁻¹ gave the strongest growth, yield (119.1 q ha⁻¹), quality (27.4% crude protein) and profitability response, at the cost of delaying maturity by about four days. Plant geometry, in contrast, separated the objectives: the closest spacing of 45 × 10 cm produced the highest marketable yield (114.8 q ha⁻¹), the highest net return and the highest benefit-cost ratio despite bearing the poorest individual plants, whereas the widest spacing of 45 × 30 cm produced the largest, most tender and most nutritionally concentrated pods at the lowest yield and return. For maximum green-pod yield and monetary return, the combination of Arka Suvidha with 45 × 10 cm spacing and 140:70:70 kg NPK ha⁻¹ is recommended for the region; where large, tender, premium-grade pods command a price advantage, 45 × 30 cm is preferable. Soil reaction and residual fertility were sustained under all treatments. These recommendations are subject to confirmation through multi-location, multi-replication testing and to a dose-response trial defining the upper limit of the nutrient response.

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