Review Article

Pigeon pea (*Cajanus cajan* (l.) Millsp) based cropping systems for sustainable production - a comprehensive review

Abstract

Intercropping systems involving pigeon pea significantly enhance productivity, economic returns, and land-use efficiency compared to sole cropping systems. Studies highlight that transplanting 4–5-week-old pigeon pea seedlings, particularly with finger millet, soybean, or mungbean, improves pigeon pea equivalent yield (PEY), land equivalent ratio (LER), and net returns due to better resource utilization and reduced competition. Legume-based intercropping systems leverage complementary nutrient dynamics and higher market value, achieving superior returns. Integrated nutrient management (INM) further optimizes growth, yield, and soil fertility, enhancing system sustainability. Strategic planting geometries, such as paired rows and additive systems, maximize the synergy between crops, while spatial arrangements like pigeon pea + black gram-wheat sequences yield high productivity (17.70 q ha^{-1}) and profitability (₹23,867 ha^{-1}). Utilizing nitrogen-fixing legumes in rotation systems significantly boosts land-use efficiency and energy utilization. Conventional tillage systems improve yields of pigeon pea and finger millet through enhanced weed control, while INM strategies provide synchronized nutrient supply in rotation systems, optimizing grain and straw yields. Intercropping pigeon peas with sorghum or sunflower notably reduces pod damage and wilt incidence. These systems also promote ecological benefits, such as enhanced activity of predators, parasitoids, and insectivorous birds, which mitigate pest populations. Integrated pest management (IPM) within intercropping systems further reduces pod borer damage and improves productivity. For instance, pigeon pea intercropped with sorghum recorded reduced pest incidence, lower pod damage, and higher productivity compared to sole cropping. These benefits stem from intercrop-emitted volatile compounds that deter pests and encourage predator activity. Overall, the adoption of intercropping systems with pigeon pea, coupled with INM and IPM practices, ensures sustainable intensification of agriculture by enhancing productivity, profitability, and ecological balance while maintaining soil health. This makes intercropping a vital strategy for achieving sustainable agricultural growth.

Keywords: Pigeon pea, Cropping system, sustainability, INM and IPM

1. Introduction

Pigeon pea (*Cajanus cajan* (L.) Millsp) is a vital tropical pulse crop in India, ranking second in area and production after chickpea. Its nutritional profile includes 22.3% protein, 1.7% fat, 3.5% minerals, 1.5% fiber, and 57.6% carbohydrates. Commonly known as red gram, arhar, or tur, pigeon pea is cultivated during both the *kharif* and *rabi* seasons. In India, it covers an area of 50.6 lakh hectares, producing 32.9 lakh tonnes with an average productivity of 650 kg/ha (Anon., 2014). Karnataka contributes significantly, with 8.24 lakh hectares under cultivation, a production of 5.87 lakh tonnes, and a productivity of 713 kg/ha (Anon., 2014).

As a sole crop, pigeon pea is relatively inefficient due to its slow initial growth and low harvest index. Consequently, it is often grown as an intercrop, enabling better resource utilization and higher productivity and profitability. It pairs well with crops like sorghum, pearl millet, green gram, black gram, maize, soybean, and groundnut, thereby enhancing production and preserving soil fertility. However, sustainable production requires agronomic, economic, and energy-efficient management of pigeon pea-based cropping systems.

Pigeon pea, a protein-rich pulse of the semi-arid tropics, is predominantly grown under rainfed conditions and holds a significant place in dryland farming systems. It serves multiple purposes, with its grain used as *dal*, green seeds consumed as vegetables, and stalks used as fuel wood. Its deep rooting system enhances soil structure by breaking plough pans, while leaf fall contributes organic matter, earning it the title of a "biological plough."

Despite India's leading position in pulse production, a significant gap persists between demand and supply. Over the past decades, the area under pulse cultivation (22–23 million hectares) and production (10–13 million tonnes) have stagnated, while population growth has reduced per capita pulse availability from 64 g/day in 1950 to less than 35 g/day in 2005, far below the FAO/WHO recommendation of 80 g/day. This has exacerbated protein malnutrition in the country.

To combat protein malnutrition, it is essential to boost pigeon pea production, a key pulse crop in India and Karnataka. While pigeon pea is typically intercropped with finger millet, groundnut, and other crops in southern Karnataka, production can be enhanced through increased cultivation area and productivity. Expanding cultivation, however, may require replacing other food crops with pigeon pea, as the total cultivable area remains constant. Sole cropping offers another avenue for boosting productivity.

Effective management strategies for pigeon pea-based cropping systems are critical to enhancing productivity, sustainability, and resilience against biotic and abiotic challenges. Sequential cropping systems, which involve cultivating pigeon pea in rotation with other crops over seasons, help optimize land use and ensure efficient nutrient cycling while reducing the risk of pest and disease buildup. Intercropping systems, where pigeon pea is grown alongside compatible crops such as sorghum, pearl millet, or groundnut, maximize resource utilization, improve soil fertility, and diversify farm income by ensuring yield stability even under adverse conditions**.** Crop rotations play a crucial role in breaking pest and disease cycles, enhancing soil health, and mitigating the risk of nutrient depletion by alternating pigeon pea with crops that have varying nutrient demands. Lastly, robust pest and disease management practices are essential to safeguarding pigeon pea yields, requiring a combination of integrated pest management (IPM), resistant varieties, timely application of biocontrol agents, and cultural practices like proper spacing and crop residue management. Together, these strategies contribute to the long-term sustainability and profitability of pigeon pea-based cropping systems.

2. Pigeon pea based cropping systems

Pigeon pea-based cropping systems are a sustainable agricultural practice that enhances productivity, soil health, and profitability. By integrating pigeon pea with crops like legumes, cereals, and oilseeds, these systems optimize resource utilization, improve nutrient cycling, and reduce pest pressure, offering ecological and economic benefits while improving land-use efficiency.

2.1. Pigeon pea in sequential cropping system

Pigeon pea (*Cajanus cajan*), a vital legume crop, plays a significant role in sequential cropping systems due to its ability to fix nitrogen, improve soil fertility, and provide sustainable yields. Integrating pigeon pea in sequential systems enhances resource utilization, diversifies cropping patterns, and boosts productivity, making it crucial for sustainable agriculture in semi-arid regions. Shivaran and Ahlawat (2000) reported that the cropping system of pigeon pea + black gram (SI)-wheat (2:2) produced a significantly higher pigeon pea-equivalent yield (PEY) of 17.70 q/ha, wheat yield of 31.60 q/ha, and net returns of ₹23,867/ha compared to the pigeon pea-wheat sequence (14.98 q/ha, 30.06 q/ha, and ₹20,621/ha, respectively). The enhanced performance was attributed to the additional black gram yield, the high wheat yield, and its favorable market price. This system was found comparable to pigeon pea + black gram (SR)-wheat (2:2). Among fertilizer treatments, 100% recommended dose of fertilizers (RDF) resulted in higher PEY (18.72 q/ha), pigeon pea yield (16.39 q/ha), wheat yield (31.13 q/ha), and net returns (₹24,505/ha) compared to control (14.90 q/ha, 12.84 q/ha, 30.13 q/ha, and ₹20,731/ha, respectively). This was attributed to improved nutrient availability and better shoot and root development. Although there were no significant differences in pigeon pea yield attributes across cropping systems, higher pod numbers (176.1–171.9/plant), grains per pod (3.00–2.96), and 100-seed weight (69.4–68.7 g) were recorded under 100% RDF compared to control (153.0–149.4 pods/plant, 2.65–2.62 grains/pod, and 64.3–63.6 g, respectively).

Srinivas and Srinivasa Raju (1997) observed that the pigeon pea-groundnut sequence yielded the highest PEY (29.60 q/ha) and net returns (₹26,825/ha), followed by pigeon pea-maize (24.00 q/ha and ₹20,898/ha), outperforming other crop sequences due to the higher market value of groundnut and greater maize yields. In contrast, the pigeon pea-sesame sequence recorded the lowest PEY (14.10 q/ha) and net returns (₹12,036/ha). The benefit-cost ratio was highest for pigeon pea-pigeon pea (5.04), owing to its lower cultivation cost, while pigeon pea-sunflower had the lowest ratio (3.49).

Tuti et al. (2013) highlighted that the pigeon pea-barley sequence achieved the highest land-use efficiency (87.6%) and PEY (2.80 t/ha) compared to pigeon pea-toria (78.01% and 2.51 t/ha, respectively). The superior performance of pigeon pea-barley was due to nitrogen fixation by pigeon pea and prolonged field occupancy (320 days). Additionally, the energy budget analysis revealed that the pigeon pea-lentil sequence had the highest energy output (194.0 x 10^3 MJ/ha), lowest energy input (100.3 x 10^3 MJ/ha), and superior energy-use efficiency (1.93), attributed to the pulse nature of both crops, which reduced cultivation costs. Conversely, the rice-wheat sequence recorded the lowest energy-use efficiency (0.93).

Singh and Ahlawat (2006) demonstrated that applying 34.4 kg P_2O_5/ha resulted in higher PEY (4.61 q/ha), pigeon pea yield (2.17 q/ha), and wheat yield (4.20 q/ha) compared to the control (3.68 q/ha, 1.57 q/ha, and 4.20 q/ha, respectively), with similar trends observed in wheat. This effect was comparable to the 17.2 kg P_2O_5 + PSB treatment. The improved yields with phosphorus application were linked to its role in root and nodule development, energy transfer, and metabolic processes, particularly in soils with low initial phosphorus availability.

2.2. Pigeon pea in intercropping

Pigeon pea (*Cajanus cajan*), a versatile legume, is well-suited for intercropping due to its deep-rooted growth habit, nitrogen-fixing ability, and compatibility with diverse crops.

Intercropping pigeon pea with cereals, pulses, or oilseeds maximizes resource use, improves soil health, stabilizes yields, and enhances farm profitability, supporting sustainable agriculture in rainfed and marginal areas.

2.2.1. **Method of Planting and Tillage**

Research has highlighted the advantages of transplanting pigeon pea over direct sowing in terms of yield and economic returns. Poornima (2009) found that transplanting 5-week-old pigeon pea seedlings as a sole crop resulted in significantly higher pigeon pea-equivalent grain yield (PEGY: 2669 kg ha^{-1}) and finger millet-equivalent grain yield (FEGY: 7512 kg ha^{-1}) compared to direct sowing (1575 and 4266 kg ha^{-1}, respectively). Similarly, intercropping 4-week-old transplanted pigeon pea seedlings with finger millet achieved better PEGY (2251 kg ha^{-1}), FEGY (5594 kg ha^{-1}), and land equivalent ratio (LER: 1.32) than direct sowing (1348 kg ha^{-1}, 3077 kg ha^{-1}, and 1.09, respectively). Superior performance was attributed to enhanced growth and yield attributes of pigeon pea, coupled with reduced weed competition.

In intercropping systems, pigeon pea with soybean recorded higher PEY (1168–1381 kg ha^{-1}), benefit-cost ratio (3.65–4.32), and LER (1.32–1.44) compared to other legumes, with paired-row systems being most beneficial (Anon., 2016). Rajesh Kumar et al. (2014) observed that tillage practices did not significantly impact yield but noted higher seed and pod yields in pigeon pea intercropped with sunhemp and soybean. Pigeon pea + soybean (1:2) cropping recorded the highest PEY (26.2 q ha^{-1}), attributed to better nutrient uptake.

Tillage had minimal effect on soil parameters, though pigeon pea + sunhemp (1:2) improved soil organic carbon, pH, and available nutrients due to green manure addition. Arjun Sharma and Guled (2012) reported that pigeon pea + greengram (1:2) on set furrows with vermicompost (2.5 t ha^{-1}) recorded the highest PEY (24.60 q ha^{-1}), net returns (₹36,126 ha^{-1}), and microbial activity due to improved planting geometry and nutrient addition.

Pramod Kumar et al. (2013) noted similar growth in sole and intercropped pigeon pea, with pigeon pea + mungbean achieving higher PEY (1.86 t ha^{-1}) than sole crops. Broad-bed and furrow planting systems also enhanced PEY (1.85 t ha^{-1}) over uniform row planting (1.59 t ha^{-1}). Murali et al. (2014) corroborated the superiority of transplanting 5-week-old pigeon pea seedlings in sole and intercropping systems for higher PEY, net returns, and reduced resource competition. These findings emphasize the role of strategic planting methods, nutrient management, and tillage in optimizing pigeon pea productivity and sustainability

2.2.2. Plant Geometry

Intercropping systems involving pigeon pea have shown substantial advantages in productivity, economic returns, and resource utilization compared to sole cropping. Anon. (2015) reported that pigeon pea (BRG-1) + cowpea achieved higher pigeon pea grain equivalent yield (753 kg ha^{-1}), RWUE (1.10 kg $ha\text{-}mm^{-1}$), net returns (₹45,332 ha^{-1}), and B:C ratio (2.51) compared to sole pigeon pea (416 kg ha^{-1}, 0.61 kg $ha\text{-}mm^{-1}$, ₹13,977 ha^{-1}, and 1.51). Similarly, Kathmale et al. (2014) found that pigeon pea + groundnut (1:3) recorded the highest mean PEY (1425 kg ha^{-1}) and net returns (₹30,703 ha^{-1}), attributed to minimal resource competition, groundnut's short duration, and complementary resource utilization. Conversely, pigeon pea + sunflower yielded lower PEY (975 kg ha^{-1}) and net returns (₹18,012 ha^{-1}) due to intense root competition. Ramachandrappa et al. (2015) reported significantly higher PEY (1173 kg ha^{-1}), B:C ratio (3.11), and sustainable yield index (0.43) in pigeon pea + field bean (1:1) compared to sole pigeon pea or field bean, driven by additional field bean yield, favorable market prices, and efficient resource utilization. Rathod et al. (2004) observed that intercropping pigeon pea with French bean (2932 kg ha^{-1}) or groundnut (2406 kg ha^{-1}) provided significantly higher PEY and net returns than sole pigeon pea (1495 kg ha^{-1}), owing to better crop yields and market prices. Anon. (2004) noted that ICPL 87119 + mungbean (1:3) attained the highest PEY (1727 kg ha^{-1}) and LER (1.554), followed by ICPL 87119 + mungbean (1:2) (1679 kg ha^{-1}, LER 1.509), outperforming sole pigeon pea varieties TTB 7 and ICPL 87119, with improvements attributed to superior mungbean yields, market value, and resource utilization efficiency.

2.3. Nutrient management

Nutrient management in pigeon pea intercropping systems has shown significant improvements in yield, nutrient uptake, and economic returns. Sangappa (2008) found that sole pigeon pea outperformed pigeon pea + finger millet (2:1) in terms of grain and stalk yield, with values of 1598 and 4220 kg/ha compared to 1265 and 3415 kg/ha, respectively. The reduced yield in intercropping was attributed to increased competition for growth factors. The application of FYM (5 t/ha) improved grain and stalk yield (1483 and 3922 kg/ha) compared to no FYM (1369 and 3620 kg/ha), likely due to organic manure's beneficial effects on soil properties and nutrient supply. Seed inoculation with PSB also resulted in higher grain and straw yield (1458 and 3855 kg/ha) compared to uninoculated seeds (1392 and 3682 kg/ha), due to enhanced phosphorus availability through the solubilizing process of PSB. Further, intercropping systems like pigeon pea + soybean (1:1) and pigeon pea + finger millet (2:1), with integrated nutrient management (fertilizers, FYM @ 5 t/ha, and PSB inoculation), showed higher pigeon pea equivalent yield (PEY) and land equivalent ratio (LER), with values of 1878 and 1894 kg/ha for the respective systems compared to sole pigeon pea with integrated nutrient management (1680 kg/ha). Sole pigeon pea recorded higher nutrient uptake of nitrogen (71.7 kg/ha), phosphorus (8.9 kg/ha), and potassium (50.2 kg/ha) compared to intercropped systems. FYM application and PSB inoculation also enhanced nutrient uptake. Pandey et al. (2013) observed that pigeon pea + urdbean (1:1) had higher growth parameters and PEY (2.17 t/ha) with improved B:C ratio (3.05) compared to sole pigeon pea. Fertilizer management with RDF + FYM (5 t/ha) further boosted growth and yield. Similarly, Arjun Sharma et al. (2010) found pigeon pea + greengram (1:2) outperformed pigeon pea + pearl millet (1:2) in PEY (17.37 q/ha vs. 15.76 q/ha) and net returns, with VC @ 2.5 t/ha + 50% RDF yielding higher PEY (19.36 q/ha). Narendra Kumawat et al. (2015) reported that pigeon pea + blackgram (1:1) had higher PEY (21.75 q/ha) and B:C ratio (4.80) compared to sole pigeon pea (18.49 q/ha and 3.98). INM treatments with 100% RDF + 50% RDN + 5 kg Zn/ha led to the highest PEY (24.24 q/ha) and B:C ratio (5.11). Willard et al. (2012) noted that pigeon pea + groundnut recorded higher biologically fixed nitrogen per unit area (82.8 kg/ha) compared to pigeon pea + maize (35.9 kg/ha) and sole soybean (35.8 kg/ha), largely due to reduced competition between the component crops.

2.4. Weed management

Weed management in pigeon pea intercropping systems has been shown to significantly impact yield and weed control efficiency (WCE). Manoj Kumar Yadav and Singh (2012) reported that applying 25 kg N/ha resulted in higher grain yield for pigeon pea (2.3 t/ha), rice (0.8 t/ha), and pigeon pea equivalent yield (PEY) (2.5 t/ha) compared to the control (1.9 t/ha, 0.7 t/ha, and 2.1 t/ha, respectively), with increased yields attributed to better translocation of photosynthates under sufficient nitrogen conditions. In terms of weed management, two hand weedings (HW) at 15 and 45 DAS led to the highest PEY (2.7 t/ha), followed by pendimethalin @ 1 kg a.i./ha plus one HW at 45 DAS (2.6 t/ha), compared to the weedy check (1.6 t/ha), due to reduced competition for growth factors by weeds. The application of 25 kg N/ha also increased weed population (286.7 No./m^2) and their dry weight (225 g/m^2), resulting in higher WCE (77.9%) compared to the control (256.9 No./m^2, 193.9 g/m^2, and 76.4%). This was because higher nitrogen levels promoted greater weed emergence and growth, leading to increased WCE. Among weed management practices, two HW at 15 and 45 DAS recorded the highest WCE (89%), followed by pendimethalin @ 1 kg a.i./ha plus one HW at 45 DAS (83.9%), compared to the weedy check (58.7%), due to more effective weed control from hand weeding and pendimethalin’s broad-spectrum activity. Anon. (1975) found that intercropping pigeon pea with crops like sorghum, millet, cowpea, and mungbean reduced weed infestation by 50 to

75%, due to the higher canopy coverage and faster ground cover provided by the intercropping system, which reduced light penetration to the soil and created unfavorable conditions for weed growth. Rafey and Prasad (1995) observed that pendimethalin (1 kg ai/ha) plus interculturing at 30 DAS resulted in lower weed density (22 No./m^2), dry weight of weeds (12 g/m^2), and higher WCE (82%) and PEY (7032 kg/ha) compared to the weedy control (63.4 No./m^2, 68 g/m^2, and 1784 kg/ha), with similar results for Butachlor (1 kg ai/ha) plus interculturing, attributing the improved weed control to effective suppression and inhibition of the second flush of weeds through interculturing.

2.5.Crop rotation

Pigeon pea crop rotation involves alternating pigeon pea with other crops like finger millet, soybean, or groundnut, enhancing soil fertility, reducing pest buildup, and improving overall crop yields through diverse cropping systems. Vijaymahantesh (2012) found that conventional tillage resulted in significantly higher seed and straw yields of pigeon pea (1025 and 2824 kg/ha) compared to minimum tillage (642 and 1677 kg/ha), with reduced tillage yielding similar results. This increase in yield was attributed to better weed control through repeated tillage operations, which promoted higher growth, yield attributes, and overall yield. A similar trend was observed in finger millet. In terms of nutrient management, the combination of 50% nitrogen through FYM and 50% nitrogen through glyricidia resulted in higher seed and straw yields (1198 and 3021 kg/ha) compared to 100% nitrogen through urea (491 and 1428 kg/ha). However, in the pigeon pea-finger millet rotation, the integrated nutrient management (INM) treatment consisting of 50% nitrogen from urea, 25% from FYM, and 25% from glyricidia produced higher grain and straw yields (2666 and 3734 kg/ha) than the 50% nitrogen from FYM and 50% from glyricidia (1665 and 2253 kg/ha), due to better nutrient supply in alignment with crop demands and higher nutrient uptake. Additionally, conventional tillage in pigeon pea resulted in significantly lower total weed dry weight (1.49 g/m^2) compared to minimum tillage (1.83 g/m^2), with a similar trend in finger millet. The higher weed dry weight in minimum tillage was attributed to increased weed seed presence in the topsoil, which germinated along with crop seeds and accumulated more dry matter. Nutrient management practices did not significantly affect the total weed dry weight in either crop.

2.6.Pest management

Pest management in pigeon pea is crucial for ensuring healthy crop growth and maximizing yields. Effective strategies include intercropping, biological control, integrated pest management (IPM), and chemical treatments. These methods help control common pests like pod borers, wilt pathogens, and other diseases, reducing crop damage and improving productivity. Potdar (2010) reported that sole pigeon pea experienced 19.30% pod damage, while intercropping with sunflower reduced pod damage to 5.95%, significantly lower than the sole crop. Pigeon pea + mesta recorded 9.97% pod damage. The lower damage in the pigeon pea + sunflower system was attributed to a significantly lower larval population of the pigeon pea pod borer, which was below the economic threshold level (ETL) from 90 to 150 DAS, whereas the population in sole pigeon pea crossed ETL multiple times. The reduction in pod borer incidence was 69% for pigeon pea + sunflower and 48% for pigeon pea + mesta. Naik et al. (1997) found that intercropping pigeon pea with sorghum resulted in a lower wilt incidence (46%) compared to sole pigeon pea (66%) due to fungitoxic exudates from sorghum roots, which inhibited Fusarium udum. Madhukeshwara et al. (2003) reported that pigeon pea + maize showed less wilt incidence, though no significant reduction in wilt was observed due to spatial factors in the rhizosphere. Ganapathi et al. (2015) found that pigeon pea + sorghum recorded significantly lower pod damage (12.36%) and higher PEY (1315 kg/ha), with increased activity of predators, parasitoids, and insectivorous birds. Malla Reddy et al. (2007) highlighted that IPM was more efficient in pigeon pea + groundnut (13.9%) and pigeon pea + sorghum (10.1%) systems, resulting in lower pod damage compared to sole pigeon pea. Suhas et al. (2009) found that pigeon pea + sorghum resulted in lower wilt incidence (3.16%) and pod damage (34.97%) with higher PEY and B:C ratio compared to sole pigeon pea. Mahesh et al. (2010) concluded that seed treatment with carbendazim and soil application of P. fluorescens and T. viride resulted in the lowest wilt incidence (7.25%) and highest yield (1203.17 kg/ha).

3. Conclusion

Intercropping pigeon pea with legumes, cereals and strategic planting systems enhances productivity, profitability, and ecological balance. Integrated nutrient and pest management practices further optimize yields, ensuring sustainable agricultural growth and improved land-use efficiency. Growing pigeon pea in rotation with lentil or barley, as well as intercropping with legumes, enhances both productivity and profitability. The broad-bed and furrow or paired row planting systems outperform normal or flat-bed planting in pigeon pea-based intercropping systems. A combined application of FYM/VC and RDF with PSB is more effective than using RDF alone in these cropping systems. For weed management, two hand weedings at 15 and 45 DAS or the use of pendimethalin at 1 kg ai/ha with one hand weeding at 40 DAS are recommended. Effective water management for rainfed pigeon pea requires one post-monsoon irrigation. Additionally, intercropping pigeon pea with sorghum reduces wilt incidence and pod damage compared to growing pigeon pea alone.

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