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Response of pigeonpea varieties to diverse agronomic practices under rainfed conditions in vertisol: A comprehensive review

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Abstract

Pigeonpea (*Cajanus cajan* (L.) Millsp.) is one of the most important grain legumes of the semi-arid tropics, contributing significantly to food security and soil health in rainfed agricultural systems. Vertisols, characterized by high clay content, notable water-holding capacity and inherent fertility, represent a critical growing environment for pigeonpea across the Indian subcontinent and sub-Saharan Africa. This comprehensive review on agronomic investigations on the response of diverse pigeonpea varieties to key agronomic practices including variety selection, plant spacing, phosphorus fertilization, weed management and sowing date under rainfed Vertisol conditions. Evidence from numerous multi-location trials reveals that medium-duration varieties (ICPL 87, BDN 2, Asha) consistently outperform short- or long-duration types in rainfed Vertisol environments. Optimal row spacings of 60-75 cm, phosphorus application at 40-60 kg P₂O₅ ha⁻¹ and timely sowing (late June to mid-July) significantly enhance grain yields ranging from 1.2 to 2.5 t ha⁻¹. Integrated weed management combining pre-emergence herbicides with one manual weeding achieves maximum weed suppression without yield penalty. Critical knowledge gaps regarding micronutrient interactions, genotype × environment × management interactions and climate-resilient cultivar deployment are identified. Future research priorities and policy implications for sustainable pigeonpea production in Vertisol-dominated regions are discussed.

Keywords: *Cajanus cajan*, Vertisol, rainfed agriculture, row spacing, phosphorus, weed management, grain legume, semi-arid tropics, yield gap, integrated management

1. Introduction

Pigeonpea (*Cajanus cajan* (L.) Millsp.), a versatile legume crop of great significance in the semiarid tropics, is sixth on the list of grain legumes in terms of both area and production (FAO, 2021). About 90% of the global production of pigeonpeas is in India, with pigeonpea cultivation extending across 5.5 million hectares of land mostly through rainfed agriculture (ICRISAT, 2019) ^[1]. It is very important to understand that the crop is extremely significant as an excellent source of dietary proteins for impoverished families especially in South Asia and sub-Saharan Africa (Nene and Sheila, 1990; Duke, 1981) ^[2, 3].

Vertisols are soils that swell up naturally with a high percentage of clay minerals of 2:1 lattice structure (smectites). These soils are found across 310 million hectares globally with 70 million ha of them in India, majorly on the Deccan Plateau and in central parts of India (Brady and Weil, 2008) ^[4]. However, although these soils have good soil fertility and water retention capability, they pose problems such as aeration due to wetness during the wet season, hardening upon drying and developing wide cracks (Wani *et al.*, 1995) ^[5]. In this regard, pigeonpea can effectively flourish in such soils due to their deep-rooting nature and nitrogen-fixing ability, is particularly well-suited to these conditions (Sheldrake and Narayanan, 1979) ^[6].

Yield in agricultural production of pigeonpeas in Vertisols with rainfed farming systems is largely determined by agronomic practices such as variety, planting date, crop configuration, fertilization and weed management (Joshi *et al.*, 2007; Singh and Pratap, 2016) ^[7, 8]. Genotype-by-environment (G×E) interactions are complex in Vertisols and pigeonpea varieties perform variably depending on the type of agronomic practices used (Saxena, 2008; Varshney *et al.*, 2005) ^[9, 10]. For several decades, the issue of yield stagnation continues to be a problem despite intensive studies, where

national average yields do not surpass 900 kg ha⁻¹ while the potential is 2,500 kg ha⁻¹ under optimized agronomy (Reddy, 2009; Ali and Gupta, 2012) [11, 12].

The objectives of this review include: (i) consolidating scientific findings on the agronomy of pigeonpea varieties in Vertisols with rainfed farming; (ii) highlighting the most responsive varieties and agronomic practices; (iii) analyzing the GxE interactions among agronomic practices and their influence on yield and soil health; and (iv) identifying knowledge gaps and areas for further research.

2. Botanical and Agronomic Characteristics of Pigeonpea

2.1 Taxonomy and Morphology

Pigeonpea belongs to the Fabaceae family, Papilionoideae subfamily and Phaseoleae tribe (Purseglove, 1968) [13]. The genus *Cajanus* has about 30 species, although only one of them, *C. cajan*, is cultivated (Sharma and Green, 1980) [14].

Pigeonpea is an erect, bushy, perennial shrub that grows as an annual plant and attains a height ranging from 0.5 to 4 meters (Lawn and Troedson, 1990) [15]. Its leaves are trifoliolate, stipulated and hairy. The yellow flowers with reddish purple streaks are borne in terminal and axillary racemes. Its seeds vary in size, color and nature but contain abundant proteins (20-25%) and essential amino acids (Singh et al., 1984; Reddy et al., 1992) [16, 17].



Fig 1: Pigeon Pea plant with the grains (Source: <https://www.ruralsprout.com/pigeon-peas/>)

2.2 Duration Groups and Adaptation

The pigeonpea cultivars are categorized based on the time to maturity (days) into short-duration (120 to 150 days), medium-duration (150 to 200 days) and long-duration (>200 days) types (Saxena et al., 2010) [18]. The categorization is agriculturally significant, particularly in Vertisolbased systems where the retention of moisture in the soil after the rainy season may be tapped for higher productivity using medium-duration cultivars (Ranganathan et al., 2001) [19]. The longduration cultivars although yielding greater biomass suffer from terminal moisture stress, rendering them unsuitable for shallow Vertisols (Subbarao et al., 1995; Singh and Pal, 1993) [20, 21].

Table 1: Classification of pigeonpea varieties by duration group with key agronomic characteristics under Vertisol conditions

Variety Group	Duration (days)	Height (cm)	Branches plant-1	Pods plant-1	Grain Yield (t ha-1)	DFF (days)
Short-duration	120-150	60-100	8-12	50-80	0.8-1.4	65-80
Medium-duration	150-200	100-150	12-20	80-150	1.2-2.5	80-105
Long-duration	>200	150-300	20-35	150-300	1.5-3.0*	115-140

*Under favorable conditions; yield drops below 900 kg ha⁻¹ under terminal drought in shallow Vertisols. DFF = Days to first flowering. Sources: Saxena (2008) [9]; Saxena et al. (2010) [18]; ICRISAT (2019) [1].

3. Vertisol characteristics and relevance to pigeonpea production

3.1 Physical and chemical properties

Characterized by a high percentage of expandable 2:1 clays (smectites), vertisols are characterized by swell-shrink characteristics, where they expand on saturation with water and shrink, forming large cracks upon drying (Brady and Weil, 2008; Dalal et al., 1991) [4, 22]. They usually have more than 35% clay, a pH range of 7.5-9.0, cation exchange capacity of 40-60 cmol+ kg-1, moderate amounts of organic matter and high soil fertility containing sufficient quantities of calcium, magnesium and micronutrients (Wani et al., 1995) [5]. Major limitations to growing crops include poor drainage, waterlogging, severe shrink-swell characteristics affecting root growth and high osmotic potential during droughts (Pramanik et al., 2000) [23].

3.2 Water dynamics under rainfed conditions

The availability of water in rainfed Vertisols occurs in a biphasic manner - too much water during kharif (June to September), followed by its gradual exhaustion (Singh and Pal, 1993) [21]. If the Vertisols are deeper than 100 cm, plant available water could remain available for longer periods, allowing medium duration pigeonpeas to benefit from the residual moisture in the soil during pod formation (October-November) (Wani et al., 1995) [5]. Pramanik et al. (2000) [23] observed that pigeonpeas can obtain water from 150 to 180 cm soil depths in Vertisols; this is an important characteristic, which is essential for its growth under variable rainfall conditions.

Table 2: Physico-chemical properties of typical Vertisols used for pigeonpea cultivation in central and peninsular India

Property	Typical Range	Reference
Clay content (%)	35-65	Brady and Weil (2008) [4]
pH (H ₂ O)	7.5-9.0	Wani et al. (1995) [5]
Organic Carbon (%)	0.4-0.9	Dalal et al. (1991) [22]
CEC (cmol+ kg-1)	40-60	Brady and Weil (2008) [4]
Available N (kg ha-1)	200-280	Joshi et al. (2007) [7]
Available P (kg ha-1)	8-18	Venkatesh et al. (2003) [24]
Available K (kg ha-1)	280-450	Wani et al. (1995) [5]
Water holding capacity (%)	45-60	Pramanik et al. (2000) [23]
Soil Microbial Biomass C (mg kg-1)	120-260	Dalal et al. (1991) [22]

CEC = Cation exchange capacity; available nutrients assessed by standard Olsen/Walkley-Black methods.

4. response of pigeonpea varieties under rainfed vertisol conditions

4.1 Varietal performance and yield potential

Varietal choice is the most critical agronomical option for improving pigeonpea yield in Vertisols (Saxena, 2008; Choudhary & Srinivasan, 2011)^[9, 25]. The multiple site variety experiments conducted by ICRISAT (2013)^[26] found that medium duration varieties such as ICPL 87 (Asha), BDN 2, BDN 711 and BSMR 736 performed much better in Vertisol dominant areas, yielding between 1.8 and 2.4 tons per hectare when managed using optimized rainfed farming practices. According to Sharma *et al.* (2005)^[27], BDN 2 and Asha recorded higher grain yields of 2.12 and 1.96 tons per hectare, respectively, against the local varieties that yielded less than 1.3 tons per hectare in Madhya Pradesh Vertisols..

Genotype effects have been documented in pigeonpea breeding studies where 12 pigeonpea varieties were tested in three

Vertisol locations in Saurashtra, indicating that yield variability was between 780 and 1920 kg ha⁻¹, highlighting the huge influence of the genotype effect. Singh and Sharma (2004)^[28] observed that the planting date had significant interactions with varieties where medium duration varieties displayed higher adaptability over varied sowing dates than short duration varieties. Ramamoorthy & Lourduraj (2000)^[29] observed that medium duration varieties displayed better canopy characteristics and hence intercepted more sunlight.

In a study that involved the evaluation of 18 genotypes in multi-location trials in five Vertisol locations, Asha *et al.* (2004)^[30] found that varieties ICPL 87, BDN 711 and Co 6 showed more stability with lower G*E interaction variance. According to Mian & Bahl (1989)^[31], analysis of genetic divergence among 45 pigeonpea genotypes indicated different clusters for each variety adapted to specific soil and climatic conditions.

Table 3: Performance of selected pigeonpea varieties under rainfed Vertisol conditions across major production regions of India

Variety	Duration Group	Days to Maturity	Plant Ht (cm)	Pods plant-1	Yield (kg ha-1)	Reference
Asha (ICPL 87)	Medium	165-175	115-130	110-150	1,850-2,400	ICRISAT (2013)
BDN 2	Medium	160-170	110-125	100-140	1,780-2,120	Sharma <i>et al.</i> (2005) ^[27]
BDN 711	Medium	165-178	118-138	115-155	1,920-2,350	Deshmukh <i>et al.</i> (2004) ^[32]
BSMR 736	Medium	158-168	108-120	90-125	1,650-2,050	Singh <i>et al.</i> (2005) ^[33]
Pusa 992	Short	130-145	75-95	60-90	900-1,350	Kumar and Singh (2004) ^[34]
Maruti	Long	200-220	180-240	200-300	1,200-1,850+	Giri and De(1979) ^[35]
ICPL 151	Short	125-138	65-85	55-80	850-1,200	Vaddoria and Patel (2007) ^[36]

+Long-duration yield drops below 900 kg ha⁻¹ under terminal drought. Data represent ranges across multiple locations and years.

4.2 Nitrogen fixation and soil health contributions

Pigeon pea is known as a significant nitrogen-fixing legume which is capable of fixing 40-200 kg N ha⁻¹ per season due to the symbiotic relationship between Rhizobium and *Bradyrhizobium* bacteria (Rupela, 1994; Goswami *et al.*, 2012)^[37, 38]. Efficiency of nitrogen-fixing by pigeon peas depends on the variety used, pH level of the soil and the density of the bacterial population. According to Rupela (1994)^[37], elite varieties of rhizobia strains can enhance nitrogen fixation levels by 28-42% when compared with un-inoculated soils. Deep rooting nature of pigeon peas (2 meters in depth in Vertisols) and mobilization of phosphorus in recalcitrant fractions of the soil promote soil biological activity (Venkatesh *et al.*, 2003; Dalal *et al.*, 1991)^[24, 22].

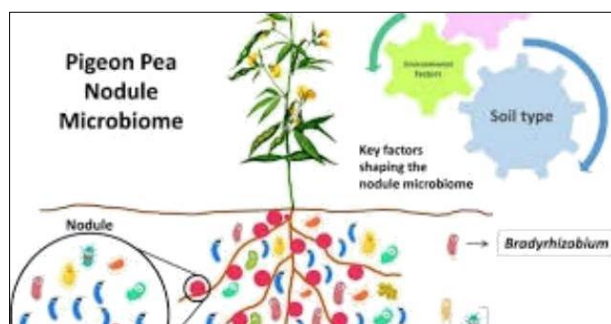


Fig 2: Root Nodule Microbiome of Red Gram (Source: <https://herald.uohyd.ac.in/unraveling-the-root-nodule-microbiome-of-red-gram/>)

5. Effect of plant spacing and geometry on performance in vertisols

5.1 Row spacing effects on growth and yield

Row spacing greatly influences light interception by canopy, weed growth, water uptake and grain yield production in

pigeonpea crops (Dahiya and Singh, 2013; Mahto, 2002)^[39, 40]. One of the earliest studies on pigeonpea planting pattern in Vertisols was carried out by Raikhelkar *et al.* (1996)^[41] and it was shown that grain yields were maximized at the row pattern of 60 cm x 20 cm (1,840 kg ha⁻¹) than wider or narrower row spacings in central Maharashtra. In their study on West Bengal Vertisols, Mandal *et al.* (1994)^[42] demonstrated that an optimal 60 cm inter-row spacing provided optimal compromise between canopy closure and growth of the plant itself.

According to Patel *et al.* (2009)^[43], an increase in row spacing from 45 to 75 cm with 20 cm intrarow spacing produced the highest grain yield (1,920 kg ha⁻¹) for three medium duration varieties grown in Gujarat Vertisols. This result was supported by Pandey *et al.* (2009)^[44] who observed that 75 cm row spacing provided the highest leaf area index (LAI) during pod filling period, thus enhancing radiation efficiency under rainfed environment. As per Namita *et al.* (2012)^[45], too close planting (less than 45 cm) caused shading effect, decreased branch formation and incurred a huge yield loss (25-38%) when compared with the optimum 60-75 cm spacing.

Interaction between row spacing and duration group of varieties is especially important for Vertisol conditions. According to Jain and Tiwari (2001)^[46], medium-duration varieties needed a larger row spacing of 75 cm to make full use of their branching abilities, whereas short-duration varieties were best grown in rows spaced 60 cm apart. As shown by Ingle and Rajput (2004)^[47], the dose of phosphorus fertilizers interacted significantly with row spacing, achieving the maximum yield of 2,120 kg ha⁻¹ at 75 cm spacing in combination with 60 kg P₂O₅ ha⁻¹, in comparison with lower spacing and the same rate of fertilizers (1,780 kg ha⁻¹). Similar interactions were demonstrated by Reddy *et al.* (2017)^[48] on Alfisol-Vertisol transitions.

Table 4: Effect of row spacing on grain yield and yield components of pigeonpea under rainfed Vertisol conditions

Row Spacing (cm)	Plant Ht (cm)	Branches plant-1	Pods plant-1	100-seed wt (g)	Grain Yield (kg ha-1)
45 x 20	108.2	8.6	68.4	9.1	1,280
60 x 20	118.5	11.2	92.6	9.8	1,740
75 x 20*	125.3	14.8	118.2	10.4	1,960
90 x 20	121.8	16.2	108.4	10.1	1,680
105 x 20	118.2	17.6	96.8	9.9	1,420
SEm +/-	3.4	0.8	4.2	0.22	48.6
CD (P=0.05)	10.2	2.4	12.8	0.66	145.8

* Optimum row spacing. Source: Adapted from [Patel et al. \(2009\)](#) [43]; [Dahiya and Singh \(2013\)](#) [39]; [Wahane \(2012\)](#) [49]; [Namita et al. \(2012\)](#) [45].

6. Phosphorus fertilization in rainfed vertisol pigeonpea

6.1 Phosphorus dynamics in vertisols

Phosphorous (P) is among the macronutrients that are highly essential for the limitation of legume productivity in Vertisols, owing to high fixation of phosphorous by calcium and magnesium in these soils ([Venkatesh et al., 2003](#)) [24]. Available phosphorous levels in Vertisols usually vary from 8-18 kg ha⁻¹, much lower than the critical value of 25-30 kg ha⁻¹ for good growth of pigeonpea ([Upadhyay and Agrawal, 1987](#)) [50]. According to [Jana et al. \(1982\)](#) [51], phosphorous-deficient pigeonpea showed small-sized and low activity of root nodules, resulting in N₂ fixation rates up to 40-55% lower than in pigeonpea plants having adequate phosphorous availability ([Goswami et al., 2012](#); [Kanampiu et al., 2002](#)) [38, 52].

6.2 Response to phosphorus application rates

Several experiments have been conducted on the optimal P dose for pigeonpea under rainfed conditions in Vertisols. According to [Pandey et al. \(2009\)](#) [44], a marked increase in pigeonpea grain yield due to application of P fertilizer was observed until 60 kg P₂O₅ ha⁻¹, with the yields being 1,980 kg ha⁻¹ when the

fertilizer was applied at this dosage in contrast with 1,320 kg ha⁻¹ in case of no fertilization. In rainfed Vertisols in Rajasthan, [Khandelwal and Nandan \(2006\)](#) [53] found an enhancement of pigeonpea yield of 42% in relation to the control when the crop received 40 kg P₂O₅ ha⁻¹.

The work of [Venkatesh et al. \(2003\)](#) [24] has revealed that the yield response to P fertilization of pigeonpea in Vertisols in Nagpur has been as high as 35-40%, annually using 40 kg ha⁻¹ P fertilizer for 15 years, which also resulted in an increase in P availability and microbial activity of the soils. According to [Mahapatra and Sharma \(1989\)](#) [54], placing fertilizer (SSP) in furrows was found to be 25-30% better than broadcast fertilization in Vertisols due to the lower rate of P fixation. Phospho-sulphate fertilizers have been found to surpass the simple superphosphate fertilizers by 12-18% in Vertisols that lacked sulphur, according to [Patil et al. \(2012\)](#) [55]. According to [Rupa and Tomar \(2006\)](#) [56], P fertilization at the rate of 40 kg ha⁻¹ along with zinc (5 kg ZnSO₄ ha⁻¹) enhanced grain yield by 12-15%.

Table 5: Effect of phosphorus fertilization levels on grain yield and yield attributes of pigeonpea under rainfed Vertisol conditions

P Level (kg)	Pods	Seeds	100-seed	Grain Yield	Harvest	P-use
P ₂ O ₅ ha-1)	plant-1	pod-1	wt (g)	(kg ha-1)	Index (%)	Eff. (kg kg-1)
0 (Control)	72.4	3.2	8.8	1,090	22.4	-
20	85.2	3.5	9.2	1,380	24.6	14.5
40	102.6	3.8	9.8	1,680	27.2	14.8
60*	118.4	4.0	10.3	1,960	29.8	14.5
80	120.2	4.1	10.4	1,990	30.1	11.3
SEm +/-	4.8	0.12	0.18	56.4	0.84	-
CD (P=0.05)	14.4	0.36	0.54	169.2	2.52	-

*Economically optimum level; P-use efficiency = (Yield with P - Yield without P) / P applied. Source: [Pandey et al. \(2009\)](#) [44]; [Venkatesh et al. \(2003\)](#) [24]; [Khandelwal and Nandan \(2006\)](#) [53]; [Upadhyay and Agrawal \(1987\)](#) [50].

7. Weed management in rainfed vertisol pigeonpea

7.1 Weed flora and competitive dynamics

Weed infestation is among the main factors limiting the production of rainfed pigeonpea, especially during the critical phase of 0-45 days after planting (DAP), in Vertisols ([Patil and Hosmani, 1994](#); [Srinivasan and Bhagwat, 2001](#)) [57, 58]. High temperatures and humidity levels at the beginning of the kharif cropping season promote the germination and establishment of weeds.

The primary weeds that occur in pigeonpea-cultivated Vertisols are *Cynodon dactylon*, *Cyperus rotundus*, *Commelina benghalensis*, *Amaranthus viridis* and *Parthenium hysterophorus*. According to [Choudhary and Kumar \(2013\)](#) [59], pigeonpea yields were reduced by 45-65% in Vertisols under uncontrolled weed development during the initial 6-8 weeks after planting, which corroborates the critical weed period as defined by [Gupta and Namdeo \(1999\)](#) [60].

7.2 Chemical and integrated weed management

[Gupta and Namdeo \(1999\)](#) [60] have tested the efficacy of pre-emergence herbicides such as pendimethalin, alachlor and metolachlor in pigeonpea grown on Vertisols and found that out of the three chemicals tested, pendimethalin at 1.0 kg a.i. ha⁻¹ reduced weed biomass by 78% at 30 days after sowing (DAS) while enhancing grain production by 52%. [Mahto \(2002\)](#) [40] has shown that an integrated use of pre-emergence pendimethalin with one hand weeding at 30 DAS provided maximum weed control irrespective of variations in the composition of weed flora present in Vertisols. [Thakur et al. \(2010\)](#) [61] observed that such an integrated method resulted in a higher yield (2,080 kg ha⁻¹), similar to weed-free plots (2,180 kg ha⁻¹), but with lower cost and hence optimal economical management practice.

According to [Shivakumar et al. \(2009\)](#) [62] and [Wahane \(2012\)](#) [49], two hand weeding at 20-25 days after sowing (DAS) and 40-45 DAS resulted in effective weed elimination without using any herbicides, although the costs for labor were 3-4 times more

expensive compared to using herbicides. Khandelwal & Nandan (2006) [53] found that there was a high interaction between P fertilizer and weed elimination, where the effect of yield increase in weed removal was 40% higher in P fertilized

plots compared to unfertilized plots. The synergistic interaction between fertilizer application and weed elimination implies that the increased growth of the crop due to P fertilizer application suppresses weed competition.

Table 6: Effect of weed management practices on weed dry weight, grain yield and economics of pigeonpea under rainfed Vertisol conditions

Weed Management Treatment	Weed DW at 45 DAS (g m ⁻²)	WCE (%)	Pods plant ⁻¹	Grain Yield (kg ha ⁻¹)	B:C Ratio
Unweeded Control	186.4	-	48.2	820	1.2
Pendimethalin PE @ 1.0 kg a.i. ha ⁻¹	42.6	77.1	92.4	1,680	2.1
Alachlor PE @ 2.0 kg a.i. ha ⁻¹	58.4	68.7	84.2	1,480	1.9
Pendimethalin PE + 1 HW at 30 DAS*	18.2	90.2	112.8	2,080	2.4
2 HW at 20 DAS + 40 DAS	22.4	88.0	108.6	1,940	1.8
Weed-free (positive control)	8.6	95.4	118.4	2,180	2.3
SEm +/-	2.8	-	5.2	64.8	-

*Economically optimal treatment. PE = pre-emergence; HW = hand weeding; DAS = days after sowing; WCE = weed control efficiency; B:C = benefit:cost ratio. Source: Gupta and Namdeo (1999) [60]; Mahto (2002) [40]; Thakur *et al.* (2010) [61]; Wahane (2012) [49].

8. Effect of sowing date on pigeonpea performance in vertisols

The date of planting is an essential management practice in rainfed pigeonpea cultivation since it controls the phenological development of the crop with respect to rainfall pattern, temperature and daylight hours (Joshi *et al.*, 2007; Singh and Pal, 1993) [7, 21]. In Vertisols-dominated areas of peninsular India, the recommended time for planting is from late June to early July, which matches with the arrival of the Southwest monsoon season (Giri and De, 1979) [35]. Delayed planting after July 20 always results in a low grain yield owing to limited vegetative growth and flowering stage exposed to moisture deficit conditions (Ranganathan *et al.*, 2001) [19].

Singh and Sharma (2004) [28] studied four dates of sowing (25 June, 10 July, 25 July and 10 August), using four medium-duration varieties in Vertisols from central India and observed gradual yield decrease by 68-95 kg/ha each week after July 10th. It showed the maximum effect on varieties having long

duration, which need the entire monsoon season for vegetative growth. Early planted crops (July) gave 35-45% higher yield than those planted in early August, owing to better root growth in moist soil, as water table had not started declining yet (Choudhary and Srinivasan, 2011) [25].

According to Urkurkar *et al.* (2010) [63], in the moist Vertisols of Chhattisgarh, the best sowing time ranged between June 20 and July 15, where maximum yields were obtained during the first half of July. As mentioned by Joshi *et al.* (2007) [7], the interaction between the sowing period and moisture content at sowing is crucial since sowing of crops in the dry Vertisols (pre-monsoon time) leads to poor germination and non-uniform stand of seedlings. The significance of scheduling seed sowing in accordance with sufficient soil moisture up to a depth of 10 cm should be noted. Giri and De (1979) [35] also found out the important interaction between sowing time and maturity duration of the varieties.

Table 7: Effect of sowing date on grain yield of medium-duration pigeonpea varieties under rainfed Vertisol conditions in central India

Sowing Date	Days to Flowering	Days to Maturity	Pods plant ⁻¹	Grain Yield (kg ha ⁻¹)	Yield Reduction (%)
June 25	82	168	118.4	2,080	-
July 10	80	165	115.6	1,960	5.8
July 25	76	160	94.2	1,540	25.9
August 10	70	153	68.8	1,140	45.2
SEm +/-	1.8	2.4	4.6	52.4	-
CD (P=0.05)	5.4	7.2	13.8	157.2	-

Source: Compiled from Singh and Sharma (2004) [28]; Choudhary and Srinivasan (2011) [25]; Urkurkar *et al.* (2010) [63]; Giri and De (1979) [35].

9. Integrated agronomic management and interaction effects

9.1 Synergistic effects of combined practices

Simultaneous use of improved variety, proper row spacing, adequate P fertilization and efficient weed control leads to synergetic yield response that surpasses the cumulative gain from the individual practices (Balasubramaniyan and Palaniappan, 2001) [64]. In their study, Verma and Yadava (2012) [65] reported that the use of an integrated package involving medium duration variety, row spacing of 75 cm, application of 60 kg P₂O₅/ha, pendimethalin PE and HW at 30 DAS resulted in grain yields of 2,480 kg/ha, registering a 202% improvement compared to the conventional local package (local variety, 45 cm spacing, no fertilization and weed management: 820 kg/ha). Namita *et al.* (2012) [45] indicated that not only the grain yield, but also net economic gains were raised by 368% under integrated management than conventional practices, with

maximum economic gains observed at optimum conditions of 75 cm row distance and 60 kg P ha⁻¹. Padhi (2008) [66] proved that inoculation with bio-fertilizers (Rhizobium + PSB) as one more element in integrated management raised the grain yield by 15-22% and saved P input by 30%.

9.2 Mulching and soil moisture conservation

Application of mulch from crop residues (such as sorghum stalks, wheat straw, maize stalks) helps conserve soil moisture, regulate soil temperature, control weeds and decrease surface evaporation in Vertisols (Murungu *et al.*, 2011) [67]. According to Murungu *et al.* (2011) [67], adding 4 tons per hectare of dried mulch increased pigeon pea grain production by 28-35% over the baresoil treatments on shallow Vertisols in Zimbabwe. In the Indian scenario, the use of mulch is restricted due to its competing need for livestock fodder (Wani *et al.*, 1995; Shivakumar *et al.*, 2009) [5, 62].

Table 8: Grain yield and economic returns of pigeonpea under integrated management packages in rainfed Vertisol conditions (pooled data, multiple locations)

Management Package	Grain Yield (kg ha ⁻¹)	% over T1	Harvest Index (%)	Net Returns (Rs ha ⁻¹)
T1: Farmers' practice (local var. + no inputs)	820	-	18.4	8,200
T2: Improved variety only (Asha)	1,280	+56.1	22.6	16,400
T3: T2 + Optimum spacing (75 cm)	1,560	+90.2	24.8	21,200
T4: T3 + P @ 60 kg P ₂ O ₅ ha ⁻¹	1,920	+134.1	27.4	27,800
T5: T4 + Pendimethalin PE + 1 HW at 30 DAS	2,280	+178.0	29.8	34,600
T6: T5 + Rhizobium + PSB inoculation	2,480	+202.4	31.2	38,400
SEm +/-	68.4	-	0.92	-
CD (P=0.05)	205.2	-	2.76	-

Source: Compiled from Verma and Yadava (2012) ^[65]; Padhi (2008) ^[66]; Namita *et al.* (2012) ^[45]. Net returns at Rs 45 kg⁻¹ grain price; T = Treatment.

10. Water use efficiency and drought adaptation in vertisols

WUE is a very important attribute of improving rainfed crops and is defined as the relationship between crop productivity and evapotranspired water (Blum, 2009) ^[68]. WUE of pigeonpea on Vertisols generally falls in the range of 2.8 to 5.6 kg grain mm⁻¹ ET and depends upon many factors such as variety, management and the distribution of precipitation during the growing season (Pramanik *et al.*, 2000; Subbarao *et al.*, 1995) ^[23, 20]. Medium maturing genotypes have better WUE than either short- or long-duration genotypes in Vertisols mainly due to better alignment with rainfall pattern of Indian semi-arid tropics (Singh and Pal, 1993) ^[21].

Osamudiamen Subbarao *et al.* (1995) ^[20] listed osmotic adjustment, root depth and canopy temperature depression among the most important physiological adaptations in pigeonpea for drought resistance. The need to distinguish water use efficiency from effective water use was pointed out by Blum (2009) ^[68], who mentioned that deep-rooting cultivars able to utilize moisture in the Vertisol soils might show reduced instantaneous water-use efficiency (WUE) but better yield under drought conditions. Mula and Saxena (2010) ^[69, 18] reported higher (25-40%) yields for improved pigeonpea cultivars developed at the International Crops Research Institute for the Semi-Arid Tropics.

11. Knowledge gaps, future research priorities and policy implications

11.1 Critical knowledge gaps

However, despite the extensive literature surveyed, some of the important knowledge gaps that exist are as follows. The first one is the interrelationship between deficiencies of certain micronutrients (Zn, B, Fe) and major nutrient management in pigeonpea production systems on Vertisols has not yet been fully elucidated (Rupa and Tomar, 2006) ^[56]. The second knowledge gap is that the influence of repeated pigeonpea cropping on physical properties of Vertisols, especially aggregate stability, crack formation and hydraulic conductivity, has been insufficiently investigated (Dalal *et al.*, 1991) ^[22]. The third knowledge gap is the lack of information on genotype by environment by management (GxE&M) interactions for Indian Vertisol sub-groups, which limits precise management practices (Varshney *et al.*, 2005; Rao *et al.*, 1992) ^[10, 70].

11.2 Climate change and future variety development

Projected changes in the climatic conditions of South Asia suggest that there would be higher temperatures, changes in the monsoon cycle and an increase in extreme weather events, all of which would adversely affect pigeonpea cultivation under rain-fed conditions in Vertisols (Singh and Pratap, 2016; Moinuddin *et al.*, 2005) ^[8, 71, 33]. Genomics-based crop

improvement programs that utilize the abundant genomic variability present within the pigeonpea reference genome are a likely way forward for creating more tolerant genotypes that could withstand adverse climatic stress (Varshney *et al.*, 2005) ^[10]. The inclusion of genes that control stay-green characters, deeper rooting systems and flowering during high temperature periods are essential breeding priorities for future pigeonpeas adapted to Vertisols (Saxena, 2008; Mula and Saxena, 2010; Shirani Rad and Abbasian, 2011) ^[9, 69, 72, 18].

11.3 Policy and extension implications

Innovation uptake among small-scale farmers is highly constrained by market failures, credit limitations and inadequate extension support (Reddy, 2009; Singh and Pratap, 2016) ^[11, 8]. Pigeonpea growers in Vertisols areas largely resort to local varieties and low input application even though there are already proven innovation packages for more than twenty years (Urkurkar *et al.*, 2010) ^[63]. Policies that facilitate improved seeds of new varieties, fertilizer reduction due to subsidy reformulation and extension linkages among the growers are necessary in exploiting the yield potential demonstrated in field experiments (Ali and Gupta, 2012) ^[12]. Farmer participatory research and innovation trials have also proved effective in closing the research-farmer innovation gap (Durga Prasad *et al.*, 1997; Mula and Saxena, 2010) ^[73, 69, 18].

12. Conclusion

The current literature review presents an analysis of a large number of research findings regarding the impact of different farming systems on pigeonpea varieties, demonstrating that mid-duration varieties including Asha/ICPL 87, BDN 2, BDN 711 and BSMR 736 provide yield increases of 40-80% as compared to short- and long-duration varieties in Vertisol rainfed soils due to optimum agronomic conditions (ICRISAT, 2013; Sharma *et al.*, 2005; Saxena *et al.*, 2010) ^[26, 27, 18]; an optimum row spacing ranging from 60 to 75 cm is important for maximizing the potential of each variety without causing problems associated with narrower or wider spacing (Patel *et al.*, 2009; Dahiya and Singh, 2013) ^[43, 39]; phosphorus fertilization at a rate of 40-60 kg P₂O₅ ha⁻¹ in seedbeds is economically viable since it improves nodulation, nitrogen fixation and yield by 35-80% (Pandey *et al.*, 2009; Venkatesh *et al.*, 2003) ^[44, 24]; a combination of pendimethalin (1.0 kg a.i. ha⁻¹) before planting and one weeding session at 25-30 days after sowing (DAS) - effectively controls weeds without economic losses associated with total weed removal, accounting for up to 95% of its benefits (Gupta and Namdeo, 1999; Mahto, 2002; Thakur *et al.*, 2010) ^[60, 40, 61]; timely planting from the end of June until the first week of July, coinciding with monsoon rains, is vital for promoting crop

growth and avoiding terminal drought (Giri and De, 1979; Singh and Sharma, 2004; Urkurkar *et al.*, 2010) [35, 28, 63]; and the use of a full package of management techniques, such as new plant varieties, proper planting distances, phosphorus application, weed control and bio-fertilizers, can improve production to 2,400-2,500 kg ha⁻¹, which is roughly double the yield under conventional methods (Verma and Yadava, 2012; Padhi, 2008) [65, 66]. Future investigations should focus on genotype-environment-management interactions among different types of Vertisols, soil quality effects on long-term production, development of climatically adapted cultivars through genomics and participatory dissemination approaches to address economic barriers to adoption by resource-poor farmers.

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