



RESEARCH ARTICLE

# Optimisation of phosphorus dose with beneficial microorganism application for enhancing growth, yield and economic efficiency in Raikia bean (*Phaseolus vulgaris* L.)

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## Abstract

Raikia, which is a pole type French bean native to southern Odisha and recently notified as IC 632961 by CHES (ICAR-IIHR), is rich in nutrients but is underutilised because of low agronomical research. Scientific information on optimising phosphorus fertilisation and beneficial microorganisms on improving the productivity and profitability of this indigenous legume is scarce. The present study was an attempt to identify appropriate levels of phosphorus, as well as biofertiliser combinations, to improve the growth, yield and economic returns of Raikia bean. A field experiment was carried out during the rabi season of 2024-25 based on a factorial randomized block design, with 4 biofertiliser treatments that included no inoculation, vesicular arbuscular mycorrhiza (VAM), *Rhizobium* and PSB and 3 phosphorus levels (0, 30 and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>). Growth parameters, yield attributes, pod yield and economic indices were assessed using the appropriate statistical analyses. The results revealed that *Rhizobium* inoculation significantly improved growth and yield characteristics especially when used in conjunction with higher levels of phosphorus. The greatest pod yield, gross and net returns were recorded with *Rhizobium* + 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. However, the benefit - cost ratio was maximized under *Rhizobium* + 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, which indicates greater economic efficiency at a moderate dose of phosphorus. Multivariate analyses (MANOVA) and principal component analysis (PCA) showed that there was significant variability induced by the treatment and there were strong interrelationships among growth and yield traits and that *Rhizobium* combined with moderate to higher phosphorus levels are the most influential treatment combinations. The study concludes with the integration of *Rhizobium* inoculation with 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> providing an economically viable and sustainable nutrient management system for Raikia seedling cultivation and making a practical recommendation for farmers to use and encourage the use of this indigenous crop among other farmers.

**Keywords:** benefit-cost ratio; biofertiliser inoculation; multivariate analysis of variance; *Phaseolus vulgaris*; phosphorus application; principal component analysis; Raikia bean; *Rhizobium*; yield enhancement

## Introduction

*Phaseolus vulgaris* L. is one of the important legume vegetables growing in eastern India, especially in the tribal dominated areas of southern Odisha where pole type indigenous landraces are an important source of household nutrition and farm income. In Kandhamal and adjoining districts, the locally adapted variety 'Raikia' is grown widely under rainfed and low-input conditions because of its tolerance to marginal soils and the consumer's preference for long fleshy green pods. Despite the regional importance and the nutritional value of Raikia bean, productivity of Raikia bean is low and highly variable mainly due to lack of proper nutrient management practices and lack of scientific recommendations based on local agro-ecological conditions.

Phosphorus is a key macronutrient in French bean culture because it plays a vital role in energy transfer, root development, nodulation and symbiotic nitrogen fixation which all ultimately have an impact on growth and yield (1). However, over-reliance on chemical phosphorus fertilisers has raised concern on the issues of soil health, nutrient use inefficiency and environmental sustainability. In this context, biofertilisers like *Rhizobium*, vesicular arbuscular mycorrhiza (VAM) and phosphate-solubilising bacteria (PSB) are sustainable alternatives, which increase the nutrient availability, improve the root-microbe interactions and increase phosphorus-use efficiency. Despite their proven benefits in several legume crops, information on the integrated use of phosphorus and biofertilisers on indigenous French bean varieties is limited. Raikia bean, a pole type French bean which is

traditionally grown in the Kandhamal district of South Odisha, is a type of rich variety in terms of nutrients, with long bold fleshy dark-green pods and early maturity. It has recently been recognized as an indigenous collection (IC 632961) by CHES (ICAR- IIHR), Bhubaneswar (2). However, Raikia bean is still underexploited because of the lack of scientific research in studying nutrient management especially the optimal levels of phosphorus and application of biofertilisers. Therefore, the present study was undertaken to fill this gap in knowledge in order to assess the effects of different biofertilisers and levels of phosphorus on growth, yield and economic efficiency of French bean variety Raikia with the hypothesis that integrated nutrient management can improve productivity with sustainability and increase the farmer's profitability.

## Materials and Methods

### Experimental site overview

The field experiment was done in rabi season in year 2024–2025 at the research farm of Centurion University of Technology and Management, Paralakhemundi, Odisha, India. The site is a typical representative of hot and moist sub humid agro climatic zone of southern Odisha with sandy loam soil and slightly acidic reaction (pH 6.27). The seasonal rainfall and temperature conditions during the experimental period were good for the French bean cultivation.

### Experimental design and treatments

The experiment was arranged in a two-factor factorial randomized block design (FRBD) with three replications. Each replication was a block to account for heterogeneity of the field and all 12 treatment combinations were randomly assigned within the block. Factor A was comprised of four biofertiliser treatments, A<sub>0</sub>- no biofertiliser (control), A<sub>1</sub>- VAM, A<sub>2</sub>- *Rhizobium* and A<sub>3</sub>- PSB. Factor B consisted of three levels of phosphorus: B<sub>0</sub> (0 kg ha<sup>-1</sup>), B<sub>1</sub> (30 kg ha<sup>-1</sup>) and B<sub>2</sub> (60 kg ha<sup>-1</sup>) which is presented in Table 1.

Certified inoculants with a minimum viable count of 10<sup>8</sup> CFU g<sup>-1</sup> were procured from authorised sources and stored under refrigerated conditions until use. Seeds were inoculated with VAM (20 mL kg<sup>-1</sup> seed), *Rhizobium* and PSB (20 g kg<sup>-1</sup> seed) using a sticker solution, shade-dried for 30 min and sown immediately. Phosphorus was applied as single super phosphate (SSP) as a basal dose. Sowing was done on 1<sup>st</sup> November 2024 at a spacing of 1.0 m × 0.45 m.

### Data collection

Plant emergence was recorded daily until stabilization and expressed as days to first and 50 % emergence. Five representative plants per plot were tagged for recording plant height at 30, 60 and 90 days after sowing (DAS). Leaf area was determined at 60 DAS by measuring completely expanded leaves from tagged plants and scanning the images with the software package IMAGEJ. Leaf area index (LAI) was calculated accordingly. Stem diameter and pod measurements were taken with a digital vernier caliper. Pods were harvested at marketable maturity from each plot at regular intervals and cumulative pod weight recorded and converted to yield per hectare.

### Statistical analysis

Data were tested for normality and homoscedasticity before

**Table 1.** List of treatment combinations

| Notation                      | Treatment combination                                                                 |
|-------------------------------|---------------------------------------------------------------------------------------|
| A <sub>0</sub> B <sub>0</sub> | : 100 % RDF + without biofertilisers and phosphorus                                   |
| A <sub>0</sub> B <sub>1</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 30 kg ha <sup>-1</sup>                    |
| A <sub>0</sub> B <sub>2</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup>                    |
| A <sub>1</sub> B <sub>0</sub> | : 100 % RDF + Sole VAM                                                                |
| A <sub>1</sub> B <sub>1</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 30 kg ha <sup>-1</sup> + VAM              |
| A <sub>1</sub> B <sub>2</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup> + VAM              |
| A <sub>2</sub> B <sub>0</sub> | : 100 % RDF + Sole <i>Rhizobium</i>                                                   |
| A <sub>2</sub> B <sub>1</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 30 kg ha <sup>-1</sup> + <i>Rhizobium</i> |
| A <sub>2</sub> B <sub>2</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup> + <i>Rhizobium</i> |
| A <sub>3</sub> B <sub>0</sub> | : 100 % RDF + Sole PSB                                                                |
| A <sub>3</sub> B <sub>1</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 30 kg ha <sup>-1</sup> + PSB              |
| A <sub>3</sub> B <sub>2</sub> | : 100 % RDF + P <sub>2</sub> O <sub>5</sub> 60 kg ha <sup>-1</sup> + PSB              |

analysis. Analysis of variance (ANOVA) was used to test the effects of treatments and their interaction. Treatment means were

compared by using Duncan's Multiple Range Test (DMRT) at a 5 % probability level. Multivariate analysis of variance (MANOVA) and principal component analysis (PCA) were performed on standardised data using RAISIN software (version 1.2.1; R & AI Solutions in Inferential Statistics) to evaluate trait interrelationships and identify dominant treatment combinations (3).

### Economic analysis

Profitability was assessed using gross returns, net returns and benefit–cost (B:C) ratio. A constant average open-market price of French bean (₹90 kg<sup>-1</sup>), prevailing during the experimental season, was used for all treatments to ensure uniformity in economic comparison. Costs of fertilisers and biofertilisers were based on local market rates. Sensitivity to price fluctuations was not included in the present analysis.

## Results and Discussion

Statistically significant difference among the biofertiliser and phosphorus levels was observed for vegetative, yield and its component traits. Mean performance of the treatments showed that *Rhizobium* and P<sub>2</sub>O<sub>5</sub> 60 kg ha<sup>-1</sup> performed better in term of plant height, days to plant emergence, leaf area, LAI, pod length, pod plant, pod weight and pod yield. Duncan's multiple range test revealed significant difference among the treatments by multiple comparisons of the traits. The results of this investigation are presented below with illustrative tables, reasoned explanations and a detailed analysis of factors under the following thematic headings.

### Synergistic effects of biofertilisers and phosphorus on Raikia bean vegetative development

#### Days to first and 50 % plant emergence

The interval between sowing and the first visible emergence of seedlings often quantified as "days to emergence", is a vital early indicator of crop development. The shortest durations to first and 50 % emergence (3.51 and 6.51 days respectively) were observed following seed inoculation with *Rhizobium*, while other treatments did not differ significantly which is presented in Table 2. Garden pea plant required 2.833 ± 0.38 days for first germination after *Rhizobium* inoculation (4) which corroborates the findings of this trait. *Rhizobium* inoculation accelerates seedling emergence due to the production of indole-3-acetic acid (IAA) and gibberellic acid (GA), which enhance root development, nodulation and seedling growth (5). With phosphorus and interaction effect no such significant difference was found which might be due to early seedling growth is fuelled by nutrients inside the seed, so adding

**Table 2.** Effect of biofertiliser and phosphorus levels on growth attributes of Raikia bean

| Treatment                     | Plant height (cm)  |                       |                       | Days to plant emergence |                   | Leaf area (cm <sup>2</sup> ) | Stem diameter (mm) | LAI                 | Root length (cm)    | No. of primary roots | Days to flowering         |                     | Days to 1 <sup>st</sup> picking | No. of pods plant <sup>-1</sup> | Pod length (cm)      | 10 Pod weight (g)     | Pod yield plot <sup>-1</sup> (g) |  |
|-------------------------------|--------------------|-----------------------|-----------------------|-------------------------|-------------------|------------------------------|--------------------|---------------------|---------------------|----------------------|---------------------------|---------------------|---------------------------------|---------------------------------|----------------------|-----------------------|----------------------------------|--|
|                               | 30 DAS             | 60 DAS                | 90 DAS                | Days to plant emergence |                   |                              |                    |                     |                     |                      | 1 <sup>st</sup> flowering | 50 % flowering      |                                 |                                 |                      |                       |                                  |  |
|                               |                    |                       |                       | 1 <sup>st</sup>         | 50 %              |                              |                    |                     |                     |                      |                           |                     |                                 |                                 |                      |                       |                                  |  |
| Biofertiliser                 |                    |                       |                       |                         |                   |                              |                    |                     |                     |                      |                           |                     |                                 |                                 |                      |                       |                                  |  |
| A <sub>0</sub>                | 28.20 <sup>b</sup> | 177.86 <sup>c</sup>   | 260.07 <sup>b</sup>   | 5.24 <sup>a</sup>       | 8.37 <sup>a</sup> | 156.558 <sup>b</sup>         | 9.73 <sup>b</sup>  | 4.97 <sup>b</sup>   | 24.72 <sup>d</sup>  | 7.70 <sup>a</sup>    | 45.12 <sup>a</sup>        | 55.89 <sup>a</sup>  | 80.56 <sup>a</sup>              | 17.47 <sup>bc</sup>             | 18.79 <sup>b</sup>   | 117.61 <sup>c</sup>   | 2.74 <sup>c</sup>                |  |
| A <sub>1</sub>                | 33.09 <sup>a</sup> | 193.03 <sup>b</sup>   | 287.13 <sup>a</sup>   | 5.11 <sup>a</sup>       | 8.35 <sup>a</sup> | 160.928 <sup>b</sup>         | 9.82 <sup>b</sup>  | 5.08 <sup>b</sup>   | 26.41 <sup>c</sup>  | 7.04 <sup>b</sup>    | 46.06 <sup>a</sup>        | 51.07 <sup>b</sup>  | 75.00 <sup>b</sup>              | 17.31 <sup>c</sup>              | 19.42 <sup>b</sup>   | 126.38 <sup>ab</sup>  | 3.22 <sup>b</sup>                |  |
| A <sub>2</sub>                | 31.09 <sup>a</sup> | 209.42 <sup>a</sup>   | 288.68 <sup>a</sup>   | 3.51 <sup>b</sup>       | 6.51 <sup>b</sup> | 169.983 <sup>a</sup>         | 10.72 <sup>a</sup> | 5.59 <sup>a</sup>   | 30.66 <sup>a</sup>  | 7.30 <sup>ab</sup>   | 39.82 <sup>b</sup>        | 45.10 <sup>c</sup>  | 70.22 <sup>b</sup>              | 21.11 <sup>a</sup>              | 21.11 <sup>a</sup>   | 130.72 <sup>a</sup>   | 3.92 <sup>a</sup>                |  |
| A <sub>3</sub>                | 28.05 <sup>b</sup> | 178.32 <sup>c</sup>   | 279.66 <sup>a</sup>   | 4.94 <sup>a</sup>       | 8.33 <sup>a</sup> | 156.648 <sup>b</sup>         | 9.59 <sup>b</sup>  | 4.72 <sup>b</sup>   | 28.90 <sup>b</sup>  | 6.29 <sup>c</sup>    | 41.92 <sup>ab</sup>       | 51.78 <sup>b</sup>  | 73.00 <sup>b</sup>              | 18.63 <sup>b</sup>              | 18.32 <sup>b</sup>   | 120.11 <sup>bc</sup>  | 3.19 <sup>b</sup>                |  |
| S.S.Em                        | 0.8                | 4.41                  | 6.6                   | 0.12                    | 0.2               | 2.42                         | 0.27               | 0.14                | 0.5                 | 0.18                 | 1.65                      | 1.43                | 1.7                             | 0.44                            | 0.4                  | 2.23                  | 98.2                             |  |
| CD (p=0.05)                   | 2.35               | 12.94                 | 19.35                 | 0.35                    | 0.58              | 7.1                          | 0.8                | 0.4                 | 1.47                | 0.53                 | 3.23                      | 2.79                | 4.98                            | 1.29                            | 1.16                 | 6.52                  | 287.97                           |  |
| Phosphorus levels             |                    |                       |                       |                         |                   |                              |                    |                     |                     |                      |                           |                     |                                 |                                 |                      |                       |                                  |  |
| B <sub>0</sub>                | 29.02 <sup>b</sup> | 197.64 <sup>a</sup>   | 269.48 <sup>b</sup>   | 4.69                    | 8.15              | 155.91 <sup>b</sup>          | 9.91               | 4.73 <sup>b</sup>   | 25.75 <sup>c</sup>  | 6.61 <sup>b</sup>    | 45.69 <sup>a</sup>        | 52.78 <sup>a</sup>  | 77                              | 18.06 <sup>b</sup>              | 18.48 <sup>b</sup>   | 119.58 <sup>b</sup>   | 3.16 <sup>b</sup>                |  |
| B <sub>1</sub>                | 28.28 <sup>b</sup> | 194.96 <sup>a</sup>   | 290.38 <sup>a</sup>   | 4.58                    | 7.58              | 165.22 <sup>a</sup>          | 10.31              | 5.34 <sup>a</sup>   | 29.53 <sup>a</sup>  | 7.23 <sup>a</sup>    | 43.57 <sup>ab</sup>       | 49.12 <sup>b</sup>  | 73.83                           | 18.28 <sup>b</sup>              | 19.85 <sup>a</sup>   | 124.39 <sup>ab</sup>  | 3.45 <sup>a</sup>                |  |
| B <sub>2</sub>                | 33.03 <sup>a</sup> | 176.37 <sup>b</sup>   | 276.79 <sup>ab</sup>  | 4.83                    | 7.94              | 161.95 <sup>ab</sup>         | 9.68               | 5.20 <sup>a</sup>   | 27.73 <sup>b</sup>  | 7.41 <sup>a</sup>    | 40.42 <sup>b</sup>        | 50.98 <sup>ab</sup> | 73.25                           | 19.55 <sup>a</sup>              | 19.90 <sup>a</sup>   | 127.15 <sup>a</sup>   | 3.18 <sup>b</sup>                |  |
| S.S.Em                        | 0.69               | 3.82                  | 5.72                  | 0.1                     | 0.17              | 2.09                         | 0.24               | 0.12                | 0.44                | 0.16                 | 1.13                      | 0.98                | 2.08                            | 0.38                            | 0.34                 | 1.93                  | 85.05                            |  |
| CD (p=0.05)                   | 2.04               | 11.21                 | 16.76                 | NS                      | NS                | 6.15                         | NS                 | 0.35                | 1.28                | 0.45                 | 3.32                      | 2.87                | NS                              | 1.12                            | 1                    | 5.65                  | 249.39                           |  |
| Interaction effect (A×B)      |                    |                       |                       |                         |                   |                              |                    |                     |                     |                      |                           |                     |                                 |                                 |                      |                       |                                  |  |
| A <sub>0</sub> B <sub>0</sub> | 26                 | 182.17 <sup>cd</sup>  | 250.70 <sup>cd</sup>  | 5.61                    | 9.04              | 154.64 <sup>cd</sup>         | 9.27               | 4.67 <sup>de</sup>  | 23.42 <sup>c</sup>  | 6.33 <sup>ef</sup>   | 51.62 <sup>a</sup>        | 59.50 <sup>a</sup>  | 83.00 <sup>a</sup>              | 17.22 <sup>efg</sup>            | 16.50 <sup>f</sup>   | 106.50 <sup>f</sup>   | 2.55 <sup>e</sup>                |  |
| A <sub>0</sub> B <sub>1</sub> | 25.12              | 178.37 <sup>de</sup>  | 280.90 <sup>a-d</sup> | 4.77                    | 7.66              | 163.79 <sup>bc</sup>         | 10.14              | 5.34 <sup>abc</sup> | 28.53 <sup>b</sup>  | 8.15 <sup>ab</sup>   | 48.60 <sup>ab</sup>       | 50.40 <sup>bc</sup> | 75.00 <sup>abcd</sup>           | 15.55 <sup>g</sup>              | 19.52 <sup>bcd</sup> | 119.00 <sup>de</sup>  | 3.01 <sup>de</sup>               |  |
| A <sub>0</sub> B <sub>2</sub> | 33.49              | 173.03 <sup>de</sup>  | 248.60 <sup>d</sup>   | 5.33                    | 8.41              | 151.24 <sup>d</sup>          | 9.77               | 4.92 <sup>b-e</sup> | 22.20 <sup>cd</sup> | 8.63 <sup>a</sup>    | 35.14 <sup>e</sup>        | 57.77 <sup>a</sup>  | 83.67 <sup>a</sup>              | 19.64 <sup>bc</sup>             | 20.35 <sup>a-d</sup> | 127.33 <sup>a-d</sup> | 2.66 <sup>e</sup>                |  |
| A <sub>1</sub> B <sub>0</sub> | 33.18              | 211.03 <sup>a</sup>   | 266.47 <sup>b-d</sup> | 5.13                    | 8.66              | 158.21 <sup>cd</sup>         | 9.89               | 4.86 <sup>b-e</sup> | 20.43 <sup>d</sup>  | 5.79 <sup>f</sup>    | 46.14 <sup>a-d</sup>      | 59.07 <sup>a</sup>  | 75.67 <sup>abcd</sup>           | 16.45 <sup>fg</sup>             | 18.97 <sup>cde</sup> | 125.83 <sup>a-e</sup> | 3.21 <sup>cd</sup>               |  |
| A <sub>1</sub> B <sub>1</sub> | 31.19              | 212.00 <sup>a</sup>   | 289.63 <sup>ab</sup>  | 5.02                    | 8.02              | 159.69 <sup>cd</sup>         | 9.85               | 4.92 <sup>b-e</sup> | 29.50 <sup>ab</sup> | 8.00 <sup>abc</sup>  | 43.62 <sup>a-d</sup>      | 47.33 <sup>cd</sup> | 80.67 <sup>ab</sup>             | 17.25 <sup>d-g</sup>            | 20.86 <sup>abc</sup> | 121.44 <sup>cde</sup> | 3.59 <sup>bc</sup>               |  |
| A <sub>1</sub> B <sub>2</sub> | 34.91              | 156.08 <sup>e</sup>   | 305.30 <sup>a</sup>   | 5.18                    | 8.36              | 164.88 <sup>bc</sup>         | 9.73               | 5.45 <sup>ab</sup>  | 29.30 <sup>ab</sup> | 7.33 <sup>bcd</sup>  | 48.41 <sup>abc</sup>      | 46.80 <sup>cd</sup> | 68.67 <sup>cd</sup>             | 18.23 <sup>c-f</sup>            | 18.42 <sup>def</sup> | 131.87 <sup>abc</sup> | 2.86 <sup>de</sup>               |  |
| A <sub>2</sub> B <sub>0</sub> | 30.43              | 208.90 <sup>ab</sup>  | 277.60 <sup>a-d</sup> | 3.43                    | 6.58              | 155.83 <sup>cd</sup>         | 10.8               | 4.80 <sup>b-e</sup> | 30.50 <sup>ab</sup> | 7.00 <sup>de</sup>   | 42.42 <sup>b-e</sup>      | 46.03 <sup>cd</sup> | 76.33 <sup>abc</sup>            | 19.46 <sup>cd</sup>             | 21.47 <sup>ab</sup>  | 123.67 <sup>b-e</sup> | 3.56 <sup>bc</sup>               |  |
| A <sub>2</sub> B <sub>1</sub> | 31.71              | 215.49 <sup>a</sup>   | 285.50 <sup>ab</sup>  | 3.33                    | 6.32              | 175.90 <sup>ab</sup>         | 10.94              | 5.95 <sup>a</sup>   | 30.10 <sup>ab</sup> | 7.23 <sup>cde</sup>  | 39.02 <sup>de</sup>       | 44.03 <sup>d</sup>  | 68.33 <sup>cd</sup>             | 21.75 <sup>ab</sup>             | 19.56 <sup>bcd</sup> | 135.10 <sup>a</sup>   | 3.97 <sup>ab</sup>               |  |
| A <sub>2</sub> B <sub>2</sub> | 31.13              | 203.87 <sup>a-c</sup> | 302.93 <sup>a</sup>   | 3.77                    | 6.63              | 178.21 <sup>a</sup>          | 10.43              | 6.02 <sup>a</sup>   | 31.37 <sup>a</sup>  | 7.67 <sup>bcd</sup>  | 38.03 <sup>de</sup>       | 45.23 <sup>cd</sup> | 66.00 <sup>d</sup>              | 22.12 <sup>a</sup>              | 22.31 <sup>a</sup>   | 133.40 <sup>ab</sup>  | 4.22 <sup>a</sup>                |  |
| A <sub>3</sub> B <sub>0</sub> | 26.46              | 188.46 <sup>b-d</sup> | 283.13 <sup>a-c</sup> | 4.58                    | 8.31              | 154.95 <sup>cd</sup>         | 9.69               | 4.60 <sup>de</sup>  | 28.63 <sup>b</sup>  | 7.33 <sup>bcd</sup>  | 42.58 <sup>b-e</sup>      | 46.50 <sup>cd</sup> | 73.00 <sup>bcd</sup>            | 19.12 <sup>cde</sup>            | 16.98 <sup>ef</sup>  | 122.33 <sup>b-e</sup> | 3.35 <sup>cd</sup>               |  |
| A <sub>3</sub> B <sub>1</sub> | 25.12              | 173.98 <sup>de</sup>  | 305.50 <sup>a</sup>   | 5.21                    | 8.33              | 161.49 <sup>cd</sup>         | 10.3               | 5.15 <sup>bcd</sup> | 30.00 <sup>ab</sup> | 5.53 <sup>f</sup>    | 43.05 <sup>b-e</sup>      | 54.70 <sup>ab</sup> | 71.33 <sup>bcd</sup>            | 18.56 <sup>c-f</sup>            | 19.46 <sup>cd</sup>  | 122.00 <sup>cde</sup> | 3.21 <sup>cd</sup>               |  |
| A <sub>3</sub> B <sub>2</sub> | 32.58              | 172.52 <sup>de</sup>  | 250.33 <sup>cd</sup>  | 5.04                    | 8.35              | 153.49 <sup>cd</sup>         | 8.78               | 4.41 <sup>e</sup>   | 28.07 <sup>b</sup>  | 6.00 <sup>f</sup>    | 40.12 <sup>cde</sup>      | 54.13 <sup>ab</sup> | 74.67 <sup>abcd</sup>           | 18.21 <sup>c-f</sup>            | 18.52 <sup>de</sup>  | 116.00 <sup>ef</sup>  | 3.00 <sup>de</sup>               |  |
| S.S.Em                        | 1.39               | 7.64                  | 7.64                  | 0.21                    | 0.34              | 4.19                         | 0.47               | 0.24                | 0.87                | 0.31                 | 2.86                      | 1.96                | 2.94                            | 0.76                            | 0.69                 | 3.85                  | 170.09                           |  |
| CD (p=0.05)                   | NS                 | 22.41                 | 22.41                 | NS                      | NS                | 12.31                        | NS                 | 0.69                | 2.55                | 0.91                 | 5.59                      | 5.75                | 8.63                            | 2.23                            | 2.01                 | 11.3                  | 498.78                           |  |

A<sub>0</sub>: No biofertilisers; A<sub>1</sub>: VAM; A<sub>2</sub>: *Rhizobium*; A<sub>3</sub>: PSB; B<sub>0</sub>: P<sub>2</sub>O<sub>5</sub> 0 kg ha<sup>-1</sup>; B<sub>1</sub>: P<sub>2</sub>O<sub>5</sub> 30 kg ha<sup>-1</sup>; B<sub>2</sub>: P<sub>2</sub>O<sub>5</sub> 60 kg ha<sup>-1</sup>; A<sub>0</sub>B<sub>0</sub>: Control; A<sub>1</sub>B<sub>0</sub>: VAM; A<sub>2</sub>B<sub>0</sub>: *Rhizobium*; A<sub>3</sub>B<sub>0</sub>: PSB; A<sub>1</sub>B<sub>1</sub>: P<sub>2</sub>O<sub>5</sub> 30 kg ha<sup>-1</sup>+ VAM; A<sub>1</sub>B<sub>2</sub>: P<sub>2</sub>O<sub>5</sub> 60 kg ha<sup>-1</sup>+ VAM; A<sub>2</sub>B<sub>1</sub>: P<sub>2</sub>O<sub>5</sub> 30 kg ha<sup>-1</sup>+ *Rhizobium*; A<sub>2</sub>B<sub>2</sub>: P<sub>2</sub>O<sub>5</sub> 60 kg ha<sup>-1</sup>+ *Rhizobium*; A<sub>3</sub>B<sub>1</sub>: P<sub>2</sub>O<sub>5</sub> 30 kg ha<sup>-1</sup>+ PSB; A<sub>3</sub>B<sub>2</sub>: P<sub>2</sub>O<sub>5</sub> 60 kg ha<sup>-1</sup>+ PSB \*Same alphabet indicated non-significance differences among the treatment or combination.

phosphorus to the soil at planting does not help much until the roots are active enough to absorb it.

#### Plant height (cm)

Plant height in Raikia bean, a key vegetative trait, was recorded at 30, 60 and 90 DAS. At 30 DAS, the tallest plants were observed with VAM application (33.09 cm), likely due to enhanced phosphorus uptake via mycorrhizal hyphae (6), while in phosphorus levels,  $P_2O_5$  at 60 kg ha<sup>-1</sup> recorded with (33.03 cm) which may be due to application of adequate amount of phosphorus for nodulation, root development and overall growth. At 60 DAS, *Rhizobium* treatment resulted in the highest plant height (209.42 cm), attributed to improved nodulation and phytohormone production (auxins, cytokinins) (7, 8). The combined application of *Rhizobium* and  $P_2O_5$  at 30 kg ha<sup>-1</sup> produced the maximum height (215.49 cm). At 90 DAS, the tallest plants were recorded under *Rhizobium* (288.68 cm) and  $P_2O_5$  30 kg ha<sup>-1</sup> (290.38 cm), with the highest value (305.50 cm) observed under PSB +  $P_2O_5$  30 kg ha<sup>-1</sup>, which was statistically at par with *Rhizobium* +  $P_2O_5$  30 kg ha<sup>-1</sup>.

#### Leaf area (cm<sup>2</sup>) and leaf area index

Leaf area (LA) and LAI are critical descriptors of the canopy surface available for photosynthetic activity over the entire crop lifecycle. The influence of phosphorus fertilisation levels and biofertiliser treatments on leaf area at peak flowering (60 days after sowing) was evaluated and summarised in Table 2. Seed inoculation with *Rhizobium* produced the highest leaf area (169.98 cm<sup>2</sup>) and LAI (5.59), statistically followed by VAM treatment (164.88 cm<sup>2</sup>, 5.08), in French bean (9), in cowpea (10) and in cluster bean (11) was observed that, leaf area and LAI increased significantly with *Rhizobium* inoculation. Among phosphorus levels,  $P_2O_5$  30 kg ha<sup>-1</sup> yielded more LA (165.22 cm<sup>2</sup>) and LAI (5.34) than  $P_2O_5$  60 kg ha<sup>-1</sup> (161.95 cm<sup>2</sup>, 5.20). Leaf area was increased significantly with the 100 % recommended dose of  $P_2O_5$  application as phosphorus helps to increase the overall growth and development (12). The combination of *Rhizobium* with 60 kg  $P_2O_5$  ha<sup>-1</sup> achieved the peak values (178.21 cm<sup>2</sup>, 6.02), statistically at par with *Rhizobium* + 30 kg  $P_2O_5$  ha<sup>-1</sup> (175.90 cm<sup>2</sup>, 5.95). These outcomes align with previous findings that *Rhizobium* improves nitrogen fixation and phosphorus enhances cell division structural organization, photosynthesis which will cause leaf development (13, 14).

#### Root length (cm)

Biofertiliser and phosphorus have a symbiotic relation with the legume root. The longest roots were recorded in the *Rhizobium* treated plots (30.66 cm), which were statistically at par with PSB application. A similar response was observed in cowpea following *Rhizobium* inoculation, a benefit attributed to atmospheric nitrogen fixation by *Rhizobium*, which enhances soil nitrogen levels, increases nodulation and fosters robust root development (15). In case of phosphorus, application of 30 kg  $P_2O_5$  ha<sup>-1</sup> significantly increased the root length of 29.53 cm and 60 kg  $P_2O_5$  ha<sup>-1</sup> found statistically at par. Phosphorus significantly boosts rhizobial symbiosis in legumes; it promotes lateral root growth, root hair and nodule formation and function (16). Combined effect of *Rhizobium* inoculation with 30 kg  $P_2O_5$  ha<sup>-1</sup> yielded the highest root length (31.37 cm), statistically like *Rhizobium* alone (30.50 cm). In contrast, sole VAM treatment resulted in the shortest root length (20.43 cm). This might be due to the soil pH, which is slightly

acidic and in slightly acidic soil, fungal growth is subdued, but bacterial growth remains relatively strong.

#### Influence of biofertilisers and phosphorus levels on yield and yield attributes of Raikia bean

##### Days to first and 50 % flowering

Early flowering in Raikia bean facilitates earlier pod development, which can potentially yield higher market returns. The shortest duration to first flowering (39.82 days) was observed with *Rhizobium* inoculation because *Rhizobium* inoculation boosts nitrogen availability, promoting early vegetative growth and advancing flowering for improved reproductive success. Among phosphorus levels and their interactions, the application of  $P_2O_5$  at 60 kg ha<sup>-1</sup> and the combination of  $P_2O_5$  60 kg ha<sup>-1</sup> without biofertiliser showed reduced flowering durations, recording 40.42 and 35.14 days, respectively. For 50 % flowering, *Rhizobium* treatment also resulted in the earliest response (45.10 days) compared to other treatments. With respect to phosphorus levels, the application of  $P_2O_5$  at 30 kg ha<sup>-1</sup> led to the minimum days to 50 % flowering, while the combined treatment of *Rhizobium* and  $P_2O_5$  at 30 kg ha<sup>-1</sup> resulted in the earliest flowering (44.03 days). In garden pea, it was observed that, *Rhizobium* inoculation significantly reduced the days to first and 50 % flowering (17).

##### Number of pod plant<sup>-1</sup>

The number of pods per plant, a key yield component is presented in Table 2. Seed inoculation with *Rhizobium* resulted in 21.11 pods per plant, significantly more than other treatments, consistent with earlier studies reporting increased pod numbers following *Rhizobium* application in French bean (8, 18). This might be due to the fact biofertiliser promotes plant growth and enhances photosynthetic efficiency, which diminishes competition between flowers and developing pods and consequently increases pod number. Additionally, phosphorus application also significantly influenced pod number:  $P_2O_5$  at 60 kg ha<sup>-1</sup> resulted in 19.55 pods per plant, which was statistically on par with 30 kg ha<sup>-1</sup> (18.28 pods). These results are consistent with earlier findings that phosphorus fertilisation increases pod number in legumes (19, 20). Phosphorus likely stimulates additional flowering sites, thereby increasing pod formation, which may be a possible reason. Notably, the interaction of *Rhizobium* with 60 kg  $P_2O_5$  ha<sup>-1</sup> produced the highest pod count (10, 20), highlighting a synergistic effect.

##### Pod length (cm)

Pod length was highly positively correlated with pod yield and it was improved by both inoculation with *Rhizobium* and application of P. Maximum pod lengths of 21.11, 19.90 and 22.31 cm were recorded with *Rhizobium* treatment,  $P_2O_5$  60 kg ha<sup>-1</sup> application and their combination respectively. The effect of *Rhizobium* is related to the production of gibberellins plant hormones that increase cell divisions, elongation and leaf areas and consequently the photosynthesis and biomass available for growth of the pods. Complementarily, phosphorus application promotes the development of roots to better absorb the nutrients and water and further stimulates cell division and elongation to increase the length of the pod. Application of *Rhizobium* with  $P_2O_5$  60 kg ha<sup>-1</sup> was significantly maximised the pod length in legumes (10, 19).

### Weight of 10 pods (g)

Pod weight was significantly increased by both biofertiliser and phosphorus treatments compared to the control. The highest pod weight of 130.72 g was recorded with *Rhizobium* inoculation. This effect is likely attributable to enhanced leaf area, which increases photosynthetic capacity and biomass production which may cause heavier pods. Regarding phosphorus levels, both  $P_2O_5$  30 kg  $ha^{-1}$  and  $P_2O_5$  60 kg  $ha^{-1}$  produced similar pod weights, with a maximum of 127.15 g observed at  $P_2O_5$  30 kg  $ha^{-1}$ . Phosphorus application enhances root development, nutrient and water uptake and metabolic energy processes, all of which may contribute to robust pod growth. The interaction between *Rhizobium* and  $P_2O_5$  60 kg  $ha^{-1}$  led to the highest pod weight in the study, reaching 135.10 g, underscoring a synergistic effect between microbial and nutrient treatments. The results were in accordance with earlier findings in green bean with *Rhizobium* inoculation and phosphates application (12, 21).

### Pod yield plot<sup>-1</sup> (kg)

A perusal of the data presented in Table 2 revealed that different treatment combination had a significant influence on the pod yield of Raikia bean. The highest pod yield (3.92 kg plot<sup>-1</sup>) was achieved with *Rhizobium* inoculation. This increase is likely due to enhanced production of plant growth hormones and effective root colonisation by the bacteria, which improve photosynthesis and nutrient acquisition through symbiotic nitrogen fixation and microbial activity. Application of  $P_2O_5$  30 kg plot<sup>-1</sup> resulted in a higher pod yield of 3.45 kg plot<sup>-1</sup>, it is statistically at par with  $P_2O_5$  60 kg  $ha^{-1}$  (3.18 kg). Phosphorus promotes root development, nutrient and water uptake and energy metabolism which may be

supporting enhanced pod growth. The interaction of *Rhizobium* and  $P_2O_5$  60 kg  $ha^{-1}$  produced the maximum pod yield at 4.22 kg plot<sup>-1</sup>. Numerous studies confirm that seed inoculation with *Rhizobium*, especially when paired with phosphorus fertilisation at 60 kg  $P_2O_5$   $ha^{-1}$ , consistently increased pod production across a variety of legume crops. Similar outcomes were witnessed in chickpea, cowpea, French bean and other legumes (1, 17–19, 22).

### Economic analysis

Based on the current investigation, among all the treatment combinations tested, Raikia bean exhibited the highest economic benefit when applying  $P_2O_5$  30 kg  $ha^{-1}$  alongside *Rhizobium* 5 kg  $ha^{-1}$ . While the net return with 60 kg  $P_2O_5$   $ha^{-1}$  (₹526551  $ha^{-1}$ ) slightly exceeds that of the 30 kg treatment (₹522989  $ha^{-1}$ ), but it is not economically viable in terms of B:C ratio (Table 3 and 4). Higher B:C ratio was 2.48 recorded with 30 kg  $P_2O_5$   $ha^{-1}$ , compared to a mere favorable 2.46 at 60 kg  $P_2O_5$   $ha^{-1}$  (Table 4). Moreover, the combined application of *Rhizobium* and phosphorus significantly boosted gross returns, net returns and B:C ratio in French bean, chickpea and cowpea, uniform with findings in recent studies (1, 23, 24).

### Multivariate analysis

A two-factor factorial MANOVA was conducted to assess how trait interactions affect a set of combined dependent variables (DE1<sup>st</sup>, DE50, PH30, PH60, PH90, SD, LA, LAI, RL, NPR, DF1<sup>st</sup>, DF50, DTM, PL, PW, PCS, NPP, 10PW and PY). Pillai's trace was used as the multivariate test statistic and converted to *F*-values. Table 5 represented the corresponding values of factor and interaction rows. Pillai's trace statistic for factor A, factor B and interaction effect is 2.99, 2 and 5.92 respectively. The corresponding *F*-statistic

**Table 3.** Influence of biofertiliser and phosphorus levels on economics of Raikia bean

| Fixed cost calculation                         |                                    |                              |                     |
|------------------------------------------------|------------------------------------|------------------------------|---------------------|
| Particulars                                    | Quantity                           | Price unit <sup>-1</sup> (₹) | Cost (₹ $ha^{-1}$ ) |
| <b>Fixed Cost A</b>                            |                                    |                              |                     |
| Rental value of land                           | 2.5 acre                           | 15000                        | 37500               |
| Depreciation on fixed assets                   | -                                  | -                            | 4500                |
| Subtotal(₹)                                    | -                                  | -                            | 42000               |
| Interest on fixed cost at 10 %                 | -                                  | -                            | 4200                |
| Total fixed cost A (₹)                         | -                                  | -                            | 46200               |
| <b>Fixed Cost B</b>                            |                                    |                              |                     |
| Seeds(₹)                                       | 50 kg                              | 500                          | 25000               |
| Machinery cost for land preparation            | 10 hr                              | 1200                         | 12000               |
| Compost                                        | 25 tonnes                          | 1500                         | 37500               |
| Chemical fertiliser                            |                                    |                              |                     |
| Urea                                           | 108.5 kg                           | 5.42                         | 588                 |
| SSP                                            | 375 kg                             | 13                           | 4875                |
| MOP                                            | 83.5 kg                            | 29                           | 2422                |
| Stacking                                       | -                                  | -                            | 30000               |
| Plant protection chemicals                     | -                                  | -                            | 10000               |
| Man days (MD)                                  | 30 MD                              | 462                          | 13860               |
| Transportation cost                            | -                                  | -                            | 10000               |
| Miscellaneous charges                          | -                                  | -                            | 5000                |
| Subtotal(₹)                                    | -                                  | -                            | 151245              |
| Interest on working capital at 7 % (₹)         | -                                  | -                            | 10587               |
| Total fixed cost B (₹)                         | -                                  | -                            | 161832              |
| Total fixed cost (A + B) in ₹                  | -                                  | -                            | 208032              |
| <b>Variable cost calculation</b>               |                                    |                              |                     |
| Control (without biofertiliser and phosphorus) | 0                                  | 0                            | 0                   |
| 30 kg $P_2O_5$                                 | 188 kg SSP                         | 13                           | 2438                |
| 60kg $P_2O_5$                                  | 375kg SSP                          | 13                           | 4875                |
| VAM                                            | 4.5 litters                        | 800                          | 3600                |
| VAM + 30 kg $P_2O_5$                           | 4.5 litters VAM + 188 kg SSP       | 13 + 500                     | 6038                |
| VAM + 60 kg $P_2O_5$                           | 4.5 litters VAM + 375 kg SSP       | 13 + 500                     | 8475                |
| <i>Rhizobium</i>                               | 5 kg <i>Rhizobium</i>              | 150                          | 750                 |
| <i>Rhizobium</i> + 30 kg $P_2O_5$              | 5 kg <i>Rhizobium</i> + 188 kg SSP | 13 + 150                     | 3188                |
| <i>Rhizobium</i> + 60 kg $P_2O_5$              | 5 kg <i>Rhizobium</i> + 375kg SSP  | 13 + 150                     | 5625                |
| PSB                                            | 5 kg PSB                           | 500                          | 2500                |
| PSB + 30 kg $P_2O_5$                           | 5kg PSB + 188 kg SSP               | 13 + 500                     | 4938                |
| PSB + 60 kg $P_2O_5$                           | 5 kg PSB + 375 kg SSP              | 13 + 500                     | 7375                |

**Table 4.** Influence of biofertiliser and phosphorus levels on economics of Raikia bean

| Treatments                                             | Pod yield (kg ha <sup>-1</sup> ) | Total cost of cultivation (₹) | Gross return (₹) | Net return (₹) | B:C  |
|--------------------------------------------------------|----------------------------------|-------------------------------|------------------|----------------|------|
| Absolute control                                       | 5267.44                          | 208032                        | 500407           | 292375         | 1.41 |
| 30 kg P <sub>2</sub> O <sub>5</sub>                    | 6053.06                          | 210470                        | 575040           | 364571         | 1.73 |
| 60 kg P <sub>2</sub> O <sub>5</sub>                    | 5435.15                          | 212907                        | 516340           | 303433         | 1.43 |
| VAM                                                    | 6501.88                          | 211632                        | 617679           | 406047         | 1.92 |
| VAM + 30 kg P <sub>2</sub> O <sub>5</sub>              | 7115.70                          | 214070                        | 675992           | 461922         | 2.16 |
| VAM + 60 kg P <sub>2</sub> O <sub>5</sub>              | 6020.12                          | 216507                        | 571912           | 355405         | 1.64 |
| <i>Rhizobium</i>                                       | 7163.24                          | 208782                        | 680508           | 471726         | 2.26 |
| <i>Rhizobium</i> + 30 kg P <sub>2</sub> O <sub>5</sub> | 7728.52                          | 211220                        | 734209           | 522990         | 2.48 |
| <i>Rhizobium</i> + 60 kg P <sub>2</sub> O <sub>5</sub> | 7791.67                          | 213657                        | 740208           | 526552         | 2.46 |
| PSB                                                    | 6676.73                          | 210532                        | 634289           | 423758         | 2.01 |
| PSB + 30 kg P <sub>2</sub> O <sub>5</sub>              | 6626.14                          | 212970                        | 629483           | 416514         | 1.96 |
| PSB + 60 kg P <sub>2</sub> O <sub>5</sub>              | 6202.78                          | 215407                        | 589264           | 373857         | 1.74 |

**Table 5.** Two-way multivariate analysis of variance (MANOVA)

|           | DF    | Pillai | Statistic | Num.DF | Den.DF | p value | eta sq |
|-----------|-------|--------|-----------|--------|--------|---------|--------|
| Block     | 2.00  | 1.84   | 3.13      | 38.00  | 10.00  | 0.03    | 0.92   |
| Factor A  | 3.00  | 2.99   | 123.45    | 57.00  | 18.00  | 0.00    | 1.00   |
| Factor B  | 2.00  | 2.00   | 169.91    | 38.00  | 10.00  | 0.00    | 1.00   |
| A x B     | 6.00  | 5.92   | 37.09     | 114.00 | 54.00  | 0.00    | 0.99   |
| Residuals | 22.00 | NA     | NA        | NA     | NA     | NA      | NA     |

DF: degrees of freedom; Pillai: Pillai trace statistic; Statistic: F-statistic; Num DF: numerator degrees of freedom; Den DF: denominator degrees of freedom; eta sq: partial eta square value.

is 123.45, 169.91 and 37.09. All p-values were < 0.001, indicated statistically significant effects at the 5 % level. The partial eta squared ( $\eta^2$ ) values for factor A and factor B are both 1.00, indicated that each factor independently accounts for 100 % of the variance in the dependent variables, while the interaction (A×B) has an  $\eta^2$  of 0.99, meaning it explains 99 % of the variance.

### Principal component analysis

The PCA is a statistical technique in reducing dimensionality in simplifying complex datasets while pertaining the essential information in an experiment. The PCA transform the original dataset into a new set of uncorrelated variables called principal components (PCs) to explain nature and extent variation persist in the experiment. This also highlights traits and treatments relationship unlike in normal correlation. The analysis resulted formation of twelve PCs out of which 5 viz., PC1, PC2, PC3, PC4

and PC5 were found to be significant with eigenvalue greater than one ( $p > 1$ ). PC1 and PC2 accounted 46.48 % and 14.78 % of the total variance respectively with 61.26 % as cumulative variance (Fig. 1, Table 6). Since both the PCs explained more than 60 % of the total variance was considered for biplot construction and PC based index score estimation as confirmed in scree plot and loading of each variable (Fig. 1, Table 7).

Scaled index was calculated by converting index scores to a range of 0 to 1 based on PC1 and PC2 which made easier in interpretation in finding best treatment combinations in the experiment. For consistency in selection cutoff was kept at 75 % in finding suitable treatments. As per index score based score on PC1, the treatment combinations i.e., A<sub>2</sub> × B<sub>2</sub> and A<sub>2</sub> × B<sub>1</sub> (selected) placed outside of selection cutoff line indicated its magnitude of impact on the traits under study assigned to PC1 (Table 7). Along with, treatment combination A<sub>2</sub> × B<sub>0</sub> located near

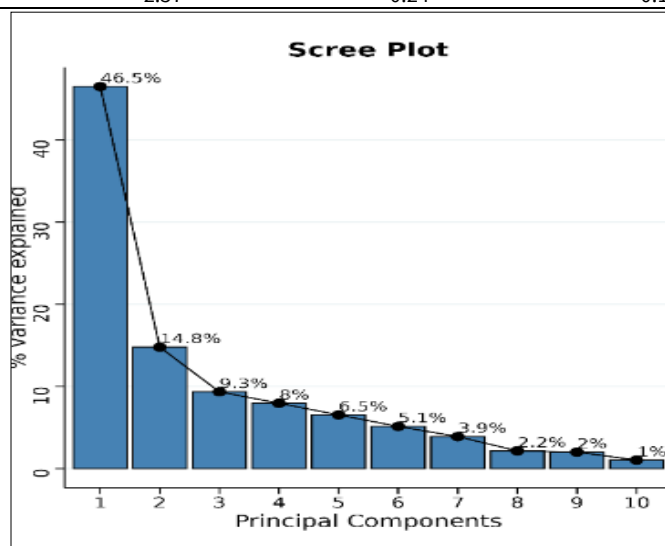
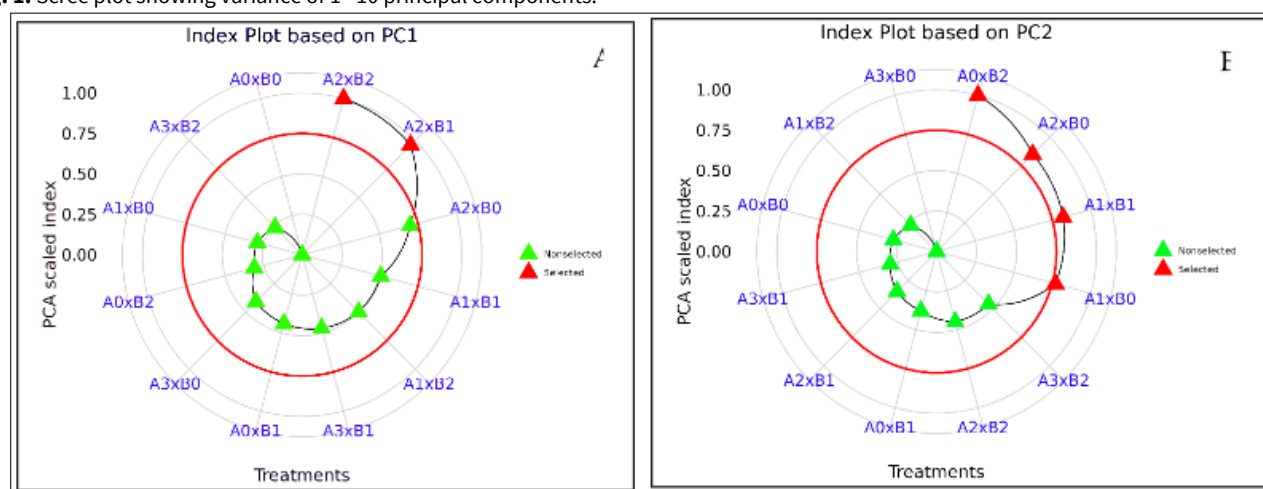
**Table 6.** Eigen value and PCs loading for vegetative, yield and yield attributing traits of Raikia bean

| Components          | PC1   | PC2   | PC3   | PC4   | PC5  | PC6  | PC7  | PC8  | PC9   | PC10  | PC11 | PC12 |
|---------------------|-------|-------|-------|-------|------|------|------|------|-------|-------|------|------|
| Eigen value         | 8.83  | 2.81  | 1.78  | 1.51  | 1.24 | 0.98 | 0.74 | 0.41 | 0.38  | 0.2   | 0.12 | 0    |
| Variance ( %)       | 46.48 | 14.78 | 9.34  | 7.96  | 6.54 | 5.14 | 3.9  | 2.17 | 2.01  | 1.04  | 0.64 | 0    |
| Cumulative variance | 46.48 | 61.26 | 70.6  | 78.6  | 85.1 | 90.2 | 94.1 | 96.3 | 98.31 | 99.36 | 100  | 100  |
| DE1 <sup>st</sup>   | -0.29 | -0.01 | 0.03  | 0.33  | 0.02 | 0.04 | 0.08 | 0.04 | 0.42  | -0.03 | 0.23 | -0.3 |
| DE50                | -0.31 | -0.06 | -0.02 | 0.21  | 0.06 | -0.1 | -0.1 | -0.1 | 0.4   | 0     | 0.09 | 0    |
| PH30                | 0.07  | 0.29  | -0.38 | 0.35  | 0.1  | -0.3 | -0.5 | 0.17 | -0.22 | -0.14 | 0.2  | -0.1 |
| PH60                | 0.17  | 0.21  | 0.14  | -0.46 | 0.25 | 0.02 | -0.5 | -0   | 0.33  | 0.02  | 0.15 | -0   |
| PH90                | 0.22  | -0.22 | 0.31  | 0.32  | -0.1 | -0.2 | 0.02 | -0.3 | 0.33  | -0.05 | 0.12 | 0.3  |
| SD                  | 0.27  | 0.08  | 0.21  | -0.1  | 0.11 | 0.22 | 0.11 | -0.6 | -0.25 | -0.08 | 0.13 | -0.4 |
| LA                  | 0.28  | -0.16 | 0.07  | 0.17  | 0.25 | 0.22 | -0.1 | 0.37 | 0.09  | -0.14 | -0   | -0.3 |
| LAI                 | 0.27  | -0.09 | 0.02  | 0.28  | 0.19 | 0.38 | 0.04 | 0.15 | -0.01 | -0.21 | 0.01 | -0.2 |
| RL                  | 0.23  | -0.21 | 0.19  | -0.02 | -0.4 | -0.3 | 0.22 | 0.27 | -0.06 | -0.03 | 0.39 | -0.1 |
| NTR                 | 0.1   | 0.16  | -0.14 | 0.14  | -0.6 | 0.57 | -0.2 | 0.03 | 0.13  | 0.12  | -0.1 | 0.02 |
| DF1 <sup>st</sup>   | -0.17 | -0.24 | 0.45  | 0.1   | 0.11 | 0.17 | -0.4 | 0.1  | -0.23 | -0.29 | -0.1 | 0.41 |
| DF50                | -0.27 | 0.15  | -0.04 | 0.03  | 0.38 | 0.12 | 0.28 | -0   | 0.11  | -0.05 | -0.3 | -0   |
| DTP                 | -0.24 | 0.32  | 0.02  | -0.2  | -0.2 | 0.24 | -0   | -0   | 0.12  | -0.33 | 0.39 | 0.11 |
| PL                  | 0.23  | 0.37  | 0.11  | 0.08  | -0.1 | -0   | 0.25 | 0.19 | 0.16  | 0.04  | -0.4 | 0.18 |
| PW                  | 0.08  | 0.47  | 0.24  | 0.15  | 0.25 | 0.09 | 0.29 | 0.19 | -0.13 | 0.2   | 0.42 | 0.32 |
| PCS                 | -0.02 | 0.41  | 0.39  | 0.18  | -0.2 | -0.3 | -0.1 | -0.1 | -0.02 | -0.33 | -0.3 | -0.3 |
| NPP                 | 0.25  | -0.03 | -0.4  | -0.12 | 0.03 | -0.1 | 0.24 | -0.1 | 0.16  | -0.68 | 0    | 0.27 |
| 10PW                | 0.27  | 0.07  | -0.22 | 0.32  | 0.11 | 0    | -0.2 | -0.4 | 0.01  | 0.26  | 0.03 | 0.23 |
| PY                  | 0.3   | 0     | 0.06  | -0.21 | 0.09 | -0.1 | -0.1 | 0.15 | 0.41  | 0.14  | -0.1 | -0   |

DE1<sup>st</sup>: Days to 1<sup>st</sup> plant emergence; DE50: Days to 50 % plant emergence; PH30: Plant height at 30 days after sowing; PH60: Plant height at 60 days after sowing; PH90: Plant height at 90 days after sowing; SD: Stem diameter; LA: Leaf area; LAI: Leaf area index; RL: Root length; NTR: Number of total root; DF1<sup>st</sup>: Days to 1<sup>st</sup> flowering; DF50: Days to 50 % flowering; DTP: Days to 1<sup>st</sup> Picking; PL: Pod length; PW: Pod width; PCS: Pod cross section; NPP: Number of pods per plant; 10PW: 10 pod weight; PY: Pod yield per plot

**Table 7.** Index based score and scaled score index of PC1 and PC2

| Treatment combination           | Index score (PC1) |              | Index score (PC2) |              |
|---------------------------------|-------------------|--------------|-------------------|--------------|
|                                 | Index score       | Scaled index | Index score       | Scaled index |
| A <sub>0</sub> × B <sub>0</sub> | -5                | 0            | -1.15             | 0.28         |
| A <sub>0</sub> × B <sub>1</sub> | -0.5              | 0.44         | -0.62             | 0.38         |
| A <sub>0</sub> × B <sub>2</sub> | -1.85             | 0.31         | 2.85              | 1            |
| A <sub>1</sub> × B <sub>0</sub> | -1.97             | 0.29         | 1.54              | 0.77         |
| A <sub>1</sub> × B <sub>1</sub> | 0.26              | 0.51         | 1.84              | 0.82         |
| A <sub>1</sub> × B <sub>2</sub> | 0.17              | 0.5          | -1.44             | 0.23         |
| A <sub>2</sub> × B <sub>0</sub> | 2.17              | 0.7          | 1.98              | 0.85         |
| A <sub>2</sub> × B <sub>1</sub> | 4.94              | 0.96         | -0.8              | 0.35         |
| A <sub>2</sub> × B <sub>2</sub> | 5.31              | 1            | -0.21             | 0.45         |
| A <sub>3</sub> × B <sub>0</sub> | -0.77             | 0.41         | -2.73             | 0            |
| A <sub>3</sub> × B <sub>1</sub> | -0.19             | 0.47         | -1.08             | 0.3          |
| A <sub>3</sub> × B <sub>2</sub> | -2.57             | 0.24         | -0.19             | 0.46         |

**Fig. 1.** Scree plot showing variance of 1<sup>st</sup> 10 principal components.**Fig. 2.** Index based and principal component analysis (PCA) scaled index of treatment combination for traits of Raikia bean. A: Index plot based on PC1; B: Index plot based on PC2

the cutoff line suggested in considering for further study. Similarly, the traits allocated to PC2 were impacted by A<sub>0</sub> × B<sub>2</sub>, A<sub>2</sub> × B<sub>0</sub>, A<sub>1</sub> × B<sub>1</sub> and A<sub>1</sub> × B<sub>0</sub> treatment combinations found out of cutoff line mark (Fig. 2). The findings were well explained by understanding the mean performance study and multivariate analysis. Therefore, the study found well justified in considering the traits and treatments.

## Conclusion

This study provides one of the first systematic evaluations of integrated phosphorus management and biofertiliser use for Raikia bean (*Phaseolus vulgaris*), an under-researched indigenous variety of southern Odisha. The results demonstrate that combining

*Rhizobium* inoculation with phosphorus fertilisation significantly improves crop establishment, growth and productivity, thereby addressing a critical knowledge gap in the agronomic management of this locally important legume. The maximum pod yield (4.22 kg plot<sup>-1</sup>) recorded under *Rhizobium* + P<sub>2</sub>O<sub>5</sub> at 60 kg ha<sup>-1</sup> represents a substantial yield enhancement for Raikia bean cultivation under the prevailing agro-climatic conditions. However, economic analysis revealed that *Rhizobium* combined with a moderate phosphorus dose (30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>) achieved statistically comparable yield performance while delivering the highest benefit-cost ratio (2.48). This indicates that beyond a certain threshold, higher phosphorus inputs may increase costs without proportionate economic gains. Multivariate analysis strengthened these conclusions. Multivariate

analysis of variance confirmed significant treatment-induced variability across multiple growth and yield traits, while PCA revealed strong trait interrelationships and consistently ranked *Rhizobium* + 30 and 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> as the most influential treatment combinations based on principal component scores and scaled indices. These statistical outcomes provide robust support for integrating agronomic, economic and multivariate evidence in recommending optimal nutrient management. While the findings are promising, the study was conducted at a single location and season and economic estimates were based on constant market prices. Therefore, caution is required when extrapolating the results to other agro-ecological zones or production systems. Overall, the integration of *Rhizobium* inoculation with P<sub>2</sub>O<sub>5</sub> at 30 kg ha<sup>-1</sup> emerges as a sustainable, cost-effective and environmentally sound practice for Raikia bean cultivation. Adoption of this strategy can reduce dependence on chemical fertilisers, enhance nutrient-use efficiency and improve farmer profitability. Future research should focus on multi-location trials, long-term soil health impacts and evaluation of combined biofertiliser consortia to further refine recommendations for broader adoption.

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## Authors' contributions

PB, CP, KP and BD conceptualised the study. PB, MV and SM were responsible for the collection of research data and its interpretation. PB, KP and CJ prepared the manuscript. PPM, SKD and KP performed data analysis and language editing. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

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