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Differential above- and belowground responses of mungbean (*Vigna radiata* L.) cultivars with diverse phenology to contrasting soil phosphorus distribution

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Abstract

Deep placement of phosphorus (P) fertilizer significantly increases crop yield and nutrient uptake in rainfed cropping systems. However, genotypic differences in root system architecture (RSA) play an important role in response to P rates and placement strategies. This study investigated genetic variation in RSA and its effect on exploiting deep P bands in four contrasting, early- to late-maturing mungbean (*Vigna radiata* L.) varieties. Four P treatments were control (no additional P), surface (30 mg P mixed in the top 5 cm), sub-layer (30 mg P mixed at 20- to 25-cm depth), and deep band (30 mg P applied in a band at 20-cm depth). The randomized complete block design included four replications. RSA was measured in the top and bottom 30 cm of the soil profile. Shallower P placement widened root growth angle by 14%, while deeper placements increased mean root diameter and root volume by 15% and 31%, respectively. Deep banding and sub-layer treatments advanced flowering and increased pod yield in the early-maturing variety Berken, without significantly altering root surface area, P uptake, or shoot P concentration. Berken also showed the lowest shoot P concentrations, least P uptake, and greatest internal P use efficiency. Genotypic differences in RSA and root functioning played a major role in response to P placement, with the strongest response observed in the deep P band treatment, despite a lack of root proliferation. These findings provide insights into optimizing P placement and selecting mungbean genotypes for improved productivity in rainfed cropping systems.

Plain Language Summary

Placing phosphorus (P) fertilizer deeper in the soil helps crops grow better and take up more nutrients, especially in areas with limited rain. This study looked at how

Abbreviations: iPUE, internal phosphorus use efficiency; RSA, root system architecture.

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different mungbean varieties, with unique root structures, respond to P placed at different depths. Four treatments were tested: no added P (control), P in the top 5 cm (surface), P mixed at 20–25 cm (sub-layer), and P in a band at 20-cm depth (deep band). When P was placed deeper, roots grew thicker and increased in volume, while shallow P made roots spread out more. The early-maturing variety, Berken, produced the most pods and used P most efficiently, even though it took up less P and had lower P in its shoots. This shows that root traits and how plants use P are important for getting the most out of fertilizer. This study helps us understand how to place fertilizer better and choose the best mungbean types for dry conditions to grow more food with fewer resources.

1 | INTRODUCTION

Inclusion of grain legumes in crop rotations can deliver many benefits, including a reduced environmental footprint, reduced use of synthetic nitrogen (N) due to biological N fixation and reduced soil pathogen populations through greater host plant diversity, while also improving food quality for livestock and human health through improved dietary intake of minerals, vitamins, and fiber (Arnoldi et al., 2015; Parida & Das, 2005; Vaz Patto et al., 2015). Mungbean (*Vigna radiata* (L.) Wilczek) is one of the most widely grown grain legumes in China, Myanmar, Australia, and India (Nair et al., 2014), with a very strong market demand and good prices. Both biotic and abiotic factors are important constraints to mungbean production, with phosphorus (P) deficiency being one of the major limitations in major semi-arid growing regions of India and Australia (Araujo et al., 2015).

Phosphorus plays critical roles in crop phenological development and the accumulation of biomass and grain yield, which has resulted in widespread application of fertilizers and soil amendments that supply plant-available P. Traditional application strategies involve application of P fertilizers to the surface soil layers, either with or without subsequent incorporation by tillage. When P is applied to topsoil layers, it is typically mixed through the cultivated topsoil layers by tillage, and it can be rapidly adsorbed (fixed) to soil particles such as clay minerals and sesquioxides of aluminum (Al), iron (Fe), and calcium (Ca) and organometallic chelate (Roy et al., 2017). Conversely, in soils where P is not rapidly adsorbed to soil particles, surface P enrichment risks the movement of P and associated soil particles into nearby creeks and rivers during episodic rainfall events, potentially leading to eutrophication and deterioration of water quality (Kim & Li, 2016; M. Yuan et al., 2018). In drier environments, this shallow P can also be effectively stranded in soil layers that quickly dry out, effectively limiting plant access to P for extended periods during crop growth (Dang et al., 2015; Eckert, 1985; Howard & Tyler, 1987; Jarvis & Bolland, 1991; Li et al., 2014; Mackay et al., 1985; Norrish et al., 2003; D. K. Singh et al., 2005). Limited access to P via loss from the field as runoff or due to dry soil surface layers leads to reduced P availability for crop uptake and a loss of crop productivity. Optimizing P application rates and placement strategies is desirable to both maximize crop production and address growing environmental challenges (Kim & Li, 2016).

Deeper placement of P is a strategy that can allow landowners to better manage the P supply to crops as well as reduce the risk of environmental damage. Nkebiwe et al. (2016) conducted three meta-analysis studies that concluded that deep-placed (more than 10 cm deep) N and P were more effective for improving deep rooting, nutrient uptake, and yield than equivalent broadcast applications based on 1022 datasets from 40 field studies published from 1982 to 2015 (85% of studies were conducted since 2000). Collectively, deeper P fertilizer placement resulted in 3.7% higher yield than broadcast, and when co-location of N and P was combined with deep placement, yields were 27.3% (urea and soluble P) and 14.7% (ammonium and soluble P) higher than with conventional shallow placement. Given the greater prevalence of conservation farming practices, including reduced or zero tillage, this deeper placement typically occurs in concentrated bands that occupy relatively small proportions of the soil volume explored by roots.

Root responses to encountering a zone of enhanced P availability, like a fertilizer band, typically involve a proliferation response in the vicinity of the band (Anghinoni & Barber, 1980; Y. Chen et al., 2018; Grewal & Graham, 1999; Ma et al., 2021; Sander & Eghball, 1999; Trapeznikow et al., 2003; Yao & Barber, 1986), which maximizes the root surface area available to exploit this scarce nutrient resource. Interestingly, D. K. Singh et al. (2005) and Ma et al. (2009) have also highlighted that deep application of nutrients like P can also encourage roots to grow deeper, increasing the exploitation of available moisture in deeper profile layers. The combination of an increased duration of P availability in subsoils that remain moist for longer and a deeper root system that can more

efficiently extract water and nutrients like N from deep profile layers can substantially improve productivity and resilience of crops and pastures grown under variable seasonal conditions (V. Singh et al., 2012; Trapeznikow et al., 2003).

Root system architecture (RSA) encompasses key root traits like length, angle, depth, and branching capacity (Gregory et al., 2009; Rabbi et al., 2017; V. Singh et al., 2010; Wasson et al., 2012), influencing the spatial configuration of the plant root system and playing a vital role in water and nutrient absorption (Fitter, 1991; J. Lynch, 1995). RSA has been shown to respond to P availability, with the spatial distribution of roots able to influence the extent and timing of access to water and nutrients, thus impacting yield potential (de Dorlodot et al., 2007; Liang et al., 2017; J. Lynch, 1995; Ye et al., 2018). In a recent review, van der Bom et al. (2020) highlighted spatiotemporal trade-offs between efficient resource capture and pre-defined RSA, and advocated for a better understanding of how these trade-offs interact with genotype, environment, and management. Under adverse soil or environmental conditions, RSA could be a critical factor in determining nutrient acquisition and profitable crop production (de Dorlodot et al., 2007; J. Lynch, 1995; Strock et al., 2019; Ye et al., 2018), particularly for the acquisition and uptake of P given its relative immobility in most soils (Barber, 1995). Despite its importance, few studies have explored the implications of selection strategies targeting RSA traits (e.g., deep versus shallow root systems) for crop performance in soils with different P availability and profile distributions. Most recently, van der Bom et al. (2023) reported wheat (*Triticum aestivum*) genotypes with narrow root growth angle and deeper root systems increased deep soil exploration during early growth, with a tendency to more rapidly acquire P placed as a deep fertilizer band, whereas wide-angle genotypes with shallower roots increased root growth in the topsoil.

A better understanding of mungbean RSA may allow more targeted approaches to improve adaptation to water- and nutrient-limiting conditions that are currently constraining yields. However, genetic improvement of crop root systems requires knowledge of the intra-species variability in key root parameters and RSA, and how these are controlled genetically (O'Toole & Bland, 1987). An understanding of the relationships between RSA and plant productivity is also necessary before effective breeding and management strategies can be developed (Gowda et al., 2011; Henry et al., 2011; Joshi et al., 2016). Lawn and Rebetzke (2006) identified substantial variation in traits of potential agronomic, adaptive, or taxonomic interest among 115 accessions of mungbean, mainly from Australia, West Timor, Papua New Guinea, and India. V. Singh and Bell (2021) reported variability in RSA between contrasting early- and late-maturing mungbean varieties. However, genetic variation in RSA and its response to P application strategies with respect to plant growth and development in mungbean are largely unknown. Most commercially grown mungbean varieties flower very early and begin to produce pods, leading to cessation of further root growth (V. Singh & Bell, 2021) that may affect root proliferation around deeper P bands and P acquisition. The main aims of this study were therefore to explore the interactions between RSA of contrasting mungbean varieties and the distribution of P fertilizer, with implications for contrasting P fertilizer application strategies.

Core Ideas

- Genotypic differences in root system architecture play an important role in response to P placement strategies.
- Deep P banding tended to advance flowering and increased the mungbean pod yield for early-maturing cultivars.
- Observed effects of deep banding on flowering and pod yield occurred without influencing the total root surface area, P uptake, or shoot P concentration.
- Shallower placement of P resulted in a wider root growth angle.
- Mungbean roots showed no evidence of proliferation in and around a P band.

2 | MATERIALS AND METHODS

2.1 | Plant material

The experiment compared four commercial mungbean varieties from Australia with contrasting growth characteristics and maturity classes (Table 1), the yield potential of these varieties in the dry zone being around 2.0–3.0 t ha^{-1}. All varieties were produced by the National Mungbean Improvement Program, Queensland Department of Agriculture and Forestry (DAF), Australia, and have been described in detail by V. Singh and Bell (2021).

Briefly, Jade-AU (3511-9 × VC 2768A, released in 2013) is an early-maturing variety that dominates production in the Australian industry. It retains green leaf area until harvest and so can respond to residual soil water and nitrogen. Celera II-AU (M 773 × OAEM58-62, released 2015) is a recently released, early-intermediate-maturing variety with short stature and resistance to the bacterial disease halo blight caused by *Pseudomonas savastanoi* pv. *Phaseolicola*. Berken (released in1975, a direct introduction from the United States with no pedigree history) is an early-maturing, older variety with low yield potential that is highly susceptible to plant

TABLE 1 Selected mungbean varieties and their characteristics.

Genotypes	Days to flowering	Days to maturity	Seed size	50 Seed weight (g)
Berken	40	69	Medium–large	3.2
Jade-AU	42	70	Large	3.5
Celera-II AU	44	74	Small–medium	2.8
Putland	55	85	Small	2.5

diseases. It is more determinate than Celera II-AU in growth pattern, with canopy senescence occurring during pod filling and grain maturation. Putland (Berken × CPI20141, released in 1991) is a longer season, photoperiod-sensitive variety that produces large biomass and is much later maturing than the other three varieties in the production environments of northeast Australia (i.e., maturing in 75–85 days after sowing, compared to 50–60 days after sowing for other varieties).

2.2 | Experimental site and unit

The experiment was conducted in a temperature-controlled glasshouse at The University of Queensland, Brisbane, Australia (27°23′ S, 153°06′ E). Purpose-built root observation chambers were constructed from perspex sheets, with chamber dimensions being 60 cm high, 40 cm wide, and 3 cm thick. Transparent perspex (8 mm thick) sides were used to enable viewing and scanning of roots. The perspex sheets were screwed to the metal frame of the chamber and the backs of the chambers were lined with black plastic to allow easy removal at harvest. The chambers were wrapped in silver insulation to prevent exposure of the roots to light and to minimize fluctuations in soil temperature.

Each chamber was filled with 9 kg of air-dried soil (Australian Soil Classification [ASC]: Gray Brown Vertosol [Isbell, 2016], equivalent to USDA's Usterts-Vertisols in semi-arid climates), which was collected in bulk from the 10–30 cm layer of the soil profile from a commercial field on the central Darling Downs, near Jandowae (QLD, Australia). This soil was characterized by a clay content of 35%–40%, with key soil chemical characteristics determined using standard methods outlined in Rayment and Lyons (2010) (Nutrient Advantage Laboratory Services, Incitec Pivot Limited). Key chemical properties of the soil are presented in Table 2. The soil P status was considered marginal for crop growth, but there were no other deficiencies of macro- or micronutrients. The soil was air-dried and then crushed to 5 mm size with a jaw crusher before being thoroughly mixed (not sieved) to provide a homogenous growing medium. The bulk density of the packed soil in the root observation chamber (based on the volume of chamber and weight of soil in chamber) was estimated to be approximately 1.25 Mg m^{-3}.

TABLE 2 Chemical characteristics of the Vertosol soil used in the experiment.

Analyte	Results	Units
pH (1:5 H_2O)	7.5	
pH (1:5 CaCl2)	6.3	
Electrical conductivity (Sat. Ext)	1.2	dS m^{-1}
Organic carbon (Walkley & Black)	0.74	mg kg^{-1}
Nitrate Nitrogen	24	mg kg^{-1}
Ammonium Nitrogen	3.7	mg kg^{-1}
Phosphorus (Colwell)	23	mg kg^{-1}
Phosphorus Buffer Index (PBI-Colwell-P)	110	
Phosphorus (BSES)[a]	33	mg kg^{-1}
Cation Exchange Capacity (Amm-acet.)	48.7	cmol (+) kg^{-1}
Potassium (Amm-acet.)	0.70	cmol (+) kg^{-1}
Calcium (Amm-acet.)	23	cmol (+) kg^{-1}
Magnesium (Amm-acet.)	24	cmol (+) kg^{-1}
Sodium (Amm-acet.)	2.9	cmol (+) kg^{-1}
Copper (DTPA)	1.3	mg kg^{-1}
Zinc (DTPA)	0.91	mg kg^{-1}
Manganese (DTPA)	23	mg kg^{-1}
Iron (DTPA)	24	mg kg^{-1}

[a]BSES-P test uses 0.005 M sulfuric acid to extract P. This test was developed by former Bureau of Sugar Experimental Stations (BSES), Australia.

2.3 | Experimental design and P treatments

The treatments consisted of four mungbean varieties and four P application methods or rates. Four replicate chambers of each combination of variety and P treatment were laid out in a randomized complete block design. The P treatments were (1) "control", with no additional P applied; (2) "surface," where an additional 30 mg P was mixed into soil in the top 5 cm.; (3) "sub-layer," where an additional 30 mg P was mixed into a 5 cm layer of soil from 20- to 25-cm depth; (4) "deep band," where an additional 30 mg P was applied in a band across the root chamber at 20-cm depth. Only 30 mg P $chamber^{-1}$ was applied for each P treatment, except for the control with no added P. An application of 30 mg P $chamber^{-1}$ mixed in 1 kg soil for applications in the surface and sub-layer treatments equates to 24 kg P ha^{-1} at a bulk density of 1.25 Mg m^3. Recommended P rates in this region is around 20–25 kg P ha^{-1} for legume crops.



FIGURE 1 Added phosphorus treatments (A) "surface" mixed in the top 5 cm, (B) "sub-layer" deep dispersed layer at 20- to 25-cm depth, and (C) "Band" deep banded at 20-cm depth.

Phosphorus was applied as monoammonium phosphate (10:22:0 N:P:K). Since other basal nutrients were sufficient, no other nutrient applications were made. A diagrammatic representation of the P placement options is presented in the Figure 1.

2.4 | Growing conditions

Soil in each chamber was slowly wet up over a period of 4–5 days before being allowed to drain to near field capacity (FC) before sowing. FC was determined using the saturation and drainage technique. The soil in the chamber was saturated with water for 4–5 days to ensure complete saturation. Following this, the soil was allowed to drain freely for 2–3 days, with the soil surface covered using plastic sheets to prevent evaporation. The gravimetric water content was calculated based on the difference between the wet and dry weights of the soil. At sowing, four seeds of one of the four chosen varieties were sown in each chamber and gradually thinned to one established plant 6 days after germination. The chambers were arranged on a stand that gave a plant-to-plant spacing of 20 cm, and chambers were watered from the top every 10 days to return the soil to FC and avoid development of water stress. The watering interval of around 10 days was based on a previous study that included the same varieties (V. Singh & Bell, 2021). The day (8 a.m. to 6 p.m.) and night (6 p.m. to 8 a.m.) room temperatures were maintained at 30˚C and 22˚C, respectively.

2.5 | Measurements

Before the harvesting of the plants at 50 days after emergence, plant height (from base to top of the stem) and total number of branches/node (at the nodes) were recorded. Plants were then destructively sampled by collecting the shoots of each plant above ground level and separating them into stem, leaf, and pod. The total number of leaves, number of fully expanded leaves, and leaf area was determined using a LICOR Planimeter (Li-3000 leaf area meter) were recorded. Note, plants were harvested at 50 days, around physiological maturity, to ensure the assessment of intact root characteristics for comparison between varieties. Delaying harvest until full maturity was avoided, as roots begin to die and decompose at that stage, which could compromise the accuracy of root trait measurements.

After removing the shoots, chambers were saturated with water overnight, after which each chamber was laid flat and the top perspex plate was removed. Purpose-built plywood pinboards that matched the chamber dimensions and fitted with 3-cm long black nails positioned in a 2 cm × 2 cm grid were then placed on top of the exposed soil. The moist soil allowed the nails to be easily pushed into the soil of the chamber while preserving most of the intact RSA. The pinboards plus soil and roots were then held erect while the soil was washed from the pinboard using a very fine, low pressure water spray to minimize disturbance of the intact root system. The total number of nodules on the root system was recorded after root washing. The washed root system was then imaged with a digital camera (Canon, SX720 HS) mounted on a tripod and the images were converted to high-contrast black and white images using Adobe Photoshop software. Images were initially cropped to the same size, and then image adjustment and threshold tools were used to convert the image into black and white. The average root angle of the first and second lateral branches was determined relative to the vertical axis using openGelPhoto.tcl (www.activestate.com/activetcl), free software (Joshi et al., 2017). After imaging, the roots were stored in 70% ethanol in a cold room (4˚C) for later detailed measurement (Jansen et al., 2013; V. Singh & Bell, 2021).

Dry matter of each plant part (stem, leaf, pods, and roots) was obtained after drying in a dehydrator for 4 days at 70°C. Development of leaf area, root surface area, biomass, shoot mass (leaf + stem) and root mass were quantitatively determined. Macro- and micronutrient analyses were performed on the composite shoot samples (which included stem + leaf + pods) from an analytical laboratory (CSBP Soil and Plant Analysis Laboratory). All macro- and micronutrients, except total nitrogen, were measured in the digested plant samples using inductively coupled plasma spectroscopy (Table S1). Total nitrogen was determined using the Dumas high-temperature combustion method with a Leco analyser. Shoot P uptake (mg P per plant) was calculated as the product of shoot P concentration (%) and shoot mass. Similarly, internal P use efficiency (iPUE) was calculated as shoot mass divided by shoot P uptake (mg shoot dry matter per mg P uptake).

2.6 | Intact root characteristics

Images of intact roots were analyzed using WinRhizo Pro 2019 software (https://regentinstruments.com/assets/winrhizo). The image was acquired from the camera by electing the "origin" setting in the software, and the following settings were chosen—image resolution was 600 dpi, the root background was changed to gray scale and calibration was performed by marking the length and width of the image (60 cm × 40 cm). The saved calibration was loaded onto each image before the start of the analysis. Before loading the calibration, the root diameter classes were changed into 10 different widths with a width interval of 0.25 mm. The total root length (cm), total root surface area (cm^2), root surface area in the top and bottom 30 cm of the chambers, mean root diameter (mm), and the number of root tips, forks, and crossings were determined from image analysis. Images of intact roots were also analyzed based on vertical distribution within the root chamber, with the top 30 cm and bottom 30 cm analyzed separately. These analyses were conducted to determine whether varieties differed in their exploration of the top (0–30 cm) and bottom (30–60 cm) parts of the soil profile with the different fertilizer P placements.

2.7 | Statistical analysis

Analysis of variance (ANOVA) was performed using XLSTAT (2023.1.4. version). Data were statistically analyzed using two-way ANOVA to understand the main treatment effects of fertilizer treatment and varieties. Normal distribution of data test and standardization are automatically performed with the XLSTAT two-way ANOVA assessment. Fisher's least significant difference test ($p < 0.05$) was used to compare the treatment means.

3 | RESULTS

3.1 | Shoot and root growth of different varieties in response to P treatments

Visual differences in the shoot and root growth of each variety grown in the deep "Band" treatment are presented in Figure 2. The late-maturing variety Putland (Figure 2B) shows a relatively poor distribution of roots in the bottom soil profile layers, has thicker topsoil roots, and has no pods, whereas the early-maturing Jade (Figure 2A) and Berken (Figure 2C) and intermediate-maturity Celera II (Figure 2D) varieties show greater root proliferation in the bottom soil profile layers. Celera II also shows greater plant height and numbers of pods compared to the early-maturing varieties Jade and Berken (Figure 2).

In general, differences between varieties and P treatments were observed for several shoot and root parameters. Except for pod yield, all aboveground measured plant parameters did not show any overarching effects of P treatments, although there were significant interactions between P treatments and varieties for the belowground total root length and root surface area. A two-way ANOVA table is presented for main treatment and interactions effects on key shoot and root traits (Table S2).

Phenological characteristics such as the leaf appearance rate and time to first flowering were not influenced by P treatments, but phenological differences with respect to the number of early flowers were noted between early-, intermediate-, and late-maturing varieties, as expected. Early flowers were first recorded in the early-maturing varieties Jade and Berken, followed by the intermediate variety Celera II (Figure 3A). Putland had not flowered before the end of this experiment, which was in the pod development stages for the early- and intermediate-maturity varieties. Although there were no effects of P treatments that were consistent across varieties for the number of early flowers, there was a trend for a greater number of flowers (1.27 vs. 1.06, or ~20% more) in the deep banded and deeper dispersed P layer treatments than in the control (no added P) and surface (shallow dispersed) P layer treatments (Figure 3B).

3.2 | Plant biomass

Plant biomass, a combination of pod mass, shoot mass (leaf + stem), and root mass, differed among varieties (Figure 4A, $p < 0.001$). Celera II recorded significantly greater ($p < 0.001$) plant biomass (12.6 g) than either Jade (10.9 g) or Putland (10.2 g). Plant biomass was not influenced by P treatment (Figure 4B), and there were no interactions between P treatment and variety for total plant biomass or individual plant parts.

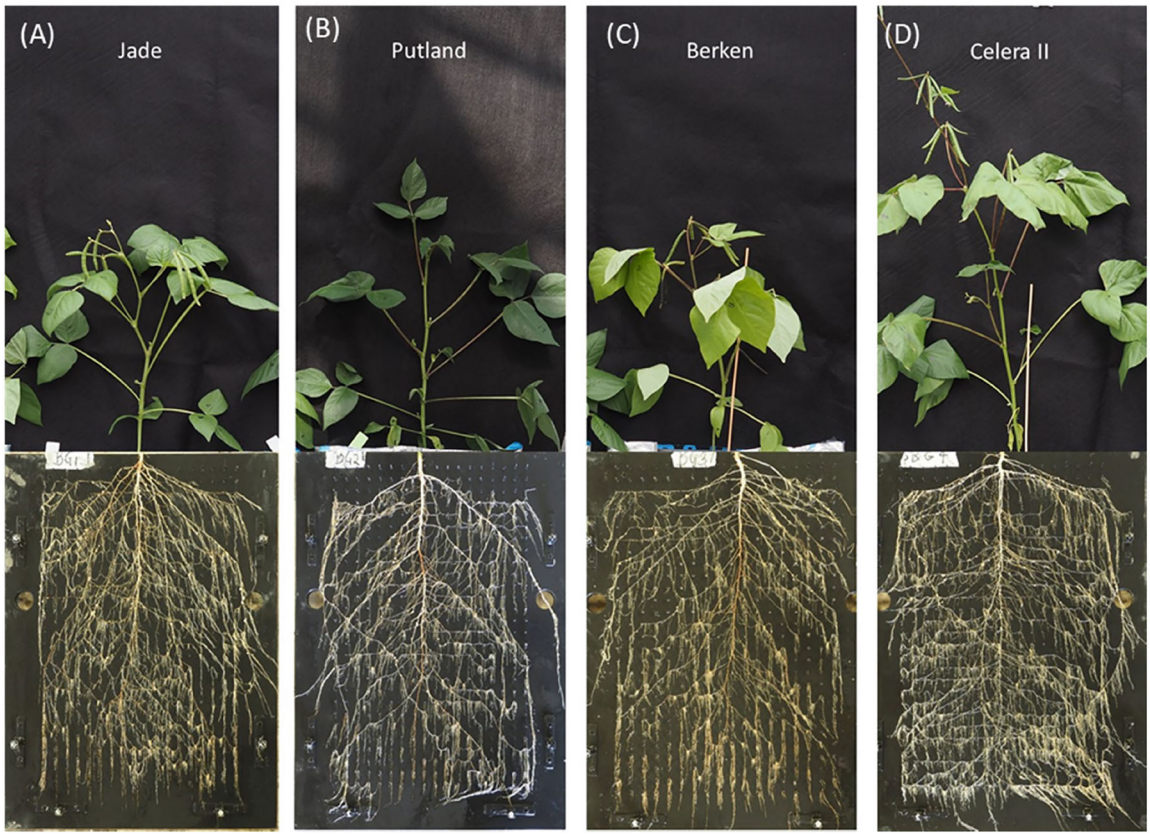


FIGURE 2 Visual differences in shoot and root morphology for varieties (A) Jade, (B) Putland, (C) Berken, and (D) Celera II for deep banded phosphorus treatment.

The mass of vegetative material (leaf + stem and shoot) differed among the varieties (Figure 4A) in a fashion that was consistent with the duration of the pre-flowering period, with Putland (8.59 g) and Celera II (8.00 g) producing significantly ($p < 0.001$) more vegetative shoot mass than either Jade (6.28 g) or Berken (6.09 g). The ratio of leaf mass to that of total vegetative matter was greatest for Putland (0.51), with the other three varieties ranging between 0.44 and 0.46 ($p < 0.001$) (Figure S1).

Root mass showed similar effects, with only varietal differences being statistically significant ($p < 0.001$). Consistent with the time to flowering and cessation of vegetative growth, the late-maturing variety Putland also had the highest root mass (1.60 g), compared with the other three varieties (0.92–1.1 g) (Figure 4A).

Unlike the responses in vegetative biomass, pod weight was influenced by both variety (Figure 4A) and, to some extent, P treatment (Figure 4B), although again there were no variety × P treatment interactions. Berken recorded the highest pod weight (5.31 g), compared with 4.14 and 3.81 g for Celera II and Jade, respectively (Figure 4A), although the total number of pods was highest for Celera II (16), followed by Berken (12) and least for Jade (8; $p < 0.001$). The deep banded P treatment recorded the highest pod weight (4.8 g), while the surface P treatment recorded the lowest pod weight (4.1 g; Figure 4B).

3.3 | Shoot P uptake and internal P use efficiency (iPUE)

Significant ($p < 0.001$) varietal differences in shoot P uptake, a product of shoot dry mass (leaf + stem + pods) and shoot P concentration, were recorded (Figure 5A). While the late-maturing Putland showed the highest P concentrations in plant biomass (data not shown), total P uptake was greatest for Celera II (30.8 mg) and lowest for Berken (19.8 mg), with Jade and Putland intermediate. P treatments resulted in statistically significant effects on P uptake ($p = 0.049$) and, to some extent, on iPUE ($p = 0.10$) (Figure 5B). There was a trend for treatments enriched with P in deeper profile layers (either deep banded or dispersed in sub-profile layers with or without topsoil P enrichment) to show greater shoot P uptake, although the lack of strong dry matter responses meant the iPUE in these treatments decreased compared with control or surface-applied treatment (Figure 5B).

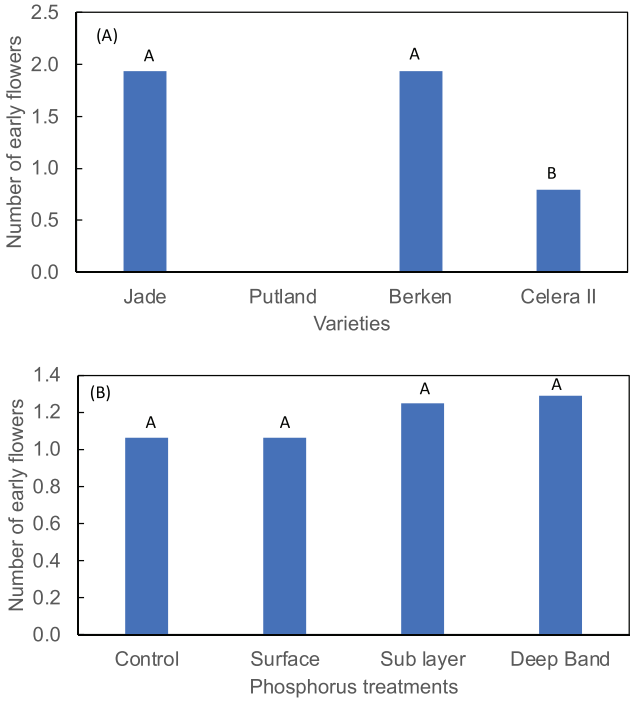


FIGURE 3 Main effects of varieties (A) and P treatments (B) on the numbers of early flowers. Letters on the bars represent Fisher's least significant differences (5%).

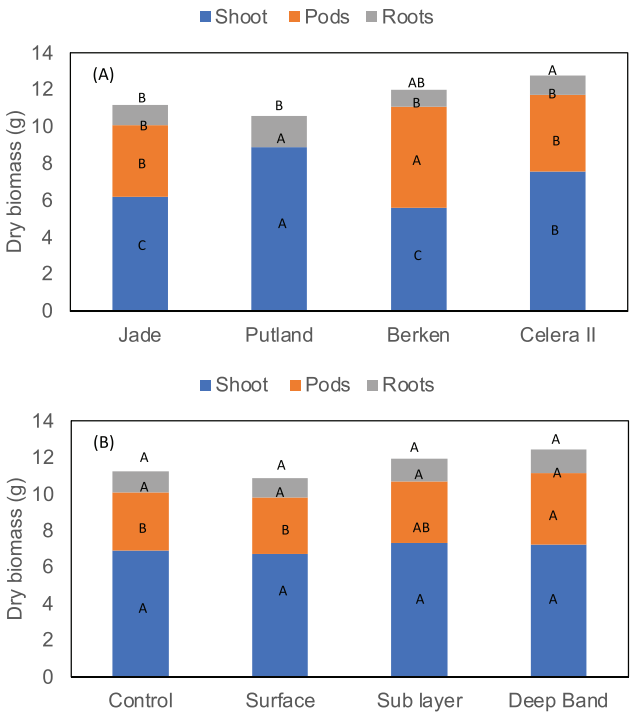


FIGURE 4 Main effects of varieties (A) and P treatments (B) on the distribution of dry matter between plant parts (shoot, pods, and roots). Letters indicating Fisher's least significant difference (5%) are shown above the bars for total plant biomass and within each shaded portion for individual plant parts (shoot, pods, and roots).

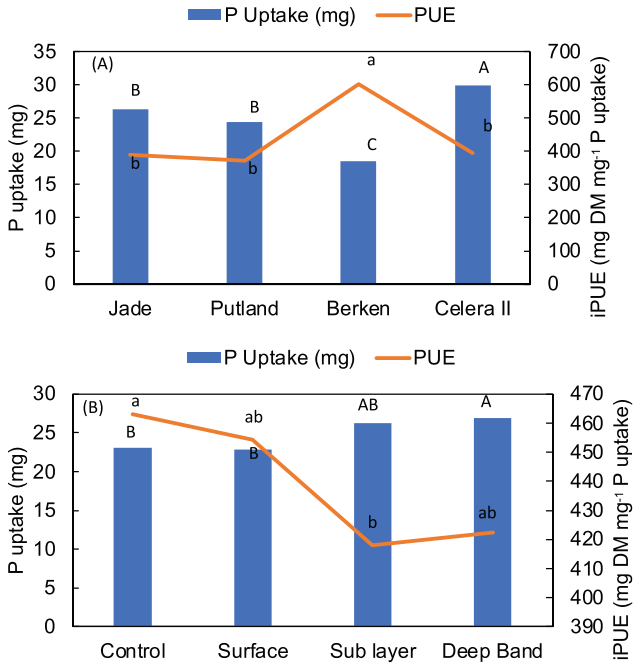


FIGURE 5 Differences in shoot P uptake and internal P use efficiency (iPUE) in response to (A) varieties and (B) P treatments. Capital letters indicate significant differences in P uptake, while lowercase letters indicate significant differences in internal P use efficiency. Letters represent Fisher's least significant differences (5%).

3.4 | Variety and P treatment effects on belowground root system architecture and root growth

Root growth angle differed among varieties, with the late-maturing Putland and intermediate-maturity Celera II recording greater root growth angles (64°–67°) than the early-maturity Jade and Berken (59°–61°; $p = 0.015$) (Figure 6A). The surface P treatment had a relatively higher root growth angle (67°) ($p = 0.060$) than the other three P treatments (around 61°; Figure 6B). Similarly, the number of nodules on mungbean roots was affected by both variety ($p = 0.053$; Figure 6C) and P treatment ($p = 0.038$; Figure 6D). Among varieties, Celera II (102) and Berken (86) recorded more nodules than either Jade or Putland (80 and 74, respectively) (Figure 6C). The deep banded and sub-layer dispersed P treatments recorded the most nodules (>90), compared with the surface P treatments with the lowest number of nodules (69; Figure 6D).

Significant root trait responses to P treatments were observed for both mean root diameter ($p = 0.050$) and total root volume ($p = 0.030$) in the whole root chamber, with these two root traits also responding similarly for roots in the bottom 30 cm of the root chambers (Figure 7). Mean root diameter and total root volume were greatest with deep P applications (either a dispersed subsoil layer or a deep band), with no differences between the other P treatments (Figure 7A,B), with

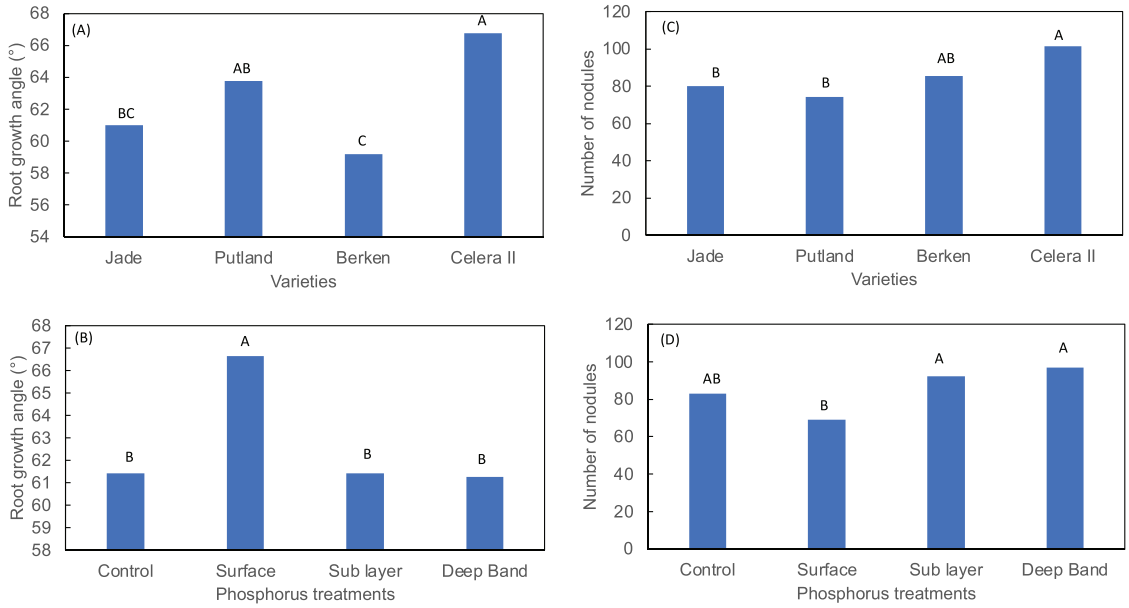


FIGURE 6 Phosphorus treatment effects on root growth parameters (A) root growth angle for varieties, (B) root growth angle for P treatments, (C) number of nodules for varieties, and (D) number of nodules for control, surface, sub-layer, and deep band treatments. Letters represent Fisher's least significant differences (5%).

the same responses recorded in the bottom 30-cm section (Figure 7C,D).

The total root length and total root surface area exhibited significant interactions between variety and P treatments ($p = 0.033$ and 0.002, respectively; Table S2). Since the P treatment responses were similar for both the traits throughout the 60-cm root chamber, we have illustrated this using root surface area responses (Figure 8). Root surface area varied from around 1200 to 1800 cm^2 with no significant differences among varieties for the control and surface P treatments (Figure 8A). However, varieties appeared to respond differently to the deep sub-layer and deep banded treatments. Jade and Berken showed significantly higher root surface areas (1630–1730 cm^2) in the deeper sub-layer treatment than either Putland or Celera II (1200 cm^2). In contrast, Celera II showed higher root surface area (1800 cm^2) in the deep banded treatment compared with the Berken (1200 cm^2) and Putland (1450 cm^2). Separate analyses of root surface area in either the top or bottom sections showed highly significant interaction effects ($p = 0.003$ and 0.014, respectively; Figure 8B,C). In the top 30-cm soil profile, P responses were like the whole soil profile with Jade and Berken showing higher root surface area in the top section compared with the Putland and Celera II, whereas Celera II showed highest root surface area compared with the deep banded treatment for Berken (Figure 8B). In the bottom 30-cm soil profile, Celera II had the highest root surface area with the deep banded treatment (979 cm^2), compared with the other P treatments (559–577 cm^2), while Jade had the highest root surface area with the deeper sub-layer, compared with control or the surface P treatments (Figure 8C).

There were clear varietal differences in root surface area in response to deep P treatments, with increases in root surface area in all compartments (whole chamber, top 30 cm, or bottom 30 cm—Figure 8A–C) in response to deeper applied P in all varieties except Putland. Responsive varieties, however, differed in how they responded to deeper P treatments. For example, in the top compartment, it was only Berken that showed significantly higher root surface area with the deeper sub-layer P treatment compared with the control or surface P treatments (Figure 8B). However, in the bottom compartment, a higher root surface area was recorded in the deeper sub-layer P treatment for Jade, while a similar response was recorded in Celera II for the deep banded treatment (Figure 8C).

4 | DISCUSSION

4.1 | Aboveground growth responses to variety and fertilizer P treatments

This study did not provide any evidence of interactions between fertilizer treatment and mungbean variety in terms of aboveground growth and development, although there were significant differences between varieties and smaller growth responses to fertilizer P placement. Differences in phenological development (time to flowering) between varieties were observed in this study, along with the rate of flower addition

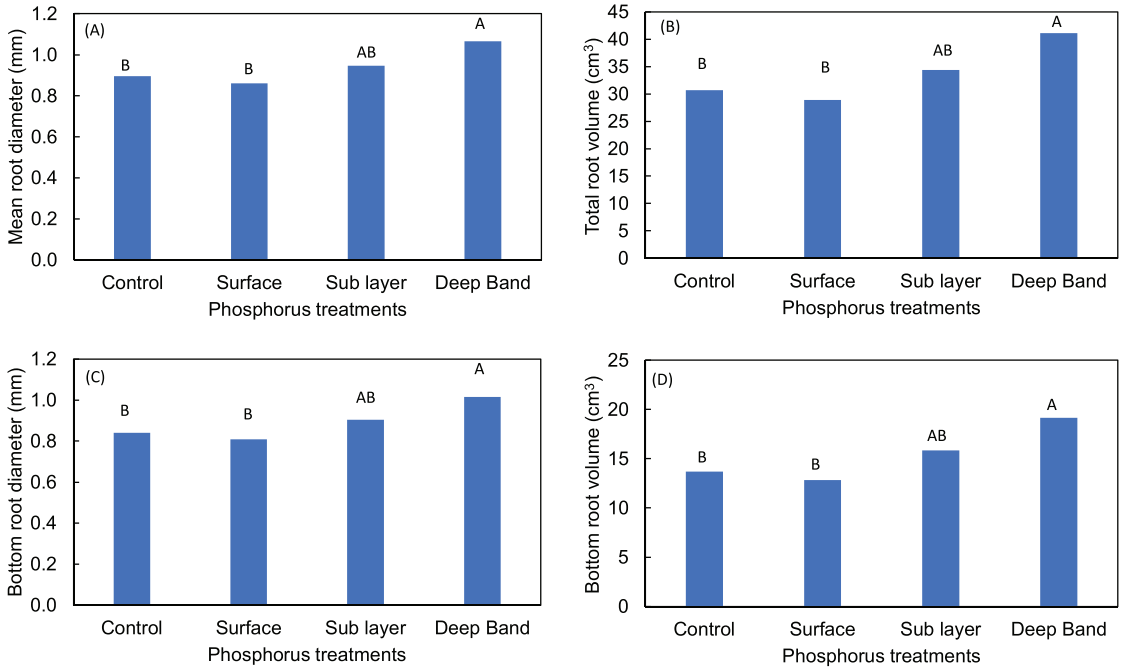


FIGURE 7 Phosphorus treatment effects on root growth parameters in the whole root chamber: (A) mean root diameter and (B) total root volume, in the bottom 30-cm root chamber; (C) bottom mean root diameter and (D) bottom root volume for control, surface, sub-layer, and deep band treatments. Letters represent Fisher's least significant differences (5%).

once flowering had commenced, with differences consistent with expected varietal characteristics and previous studies (V. Singh & Bell, 2021). While Putland did not flower during this experiment and continued vegetative growth for the duration, the early-maturing Jade and Berken flowered slightly quicker and exhibited a greater number of early flowers than the intermediate-maturity Celera II.

Increasing the supply of P (comparing the control treatment with all those with added P) had no statistically significant impact on aboveground biomass production in this study, possibly due to the combination of only moderately low P status and a low P demand from the mungbean plant, given there was only a single mungbean plant grown in each rhizobox that contained 9 kg air-dried soil. However, while there were no statistically significant increases in flower production in response to P addition, the deep-banded and deep subsoil layer P treatments had around 20% more flowers than the control or surface-applied P treatments. This suggested that deep placement of P contributed to advancement and/or increased production of flowering in the early-maturing varieties, and these effects were even stronger in terms of subsequent pod addition and growth. Increased flower production with increased P supply has been reported in many studies for various plant species (Kim & Li, 2016).

Phosphorus availability plays a critical role in plant growth and productivity, particularly in P-deficient soils where plants must rely on efficient uptake and utilization mechanisms to meet their P demands. While the overall growth responses in aboveground biomass were limited in this study, there were significant differences in P accumulation in aboveground biomass in response to both genotype and P treatments, and significant differences in iPUE were also recorded. These findings are consistent with several other studies highlighting that P uptake efficiency can vary significantly between genotypes due to differences in RSA and nutrient acquisition strategies (J. Lynch, 2011; Pang et al., 2017). While the shallow P application did not result in increased P uptake compared to the unfertilized control, consistent with the limited root development in those layers by all varieties, there were 14%–16% increases in plant P uptake with the Deep P layer and Banded treatments. Similar observations have been reported by Ma et al. (2021) and Miguel et al. (2013), who noted that plants with deeper root systems are more capable of accessing subsoil P deposits, particularly under conditions where surface soils dry out. It should be noted that surface soil would also be relatively drier than the deeper soil profile in the 60-cm deep rhizoboxes. This may explain why the Deep P layer and Deep P Band treatments in this study resulted in relatively greater increases in P uptake, as the enriched deeper P zones with relatively wetter soil were more accessible to deeper roots. Additionally, the additive effects of small increases in crop biomass (8%) and biomass P concentration (6%–8%) for deep P treatments collectively contributed to the observed increases in P uptake. Rose et al. (2011) also suggested that moderate increases in shoot biomass and P concentration are often sufficient to drive

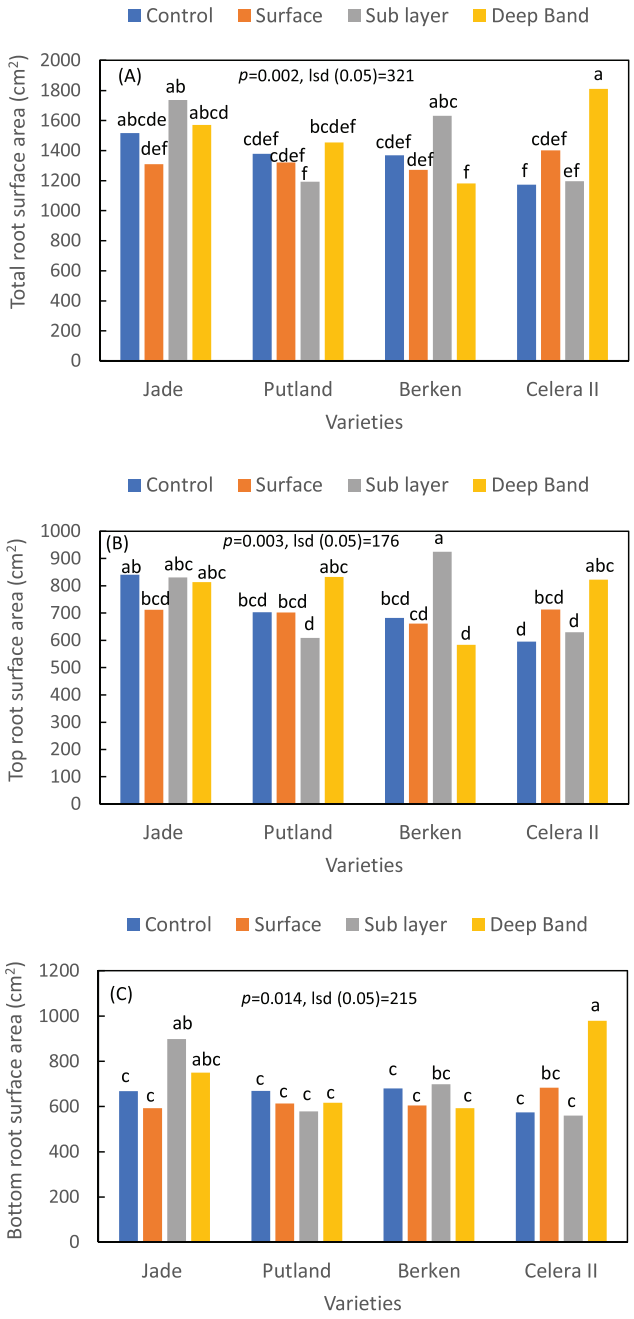


FIGURE 8 Interaction effect between varieties and phosphorus treatments on (A) total root surface area, (B) root surface area in the top 30 cm section, and (C) root surface area in the bottom 30 cm. Letters represent Fisher's least significant differences (5%).

meaningful improvements in P uptake. However, despite these increases, the P recovery efficiencies remained relatively low at 6% for the Deep P layer and 12% for the Deep P Band treatments. These values are within the range reported by Vandamme et al. (2016), who found that P recovery efficiency is typically low due to the strong sorption of P to soil particles and its limited mobility.

Interestingly, the greater relative increase in P uptake compared to biomass production resulted in a 10% decline in iPUE for Deep P treatments. This decline suggests that while plants were able to take up more P from the Deep P treatments, the excess P uptake was not effectively translated into proportional increases in biomass. Veneklaas et al. (2012) highlighted that iPUE often decreases when plants accumulate more P than is immediately needed for growth, particularly when P uptake exceeds the critical threshold required for optimal metabolic functioning. This phenomenon, often referred to as "luxury consumption" of P, has been reported in various crops, including mungbean (Irfan et al., 2017) and wheat (X. Zhu et al., 2012).

Differences in P uptake between varieties were much larger, with biomass P content in Celera II > Jade and Putland > Berken, with Berken (18.5 mg P) only acquiring 62% of the P taken up by Celera II (29.9 mg P). These varietal effects were due to contrasting differences in aboveground biomass (Celera II and Berken > Jade > Putland) and tissue P concentration (Jade, Putland, and Celera II > Berken). Interestingly, the delayed flowering in Putland, which allowed a longer time for root growth and presumably nutrient accumulation, did not result in greater uptake of P due to the slower rate of growth and dry matter accumulation (V. Singh & Bell, 2021). The low P recovery by the early-maturity variety Berken is consistent with other studies that have shown lower tissue P concentrations in response to rapid growth rates. For example, De Bauw et al. (2020) reported depleted shoot P concentrations induced by vigorous plant establishment in response to micro-doses of P placement in rice, while Vandamme et al. (2016) reported low tissue P concentrations that occurred during periods of rapid growth of plants in an initially high P medium due to rapid depletion of soil solution P in the root zone.

The differences in accumulation of plant P and biomass resulted in significant variation in iPUE between varieties, with Berken (602 mg DM mg P uptake^{-1}) > > Celera II, Jade, and Putland (372–395 mg DM [dry matter] mg^{-1} P uptake). The reason for these differences could be related to differences in leaf area index, chlorophyll content, and photosynthetic rate as reported for gluten-free wheat varieties (X. Zhu et al., 2012). In our studies, we did not directly measure these parameters; however, the early-maturing varieties Berken and Jade showed greater rates of expansion of individual leaf area during early growth (V. Singh & Bell, 2021), and both showed significantly greater dry matter accumulation per unit leaf area (1.8 g cm^{-2}) compared with the intermediate- and late-maturing varieties (1.0 g cm^{-2}) in this study. A greater dry matter per unit leaf area indicates greater photosynthetic rates for these varieties. A correlation coefficient matrix between iPUE and other key plant parameters also showed iPUE was significantly related to pod mass, specific leaf area (leaf area per unit leaf mass), plant biomass per unit leaf area, and calcium % (Table S3). Irfan et al. (2017) have also reported significant variability in the grain yield, P

accumulation, and iPUE among mungbean genotypes, with these observations suggesting there may be opportunities for further research to improve the efficiency of use of fertilizer P within existing mungbean varieties. Such experimentation would need to consider determination of leaf area expansion, shoot dry matter, tissue P concentration, and iPUE at various growth stages for a larger set of mungbean varieties.

4.2 | Belowground growth responses to variety and fertilizer P treatments

While there was little difference between varieties in aboveground biomass production, there were significant differences recorded in belowground parameters that are typically related to resource capture and nutrient supply, such as nodule numbers and root morphological traits such as root angle, root length, root surface area, and root volume, with these traits only occasionally interacting with fertilizer P treatment. Greater nodule numbers were recorded in the intermediate-maturing Celera II, which also exhibited the widest root angle and developed the largest total root volume, along with the early-maturing Berken. Both Berken and Celera II supported the largest root volumes as a result of greater total root length with narrow root diameters, with the late-maturing variety Putland unable to achieve similar metrics despite a longer period of root growth. Putland produced 16% less total root length, although these roots were significantly thicker than those of Berken and Celera II. Most previous studies have reported that a major portion of roots (>70%) are present in the top 20–30 cm layers (e.g., Gao et al., 2010). In our study, total root length in the top 30 cm and bottom 30 cm sections were generally similar, but roots in the top 30-cm compartment had a 12% greater mean root diameter. This resulted in around 10% greater root surface area and 22% greater root volume in the upper 30-cm compartment in this study.

Acquisition of water and nutrients is related to the ability of roots to exploit the available soil volume, and that ability is primarily governed by root length and root surface area in the various soil layers (Borkert & Barber, 1985; L. Li et al., 2006). However, such broad adaptive traits are likely to be less effective for enhanced recovery of fertilizer P, which is typically applied in heterogeneous patches in soils with otherwise low background P fertility. Low soil solution P concentrations and a reliance on diffusive supply to replenish rapidly P-depleted rhizosphere soil volumes result in root P uptake occurring primarily near root tips that are exploring "new" soil. An effective response to low soil P availability would therefore be expected to consist of enhanced root branching and proliferation responses that increase root length in the fertilized zone (Hill et al., 2005; Robinson, 1996), and in particular, increases the production of root tips that can exploit undepleted soil solutions (Richardson et al., 2009). However, the deep banding treatment in which the largest increases in P uptake were recorded suggested the opposite actually occurred in these mungbean varieties, with 10%–25% fewer root tips, forks, and crossings (indicators of root proliferation in response to P fertilization) than in the average of all other fertilized and unfertilized treatments (Table S4). This finding is surprising, as fewer root tips would typically indicate a reduced capacity to exploit new soil volumes. Instead, the increased P uptake observed in the deep banding treatment appears to be more strongly related to increases in root diameter, root volume, and root surface area, particularly in the bottom soil profile (Figures 7 and 8). Other studies have shown that thicker roots and greater root volume can increase acquisition and uptake of water and nutrients (J. P. Lynch, 2013; Wasson et al., 2012). These root traits likely allowed the plants to access P reserves more effectively, exploring deeper soil layers, including where the P bands are, rather than relying on fine root proliferation near the fertilizer band. This strategy proved to be somewhat effective in this study, where background P fertility was moderate, but would be less likely to be effective when those deeper soil layers are characterized by very low available P concentrations.

While there were occasionally significant interactions between P treatments and root parameters in either the top or bottom compartments (Figure 8B,C), there was no evidence of any increases in root length or proliferation in these mungbean varieties in response to P fertilization, with the predominant response being a general increase in root surface area achieved through an increase in root diameter. This was most obvious in the P treatments applied into deeper soil layers. While root thickening has been recorded as characteristic of root development in some dicotyledonous species like bean (Lynch, 2011), root expansion is typically reduced in favor of continued root elongation under conditions of low P availability. While there is evidence for thinner roots in the unfertilized control and ineffective shallow P treatments (Figure 7A,C), the thicker roots found in the deep P band or layer treatments would seem to represent an ineffective response to enhance P acquisition that is reflected in the relatively small increases in tissue P concentration and plant P uptake.

4.3 | P availability can influence the root growth angle and root distribution in the soil profile

Root growth angle has been noted to be the key indicator for a deep or shallow rooting genotype (X. Chen et al., 2017; V. Singh et al., 2011; Uga et al., 2013) and plays a major role in determining RSA. However, while root growth angle is primarily governed by plagiogravitropism (Nakamoto, 1994), it can also be influenced by other factors such as soil strength, soil water, soil temperature, and soil nutrition, especially P

and N (Liao et al., 2001; Nakamoto, 1993, 1994; Trachsel et al., 2011). Evidence from different crops has indicated that genotypes with narrow root growth angles are not only deep rooting, but they also tend to grow and develop more rapidly in both above- and belowground components, leading to early flowering and maturity (V. Singh et al., 2011). Genetic variability in root growth angle, leading to development of relatively shallower or deeper root systems, was noted for the mungbean varieties grown under high fertility conditions in a previous study, where early-maturing varieties Jade and Berken showed relatively narrower root growth angle (V. Singh & Bell, 2021). In the current study, in addition to the inherent varietal differences, P treatments also influenced the root growth angle. Shallower P treatment resulted in a wider root growth angle and a shallower distribution of root system (even though this did not result in additional P uptake), whereas availability of relatively less P in the topsoil for the control P treatment or concentrated availability of P in the deep soil resulted in narrower root growth angle and deeper distribution of root system. Other studies have reported differential stimulation of shallower basal root growth angles in P-deficient environments (Liao et al., 2001; Zhao et al., 2004). J. P. Lynch and Brown (2001) and J. Lynch (2011) reported that root growth angle has a dominant influence on P acquisition (sixfold) and yield of bean (threefold), and J. Zhu et al. (2005) reported twofold variation in P acquisition for maize genotypes, with these studies conducted in stratified soils where shallow root growth angle increased P acquisition by increasing topsoil foraging.

Phosphorus availability in shallower topsoil has been reported to control root branching, basal root length, and adventitious roots for common bean (*Phaseolus vulgaris*) (Miguel et al., 2013), but our results show mungbean does not respond similarly to increased availability of P in the shallow topsoil layer. Responses were more pronounced in response to deep P bands or enriched layers, with these placements resulting in increased root diameter and surface area that appeared to differ somewhat between varieties. Differences in varietal response to P availability differed between the top and bottom soil root compartments for the early- and intermediate-maturity varieties, but not for Putland. The early-maturing Jade and Berken showed significantly greater total root surface area for the deeper dispersed subsoil layer treatment, whereas the intermediate variety Celera II showed the greatest total root surface area for the deep banded treatment. In both cases, effects were more prominent in the bottom compartment rather than in the top compartment where the P enrichment occurred.

The lack of response to the enriched shallow topsoil in all mungbean varieties in this study may relate to the lack of strong lateral root development in that part of the soil profile. This is evident when comparing root images, showing no additional lateral root development in the surface-applied P compared with the control (Figure S2). Proliferation of roots in P-enriched topsoil would therefore appear to be determined by genetic factors that influence RSA, in addition to a response to increased availability of P in the topsoil, as reported in other studies (Y. Chen et al., 2011, 2017; Miguel et al., 2013). J. Zhu and Lynch (2004) have highlighted the genotypic variability in biomass investment by plants in response to P scarcity, with lateral root extension preferred due to the requirement for less biomass and P investment compared to extension of other root types. These authors suggested that enhanced lateral rooting in response to P stress may be harnessed as a useful trait for the selection and breeding of more P-efficient maize genotypes. Liao et al. (2001) reported basal roots of the P-inefficient common bean genotype extended deeper compared with those of the P-efficient genotype when experiencing P stress. In contrast, basal roots of the P-efficient genotype became shallower with P stress, while root growth angle reduced significantly, and roots became more horizontal (Liao et al., 2001). The extent to which such traits exist within mungbean germplasm should therefore be explored, particularly as mungbean is often grown in soil profiles that are strongly P-stratified, and the short crop phenologies do not offer much opportunity to develop deep and well-distributed root systems.

4.4 | Varietal differences in P acquisition and internal P use efficiency

This study has found significant variability in P uptake and P use efficiency between varieties (Figure 5A), with no apparent relationship between P uptake and total root surface area. The variety Jade had the greatest total root length and root surface area compared to other varieties but shoot P uptake was the second lowest. The other three varieties (early or late maturing) had similar or relatively less total root surface area or volume compared with Jade, but with contrasting P uptake. For example, Berken, Putland, and Celera II had the similar total root surface area and volume, but Berken had the lowest shoot P uptake, whereas Celera II had the highest P uptake. While there are likely to be other factors that are important for determining varietal differences in total P uptake, it is the apparent compensatory ability of the variety Berken to overcome poor P acquisition by much more efficient utilization of P within the plant to produce biomass that is of considerable interest. Rose et al. (2011) reported that internal P utilization efficiency is often lower in plants with high P acquisition efficiency as a result of high tissue P concentration. In our study, late- and intermediate-maturing Putland and Celera II had high P acquisition and shoot P concentration, compared with the early-maturing Berken, which had the highest iPUE. Interestingly, Berken had the lowest concentrations of P, N, and K in the shoot, yet it had

the highest shoot calcium concentration (Table S1). Calcium plays a critical role in cell division and expansion (Hepler, 2005) and has been shown to facilitate nutrient transport and uptake by maintaining cell membrane integrity and supporting xylem function (Gilliham et al., 2011). It is possible that the higher shoot calcium concentration in Berken contributed to more efficient nutrient distribution and utilization, resulting in greater biomass production per unit of P uptake and thus a higher iPUE. This hypothesis suggests a potential compensatory mechanism in Berken, where higher calcium concentration may offset the lower shoot P, N, and K concentrations by enhancing cellular processes critical for growth. There was also a close relationship between calcium and iPUE (Table S1; Figure S3), which requires further investigation to confirm whether calcium-driven improvements in nutrient transport and utilization directly influence P use efficiency in mungbean varieties or other crop species.

Hoad et al. (2001) and Romer and Schilling (1986) reported that nutrient requirements can vary considerably among varieties for other crop species. While relationships between P uptake and measured root traits were not recorded in our study, P uptake can also be influenced by the effective requirement of P during different stages of plant growth and development, which differed among the varieties. V. Singh and Bell (2021) have previously reported linear relationships between expanding total root surface area and leaf area obtained from sequential destructive sampling during early growth stages up to flowering for the same varieties used in the current study, but differences in phenology and the time to cessation of root growth between varieties would have potentially masked these effects when measured at a common harvest date. Root systems are known to be plastic in nature and can interact dynamically with soil physical, chemical, and biological factors at different stages of a growing season (Chen et al., 2017; J. Lynch, 1995; Wu et al., 2016). Development of roots occurs in synchrony with shoot growth (Wang et al., 2006), so characterization of RSA over time is important to understand the interactions between RSA and shoot growth dynamics and nutrient uptake. The vigorous root growth and more rapid rates of root extension seen in the early-maturing mungbean varieties appeared to be consistent with acquisition of enough water and nutrients to be able to support rapid shoot growth through increased dry matter accumulation per unit leaf area (V. Singh & Bell, 2021), or increased leaf transpiration (Pang et al., 2017), and might have been correlated with early flowering and podding characteristics for the early-maturing varieties studied (V. Singh & Bell, 2021). Collectively, our data would suggest that further exploration of mungbean germplasm for variation in iPUE could provide opportunities to improve fertilizer use efficiency in this species.

5 | CONCLUSIONS

This study highlights the significant role of RSA and P placement strategies in influencing P uptake and iPUE in mungbean varieties with contrasting phenological characteristics. The findings demonstrate that while aboveground biomass responses to P treatments were limited to flowering and podding, significant differences in P accumulation and iPUE were observed across varieties, particularly in response to deep P placement. This was especially evident when P was applied in a concentrated band compared to P applied in the shallow topsoil layers. The deep banding treatment consistently resulted in higher P uptake compared to shallow P applications, suggesting that deeper root systems and increased root surface area are more effective for accessing subsoil P reserves in stratified soils. This has important implications for optimizing P fertilizer application strategies to improve P recovery efficiency and crop performance in P-deficient environments.

The study found that varietal differences in response to P treatments were driven more by root morphological traits, such as root volume, root diameter, and root growth angle, rather than by root proliferation through increased root tips and forks. These findings challenge the common assumption that enhanced root branching is necessary for P acquisition from banded fertilizer applications. Instead, traits like increased root diameter and total root volume were more strongly correlated with P uptake, particularly in deeper soil layers. This suggests that selecting varieties with deeper and thicker roots could improve mungbean performance under deep banding P fertilizer strategies, particularly in conservation farming systems where tillage is minimized. The observed variation in iPUE among the tested varieties further emphasizes the importance of genotype-specific P use strategies. For example, the early-maturing variety Berken showed the highest iPUE despite having the lowest shoot P uptake, indicating that it was able to utilize the absorbed P more efficiently to produce biomass. This contrasts with varieties like Celera II, which had the highest P uptake but relatively lower iPUE. Varietal differences also occurred for root growth angle, a key trait influencing the vertical distribution of roots in the soil profile and, consequently, the plant's ability to access P from different soil layers. Berken had a narrow root angle compared to Celera II. Narrow root growth angles were associated with deeper root systems that effectively accessed P from deep bands, whereas wider root angles resulted in shallower root systems that were less effective in P uptake from deep placements. These differences highlight the potential for genetic improvement of mungbean varieties to enhance their P use efficiency, which could lead to more sustainable fertilizer use and better adaptation to P-deficient soils.

AUTHOR CONTRIBUTIONS

Vijaya Singh: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Marisa Collins**: Conceptualization; funding acquisition; project administration; writing—review and editing. **Michael J. Bell**: Conceptualization; formal analysis; funding acquisition; methodology; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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