

A Review on Genetic Improvement, Breeding Approaches, And Seed Management for Enhanced Pigeon Pea (*Cajanus Cajan .L*) Production

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ABSTRACT

India is well known for its agricultural production, coupled with sophisticated processing and storage methodologies. Pulses play a very significant role in India's protein diet. The most widely used pulse in daily life is pigeon pea (*Cajanus cajan*). The annual demand for pulses in India is estimated to be around 25-27 million metric tons (MMT). This demand is driven by both domestic consumption and industrial uses. The exponential growth in urbanization and numerous other forms of industrialization, a significant threat to aerobiological agricultural systems. The average annual pulse production in India is approximately 23-25 million metric tons (MMT). The major pulse-producing states in India include Madhya Pradesh, Uttar Pradesh, Maharashtra, Rajasthan, and Karnataka. The main component of all grains and crops is the seed. For sustainable seed availability, it is essential to use high-quality seeds effectively. Therefore, it becomes necessary to identify the factors that contribute to seed damage during storage, transportation, etc. There are a variety of methods and procedures available to eradicate the various diseases posing detrimental effects on overall seed quality. The precise monitoring and processing of Pigeon pea would lead to enhanced seed protein quality, amino acid content, and improvements in the crop's nutritional value globally. By effectively managing seed deterioration and upholding quality standards, losses incurred during preparation and storage can be minimized. In conclusion, this comprehensive review provides valuable insights into pigeon pea production, seed storage, and management practices, offering a holistic understanding of the challenges and opportunities associated with its cultivation while advocating for science-based interventions and inclusive policies to foster its sustainable development and utilization.

Keywords: Pigeon pea, Genetic improvement, Breeding approach, Management, and Applications.

Highlights:

- India is well known for its agricultural production, coupled with sophisticated processing and storage methodologies. Pulses play a very significant role in India's protein diet.
- Seed quality is defined as seeds of an improved variety that are both physically and genetically pure, have a high germination rate, are vigorous, free of insects or other pests, and have the ideal moisture content.
- The precise monitoring and processing of Pigeon pea would lead to enhanced seed protein quality, amino acid content, and improvements in the crop's nutritional value globally.
- The exponential growth in urbanization and numerous other forms of industrialization, a significant threat to aerobiological agricultural systems.

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INTRODUCTION

Pigeon pea, a valuable and important pulse due to its rich dietary protein, is widely cultivated in tropical and subcontinental regions of Asia and Africa. (Singh *et al.*, 2019). As the fundamental component of agriculture, seed is crucial to sustained farming. A higher-quality crop will be produced if quality seed is used. Seed quality is defined as seeds of an improved variety that are both physically and genetically pure, have a high germination rate, are vigorous, free of insects or other pests, and have the ideal moisture content. The seed coat protects the tiny plant embryo known as a seed. It is produced after the ripened ovules of angiosperm and gymnosperm plants mature. The seed is an essential part of the production of all food crops. (Mishra *et al.*, 2024)

Pigeon pea is grown in diverse agro-ecological zones, predominantly in India, Africa, and Latin America. It is cultivated as a rainfed crop and can tolerate drought, poor soils, and high temperatures, making it a suitable crop for marginal lands. Key factors influencing pigeon pea production include:

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Climate and Soil Requirements

Well-drained soils with a pH between 6.0 and 7.5 are ideal for pigeon pea growth. It is drought-tolerant but benefits from

timely monsoons or irrigation during the flowering and pod-filling stages. (Sangma *et al.*, 2020).

Argo-Management Practices

Proper agronomic practices such as crop rotation, intercropping, and balanced fertilization are essential to maximizing yields. In addition, managing pests and diseases, such as the pigeon pea wilt and pod borers, is crucial for sustainable production. The vulnerability to seed degradation is caused by a number of variables. The primary factors include temperature, relative humidity, seed moisture content, and insect and microbe invasion. (Mishra *et al.*, 2023)

Genetics and Breeding

Genetic improvement of pigeon pea has been a focal point of research to enhance its productivity, disease resistance, and adaptation to diverse climates. (Bohra *et al.*, 2020). Several key areas in pigeon pea genetics and breeding include:

Genetic Diversity

Pigeon pea exhibits considerable genetic diversity, which is critical for breeding programs aimed at improving traits such as drought tolerance, disease resistance, and pod yield. Landraces and wild relatives of *Cajanus cajan* contribute valuable genetic material for developing improved varieties.

Breeding Strategies

Traditional breeding methods, such as selection and hybridization, are commonly used to develop improved varieties. Modern biotechnological approaches like marker-assisted selection (MAS) and genomic selection are becoming increasingly important to identify genes associated with desirable traits. These include resistance to Fusarium wilt and other biotic and abiotic stresses, improved seed size, and better protein content.

Hybrid Development

Hybridization in pigeon pea is still under development, as crossing between different genotypes can often face issues related to sterility or poor fertility. However, advancements in cytoplasmic male sterility (CMS) and gametocides have facilitated the development of hybrid varieties with higher yield potential.

Transgenic Approaches

Pigeon pea cultivars with improved resistance to pests, diseases, and environmental stressors have been created through the use of genetic engineering techniques. The development of Bt pigeon pea, which expresses a gene from *Bacillus thuringiensis* to combat pod borers, is one such advancement. (Negi *et al.*, 2021).

One of from belonging to India is the pigeon pea, *Cajanus cajan* (L.) Millspaugh (Saxena *et al.*, 2014). Before 2000 BC, it is thought to have been transported to Africa (Songok *et al.*, 2010). Nowadays, pigeon pea is grown extensively over the entire tropical and subtropical world. More than 25 tropical and subtropical nations grow the crop, either as the sole crop or in intercropping cultivation with cereals or legumes. It is a food legume that is often cross-pollinated, with pollination ranging from 0-40% depending on genotype and insect pollinator

populations. It is also known as red gram, tuar, or arhar. The *cajanus cajan* belongs to the subtribe Cajaninae, tribe Phaseolea, and family Fabaceae (Varshney *et al.*, 2012).

In terms of acreage and productivity, the pigeon pea ranks sixth among all main grain legume crops (Fu *et al.*, 2008). It serves as a significant source of protein in dhal and as a green vegetable in human diets. The FAO (2021) estimates that 7.03 million hectares of pigeon peas will be planted worldwide, yielding an average yield of 695 kg/ha and a production of 4.89 million tons. The crop thrives in rain-fed areas in Kenya (0.28 m ha), Tanzania (0.25 m ha), Myanmar (0.6 m ha), and India (5.60 m ha). In all of these countries, pigeon peas are interplanted with either grains like sorghum (*Sorghum biolor*), pearl millet, and maize (*Zea mays*) or legumes like soybean (*Glycine max*), mung bean (*Vigna radiata*), and urd bean (*Vigna mungo*).

Pigeon peas are primarily produced in India, which accounts for 90% of global production (Singh *et al.*, 2019). For very young children, the National Institute of Nutrition in India suggests a cereal-to-pulse ratio of 3:1, 5:1, and 6:1, respectively. After chickpea, it is the second-largest pulse crop in India. According to Hazra *et al.*, (2023), the main states where it is grown are Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Uttar Pradesh, Gujarat, Jharkhand, Odisha, and Tamil Nadu. Gujarat is first and followed by Uttar Pradesh is the second highest in the yield rating (Fig. 1).

One of the major producing states of Tur in India is Karnataka. These 10 states make up around 98% of the nation's total pigeon pea production in terms of area. With an average output of 6.03 quintal/ha, Maharashtra is the top producer, with over 10.51 lakh ha. (Sajjan *et al.*, 2017). Pulse crops are cultivated in Karnataka on approximately 1.1 million hectares of land, which is equivalent to 11 lakh hectares (lakh ha). The average productivity of pulses in Karnataka is reported to be 665 kilograms per hectare (kg/ha). With the given cultivated area and productivity, the total production of pulses in Karnataka during the specified period is estimated to be around 0.73 million tonnes. (Anonymous, 2017) Fig.1.

Nutritional value

In particular, for vegetarian diets, pigeon pea provides a cost-effective source of protein. Pigeon peas are rich in carbohydrates,

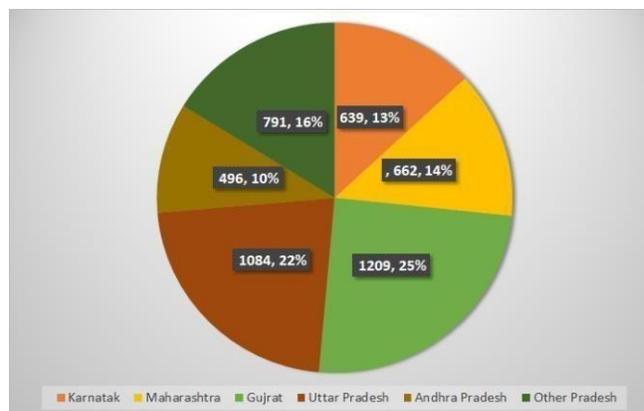


Fig. 1: Showing different states' ranking of India based on the yield of Pigeon pea

essential minerals, and B-complex vitamins. When combined with cereals, they contribute to a well-balanced diet and are nutritionally comparable to other high-protein sources like whey and soy (Akorhonor *et al.*, 2006). Incorporating red gram (pigeon pea) into the regular diet can significantly enhance overall nutritional intake (Fig. 2). The nutritional values illustrate the composition of pigeon pea seeds, emphasizing their richness in protein, carbohydrates, dietary fiber, vital minerals, and vitamins. (Table 1).

Major components

According to Roy *et al.*, (2010), the majority of the form of protein storage in pulse seeds is as globulins, albumins, and glutelins. In pigeon peas, globulins account for around 65% of the total protein. Globulins, which are soluble in salt-water solutions, albumins, which are soluble in water and comprise 10–20% of the total protein in pulses, and glutelins, which are soluble in weak acids and bases and comprise 10–20% of the total protein in pulse seeds, account for about 70% of the total protein in pulses. According to Teugwa *et al.*, (2013), globulins isolated from

specific Cucurbitaceous seeds demonstrated strong anti-hyperglycemic action. The observation regarding the relatively high lysine content in pulse seeds compared to cereals like rice and other cereal crops is indeed accurate. Pulses, being members of the legume family, possess a unique nutritional profile that distinguishes them from cereals. Lysine is an essential amino acid crucial for human nutrition, as it plays a vital role in protein synthesis and various metabolic processes in the body. While cereals typically have lower lysine content, pulses, including pigeon pea seeds, are known for their relatively higher lysine levels. This is one of the reasons why pulses are often considered complementary proteins to cereals in vegetarian diets, as they provide a more balanced amino acid profile when consumed together. The crucial amino acids needed for appropriate human nutrition are provided in large part because of their dominance in the legume family (Duranti, 2006). In the food sector, protein isolates of plant origin have great promise because of their nutritional and physicochemical qualities as well as their affordability. Adenekan *et al.*, (2018), have conducted comprehensive nutritional and functional evaluations of pigeon pea protein isolates. These evaluations likely include assessments of protein content, amino acid composition (including essential amino acids like lysine), digestibility, solubility, emulsification, gelation, foaming, and other functional properties relevant to food formulation and processing. Encouraging results from such examinations indicate that pigeon pea protein isolates possess desirable nutritional attributes and exhibit functional characteristics that enhance their suitability for use in various food products. (Table 2). These findings are significant not only for addressing protein malnutrition but also for expanding the utilization of pigeon pea as a valuable protein source in food industries. In the pigeon pea, carbohydrates, including starch and non-starch polysaccharides, make up 55% to 65% of the dry mass. The factors mentioned by Sajilata *et al.*, (2006) regarding why legume starches tend to have a lower glycemic index (GI) compared to cereal starches: (Table 3).

Table 1: The tabulated the nutrient content in pigeon pea seeds per gram (Affrifah *et al.*, 2023)

Nutrient	Amount per 100g
Protein	21.7g
Carbohydrates	62.78g
Total dietary fibers	15g
Total lipid	1.49g
Calcium	130mg
Magnesium	183mg
Iron	5.23mg
Phosphorus	367mg
Potassium	1392mg
Sodium	17mg
Zinc	2.76mg
Thiamin (VitaminB1)	0.643mg
Riboflavin (Vitamin B2)	0.187mg
Niacin (Vitamin B3)	2.965mg
VitaminB-6	0.283mg
Tryptophan	0.212mg
Threonine	0.767mg
Isoleucine	0.785mg
Leucine	1.549mg
Lysine	1.521mg
Methionine	0.243mg
Cysteine	0.250mg
Phenylalanine	1.858mg
Tyrosine	0.538mg

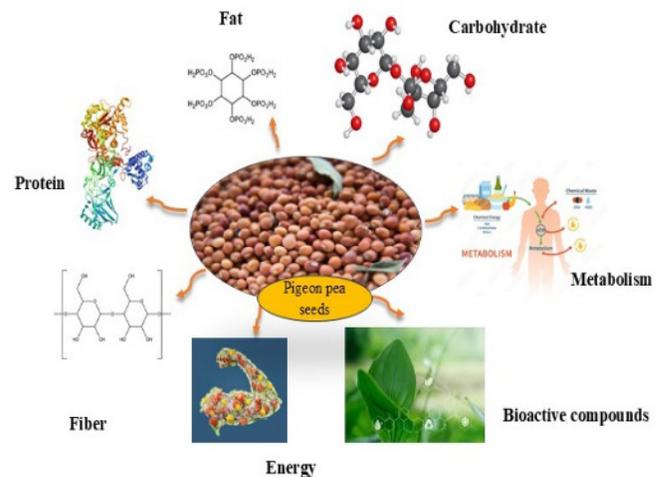


Fig. 2: A brief view of the nutrition profile of Pigeon pea seed. Sources: USDA (2023)

Table 2: Nutritional attributes in pigeon pea

Examination	Results
Protein content	High
Amino acid composition	Balanced; includes essential amino acids like lysine
Digestibility	Likely high
Solubility	Good
Emulsification	Effective
Gelation	Favorable
Foaming	Promising
Functional properties	Desirable for food formulation and processing
Nutritional attributes	Superior quality; suitable for addressing protein malnutrition
Food applications	Versatile; suitable for a wide range of food products

Table 3: summary highlighting the impact of extraction circumstances, solvent type, and heat treatment on the solubility and functional properties of proteins. (Mirmoghtadaie *et al.*, 2016)

Factors	Impact
Extraction Circumstances	pH: Influences protein solubility and stability.
	Temperature: Affects protein denaturation and Solubility. Higher temperatures may lead to Increased solubility, but could also cause protein Denaturation.
	Extraction time: Longer extraction times may Enhance protein extraction efficiency, but could Also leads to increased protein degradation.
	Solvent Type
Solvent Type	Different solvents may have varying inabilities to Solubilize proteins. Some solvents may be more Effective for extracting certain types of proteins Or may result in higher protein yields.
	Heat Treatment
Heat Treatment	Heat can induce protein denaturation, altering. Solubility and functional properties. Mild heat Treatments may improve solubility and functionality
	While excessive heat can lead to protein Aggregation and loss of functionality.

Digestibility

Legume starches exhibit a slower rate of digestion in the gastrointestinal tract compared to cereal starches. This slower digestion is attributed to several factors, including the presence of certain anti-nutritional factors such as enzyme inhibitors and lectins in legumes, which can hinder the activity of digestive enzymes. Additionally, the fibrous nature of legumes,

particularly the presence of insoluble fiber, can physically impede the access of digestive enzymes to starch molecules, leading to slower breakdown and absorption of carbohydrates. (Larsen *et al.*, 2009).

Amylase contents

Compared to cereal starches, legume starches usually have a larger percentage of amylose, a linear polysaccharide made up of glucose units connected by alpha-1,4-glycosidic linkages. Alpha-amylase, the enzyme that converts starch to glucose during digestion, is less likely to hydrolyse amylose molecules due to their more compact shape. Consequently, a lower glycaemic response results from the slower digestion and absorption of carbohydrates caused by the higher amylose content in legume starches. (Zhou *et al.*, 2004).

The combination of these factors results in legume starches having a lower glycemic index compared to cereal starches. Foods with a lower glycemic index are digested and absorbed more slowly, leading to gradual increases in blood glucose levels and a more sustained release of energy. Incorporating legumes, such as pigeon pea seeds, into the diet can therefore be advantageous for promoting overall metabolic health and reducing the risk of chronic diseases associated with elevated blood sugar levels.

Additionally, they encourage modest and slow postprandial insulin and glucose responses. Legumes are high in fiber and starch, which the small intestine finds difficult to digest. Instead, they pass into the large intestine, where bacteria ferment them to create short-chain fatty acids (Chung *et al.*, 2008).

Minor components

In addition to the primary components, like protein and carbs, the pigeon pea also contains small components that have bioactive properties (Ramakrishnan *et al.*, 2012). Das *et al.*, (2012) also discussed the phytochemical properties of *Cajanus cajan*. Numerous phytochemicals are present in pigeon pea seeds, which contribute to their nutritional value and potential health benefits. Although a thorough analysis of the small molecules in pigeon pea seeds may not be as comprehensive as that of some other legume crops, the following is a summary of the main phytochemicals present in pigeon pea seeds:

Protein

Pigeon pea seeds are rich in protein, containing about 20-22% protein on a dry weight basis. The protein in pigeon pea seeds is of high quality, containing all essential amino acids, although it may be deficient in methionine.

Carbohydrates

Pigeon pea seeds are a good source of carbohydrates, providing energy in the form of starch and dietary fibre.

Dietary Fiber

Pigeon pea seeds contain both soluble and insoluble dietary fiber, which can aid digestion, promote satiety, and support gut health.

Vitamins

Pigeon pea seeds contain various vitamins, including vitamin B complex (such as niacin, riboflavin, and thiamine) and vitamin

Table 4: Functional Roles of Anti-Nutrients in Human Health

Anti-Nutrient	Health-Promoting Qualities
Tannins	Antioxidant properties, scavenging free radicals Anti-inflammatory effects Potential anti-cancer properties
Saponins	Cholesterol-lowering effects Immune-modulating properties Anti-inflammatory effects
Phytic Acid	Antioxidant properties, chelating metal ions Potential anti-cancer effects Reduction of iron overload in the body Protection against kidney stones

Table 5: Reduction Strategies for Anti-Nutritional Factors in Food Preparation

Anti-Nutrient	Handling Methods
Tannins	Proper cooking methods, such as soaking and boiling Fermentation
Saponins	Heat treatment, such as boiling or roasting Soaking in water
Phytic Acid	Soaking in an acidic medium (e.g., lemon juice) Sprouting Fermentation

E. These vitamins play essential roles in energy metabolism, antioxidant defense, and overall health.

Minerals

Pigeon pea seeds are rich in minerals such as potassium, phosphorus, magnesium, and iron. These minerals are important for various physiological functions, including muscle function, bone health, and oxygen transport.

Phytochemicals

While specific small-molecule phytochemical profiling may be limited, pigeon pea seeds contain various bioactive compounds such as flavonoids, phenolic compounds, and tannins. These phytochemicals have antioxidant properties and may contribute to the potential health benefits associated with pigeon pea consumption, including anti-inflammatory and anti-cancer effects.

Lectins

Pigeon pea seeds contain lectins, which are proteins that can bind to carbohydrates. Lectins may have various biological activities, including immunomodulatory effects. Chemicals that are created by plants through either their primary or secondary metabolism are known as phytochemicals. Campos-Vega *et al.*, (2010) enumerated lectins, fatty acids, phytosterols, phenolic compounds, enzyme inhibitors, phytic acid, and saponins as

trace amounts of pulses. According to current research, the majority of so-called anti-nutrients—such as tannins, saponins, and phytic acids—have health-promoting properties when used appropriately Bawadi *et al.*, 2005) (Tables 4 and 5).

Certain bioactive substances are susceptible to processing conditions; for example, lectins and enzyme inhibitors have little effect after cooking. Among the several bioactive ingredients of pulses, phenolic compounds, phytic acid, and saponins are the most thoroughly researched substances. (Marathe *et al.*, 2011). According to Campos-Vega *et al.*, (2010), the principal phenolic chemicals found in pulses include phenolic acids, flavonoids, and tannins. One of the primary factors in plants' antioxidant activity is phenolic compounds. By neutralizing free radicals by donating one of their electrons, antioxidants defend the organism from the harmful effects of these molecules (Fang *et al.*, 2002). Chemically speaking, phenolic compounds (also known as polyphenols) are made up of aromatic hydrocarbons and one or more hydroxyl groups. These molecules can range in complexity from simple to highly polymerized. According to the quantity and positioning of the hydroxyl groups about the carboxyl functional group, phenolic acids have antioxidant action (Robards *et al.*, 1999). Flavonoids, a broad class of polyphenolic compounds produced by plants, have important roles in a number of organs to support plant growth, development, and health (Falcone Ferreyra *et al.*, 2012). Flavonoids in Leguminosae can function as phytoalexins, photoprotectors, and nod inducers for nitrogen-fixing bacteria. It has been demonstrated that flavonoids influence the feeding preferences of pest invertebrate species, and flavonoid profiles have also been used in plant chemotaxonomy to elucidate evolutionary links (Emerenciano *et al.*, 2001). Due to their antioxidant and anticancer characteristics, flavonoid glycosides have drawn a lot of attention in medical research (March *et al.*, 2006). Vitexin and isovitexin, two flavone C- C-glucosides found in pigeon pea, are recognized to have antibacterial properties (Agnese *et al.*, 2001). Vitexin has been proven to have lower antioxidant activity and less effective free radical scavenging capacities than orientin, another flavone C-glucoside from Pigeon pea (Wu *et al.*, 2009). Pigeon pea leaves contain a significant amount of luteolin, a flavone with a range of 0.05– 100 mg L⁻¹, pharmacological characteristics (Lee *et al.*, 2002).

Production

India received the top spot in the world for both production and area, accounting for 67.28% and 79.65% of global production and acreage, respectively. Saint Vincent and the Grenadines led the world in productivity with 7926 kg/ha, followed by Malawi and Trinidad and Tobago. FAO (Food and Agriculture Organization) statistics from 2020, pigeon pea (*Cajanus cajan*) is an important pulse crop cultivated in various regions worldwide. Pigeon pea production statistics might range from one year to the next, as well as between nations and areas. Nigeria, Tanzania, Malawi, India, and Myanmar are some of the major producers of pigeon peas. 3.9 million hectares, or 72% of the total area, are planted to pigeon peas in India (FAO, 2018). About 90% of the world's pigeon pea production comes from India, which is a major producer (Singh *et al.*, 2017). Red gram is another name for pigeon pea. In Uttar Pradesh, red gram is cultivated on an area of about 0.87 lakh acres.

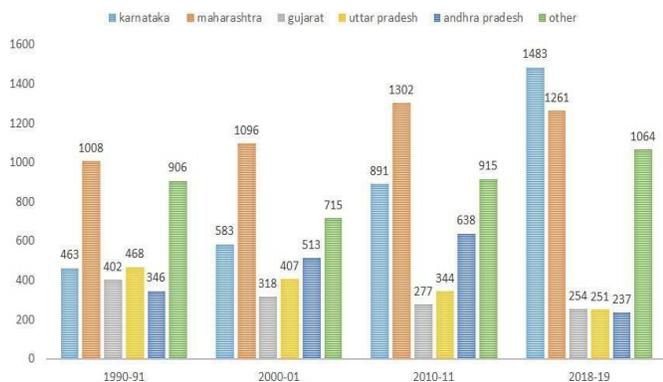


Fig. 3: Total area coverage from 1990 to 2019 years of major states of India, Area'000ha. (Agriculture Market Intelligence Centre-Redgram Report Jan– May 2021)

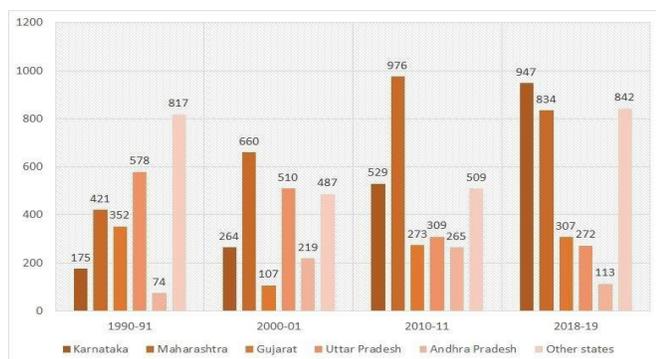


Fig. 4: Total production from 1990 to 2019 years of major states of India, production 000 tonnes. (Agriculture Market Intelligence Centre – Pigeon pea Report Jan –May 2021)

Nearly all types of soil can support the crop's growth. But it thrives in light to medium, well-drained soils that are deep enough to allow for the free development of roots. During the stages of flowering and pod ripening, bright, sunny weather is required. Pigeon pea's major output (Fig. 3) and area coverage (Fig. 4) from 1999 to 2019 in India's states revealed various production and area fluctuations during the previous ten years.

Climate

Pigeon pea crops thrive in the summer, rainy, and winter seasons (April-Summer, June-Kharif or rainy, September-Rabi or winter), so rainfall during the crop's flowering stage results in poor pollination. Because arhar requires moist and warm weather, it requires temperatures of 30 to 35 degrees Celsius for germination and 20 to 25 degrees Celsius for vigorous vegetative growth. It also requires 15-18 degrees Celsius during the flowering and pod setting period and a much higher temperature of approximately 35-40 degrees Celsius at maturity.

Soil

All types of soil are favorable for pigeon pea growth; however, loam to sandy loam soil is preferred. This crop does well in muddy mid-hill terrain as well. Additionally, it may grow well on neutral soils with a pH range of 6.5 to 7.5. Keep in mind that the field wouldn't be waterlogged.

Fertilizers

N: P: K (15:45:30 kg/ha) and FYM (10 tons/ha), respectively. Seed rate: - 12-15 kg/ha.

Seed treatment

Before planting, treat seeds with either 10 g/kg of *Pseudomonas fluorescens* or 2 g/kg of carbendazim or Thiram. The best germination and genuine value seeds should be selected for planting after the required variety of seeds has been treated. Seeds for this crop should not be more than two seasons old. It needs to be ready from the previous season. For improved germination and quality seedlings, use good-quality boulder seeds.

Time of sowing

As the monsoon season begins in June or July, pigeon peas are traditionally grown as a Kharif crop in various agroclimatic zones around the country. Pigeon peas should be planted early, before the wet season starts in June, for higher crop yields. This crop should be seeded under irrigated conditions by giving one pre-monsoon irrigation at least two weeks before the first shower to ensure that plants can grow adequately during the rainy season. However, under rain-fed circumstances, you can start sowing as soon as the rains begin. Consequently, it is never advisable to delay the sowing past the final week of June.

Spacing

The tall, spreading, and field-occupying long-duration pigeon pea should be planted in a broader row with a 90–120 cm spacing and about 30–35 cm between the plants, especially in rain-fed conditions. When being watered, early maturing varieties are planted with a row spacing of 50-75 cm and a plant-to-plant distance of 15-20 cm. Given that vegetative growth is significantly higher in April than in June, pigeon peas should be planted with a row spacing of 90 to 120 cm. Red soils should be 60 x 20 cm apart, whereas black soils should be 90 x 20 cm.

Isolation

Pigeon pea frequently cross-pollinates, so they must be kept apart from other varieties by 100 meters.

Plant habit

The pigeon pea plant is often upright and branching. Its metabolism is of the C₃ type and short-day type. The stem is tough and fibrous. Growth can be of the definitive, semi-determinate, or indeterminate type depending on the flowering pattern. It has a tap root system, and during the seedling stage, the tap root structure thickens as a result of cambial activity. Long-lived genotypes' roots can penetrate the soil up to 2 meters deep. Pigeon pea nodulation typically starts 12 days after seedling emergence and lasts for 115–120 days in extended duration kinds.

Inter-cropping

Intercropping is the practice of cultivating two or more crops with different growth patterns on the same plot of land to maximize net earnings and overall yields per unit area. Typically, red gram is grown close to cereals, short-grain legumes (pulses), oilseeds, or cotton. In addition, grain crops, including sorghum,

maize, pearl millet, finger millet, etc., are typically interplanted with red gram. Red gramme: Groundnut, soybean, and sesame are the oilseed crops used in the increasingly widespread practice of intercropping. The short-duration pulse crops mungbean, blackgram, chickpea, etc., can be interplanted with red gram.

Weed control

Pigeon peas grow relatively slowly throughout the first 45–50 days of their growth cycle, which reduces their weed competitiveness. If the weeds are not rapidly eliminated, the seed production may be reduced by up to 90%. Therefore, it is recommended to prevent weed growth in the fields. We need to weed the field twice with two hands after sowing the crop: once after about 25–30 days and once after about 45–50 days.

Harvesting

There are several uses for green pigeon peas. A fully formed, vibrant green seed chosen to become a vegetable. Consequently, pods should be plucked just as their green color begins to fade. Typically, the hand-picking method is utilized to accomplish this. Pigeon pea leaves continue to be green when the pods are ready to be harvested, unlike other crops. Choosing the best time to harvest their crops can be very difficult for farmers at times. To benefit from pigeon pea, harvest it after 75–80% of the pods have become brown and are dry. Delaying harvesting during harsh weather may increase the chance of mature seed being damaged.

Productivity

Pigeon pea has the lowest productivity of any pulse crop at 789kg/ha (Sarkar *et al.*, 2017), with floral and pod abscission acting as its two main physiological restraints. Genetic variables, a lack of water during the pre-flowering period, timing changes, and strong winds are the main reasons for flower and pod drop. Short-duration types showed floral abscission of roughly 70–96% (Saxena *et al.*, 2010). Pigeon peas have the lowest harvest index of 19% among pulses as a result of significant blossom and pod abscission.

Role of Farmers in Pigeonpea Breeding:

Modern food crop cultivars are not widely adopted by small-scale farmers in India because newly generated plant varieties do not fully meet the needs and preferences of farmers, processors, merchants, and consumers. According to Walker and Alwang (2015), a demand-led strategy to plant breeding is the most effective technique to ensure that the development of high-performing and high-quality crop varieties really satisfies consumer criteria and market expectations. This will increase the adoption rate. The strategy adheres to the rules and procedures for involving stakeholders in cultivar development and marketing.

A quick and affordable method for identifying and choosing the farmers' favorite varieties for extensive production is Participatory Rural Appraisal (PRA) (Ceccarelli, 2012). It helps locals to exchange, improve, and critique their understanding of life and circumstances. PRA is a well-liked and efficient method for learning about farmers' expertise in plant breeding (Dorward *et al.*, 2007).

Plant breeders employ PRA to comprehend the production limits, perceptions, and preferences of farmers so that breeding programs can be adjusted to create cultivars that farmers will accept (Machida *et al.*, 2014). Information is gathered using a variety of PRA instruments, such as focus groups and semi-structured interviews. Ayenan *et al.*, (2017) gathered data on Beninese pigeon pea production limits and favored features through focus groups and individual conversations.

They identified poor seed quality and a lack of better varieties as the main production constraints for pigeon peas. Early maturity, high yields, and resistance to pod borers were the most sought-after characteristics. According to reports, farmers prioritized high yields, early maturity, drought resistance, short cooking times, indeterminate variety, cream seed colour, and large seed size, whereas insect infestations were cited as the primary obstacle to Tanzanian pigeon pea production (Kimaro *et al.*, 2017).

Deteriorate Quality of Seed During Production (Abiotic and Biotic):

The crop growth and development are influenced by environmental factors like light intensity, temperature, rainfall, and soil fertility. Soil-incorporated residues enhance soil organic matter, fertility, and productivity. (Singh *et al.*, 2024). Kimaro *et al.*, (2017), indicated that poor seed quality and a lack of better varieties were the main problems limiting the output of pigeon peas. The three characteristics that were considered most desirable were resistance to pod borers, early maturity, and high yields. High yields, early maturity, drought tolerance, quick cooking time, indeterminate types, cream seed colour, and large seed size were found to be the traits that farmers valued most in Tanzania, where insect pests were found to be the primary obstacle to pigeon pea production. To increase pigeon pea output and resilience, it is essential to improve its tolerance to biotic and abiotic stressors. New developments in biotechnology and breeding have helped create better cultivars that are more resilient to a range of stressors. (Table 6). These improved varieties offer promising solutions to mitigate the impact of biotic and abiotic stresses on pigeon pea production, ultimately contributing to food security and livelihood improvement for farmers.

Fungi, viruses, and insect pests are examples of biotic limitations that have an effect on plant growth and the production of quality seeds. 210 pathogens were recorded in a global assessment of 58 nations that cultivate pigeon pea, with a maximum of 98 pathogens being found in India (Utkarsh *et al.*, 2018). Wilt, *phytophthora* blight, *cercospora* leaf spot, and sterility mosaic diseases are the main causes of biotic stress. The primary soil-borne fungus that affects pigeon peas and causes yield losses of 30–100% has been documented in India. Pigeon pea has a widespread foliar disease called *Alternaria* blight. One of the principal diseases that seriously harms pigeon peas is Fusarium wilt. Fusarium is a facultative parasite that enters plants through root hairs and spreads throughout the entire plant. The wilt toxin fusaric acid disrupts the source-sink interaction by blocking vascular tissues. According to a survey study produced by ICRISAT, Fusarium can survive in the soil for three years by infecting plant debris. Fusarium infections are rarely found in seedlings older than a month and are typically detected at the blooming and pod development stages.

Table 6: Improved varieties mitigate the impact of biotic and abiotic stresses on pigeon pea

Variety	Resistance to Biotic Stress	Resistance to Abiotic Stress	References
ICP8863	Fusariumwilt	Drought	Saxena <i>et al.</i> , 2012
ICPL87119	Sterility mosaic virus	Drought, salinity	Saxena <i>et al.</i> , 2013
ICPL20096	Fusarium wilt, pod borer	Drought, salinity	Singh <i>et al.</i> , 2017
ICPL15028	Fusarium wilt, pod borer	Drought, salinity	Singh <i>et al.</i> , 2019
ICPL161	Pod borer, sterility mosaic virus	Drought	Thudi <i>et al.</i> , 2016
Pusa Dwarf	Podborer, sterility mosaic virus	Drought, salinity	Singh <i>et al.</i> , 2019

The damaging viral disease is sterility mosaic disease (SMD), sometimes referred to as the Green Plague of Pigeon Pea. Aceriacajani, an eriophyoid mite, is the carrier. Early infection causes severe stunting, total sterility, and yield losses of 80–90% (Vasudha *et al.*, 2022). Reduced pod length, pod breadth, number of seeds per pod, seed size, and test weight are the effects of infection during the flowering stage, which also causes partial sterility. The first state to disclose Sterility Mosaic Disease in India is Bihar. It has recently expanded to the states of Tamil Nadu, Karnataka, Maharashtra, and Uttar Pradesh.

One of the most pervasive and harmful foliar diseases of Pigeonpea is *Alternaria* leaf blight, which is brought on by *Alternaria tenuissima*. Regardless of the cultivars sown, the disease was found in 60% of the fields surveyed, and its incidence ranged from 20% to 80%. All aerial plant components (leaves, stems, buds, and pods) of infected plants in the field displayed symptoms. Small, circular necrotic patches that quickly formed into the classic concentric rings were the symptoms on leaves (Sharma *et al.*, 2012). Later, these patches consolidated and resulted in leaf blight. The spots started light brown and eventually changed to a dark brown colour. Spots on the stems had concentric circles around them. Defoliation and drying of diseased leaves, branches, and flower buds were seen in cases of severe infection. In various parts of Central Uttar Pradesh, the incidence ranged from 12.0% to 37.5% (Kushwaha *et al.*, 2014).

Loss of Seed Quality During Processing and Storage

Smallholder farmers are the main producers of pigeon peas, and they often keep the whole seeds for eating in storage for around 6 to 12 months per year. Farmers in rural areas de-hull grain in tiny batches as and when necessary, using hand-operated traditional grinding stones called chakki or quern. Since the cotyledons of pigeon peas are firmly linked to the seed coat by a variety of gums, the de-hulling procedure entails dissolving the gum layers by soaking whole seeds in water, heating the mucilage, or adding oil after scarifying the surface. After that, the cotyledons are dried, dehusked, and divided. It is inevitable that some cotyledons would be lost during this process; it is estimated that 15%–17% of the grain mass is lost when employing advanced processing equipment; however, with chakki, these losses could reach up to 20%–25%.

A seed's capacity to store depends on a number of parameters, including seed quality at storage time, pre-storage history (environmental factors throughout pre- and post-harvest phases), moisture content or ambient relative humidity, storage environment temperature, storage length, and biotic agents.

Storage ability is primarily a genetically regulated trait. It is quite challenging to keep these environmental conditions throughout storage. The length of seed survival is significantly influenced by the storage environment, in a cool, dry environment, to minimize metabolic activity and prevent deterioration. The ideal temperature for seed storage is typically between 5°C to 10°C (41°F to 50°F) with 40 to 50% relative humidity. Extreme temperatures should be avoided as they can reduce seed viability (Vales *et al.*, 2014). When damaged seeds are planted, seedling emergence may be poor, and disease transmission to the new crop may take place. Lower temperature and humidity delay the process of seed deterioration, extending the duration of viability (Mohammadi *et al.*, 2011).

Pigeon pea seeds are classified as protein-amyl which means Pigeon pea seeds are indeed valued for their nutritional content, particularly their protein and carbohydrate (amylose and amylopectin) content from the medium to long term due to the concentration of protein as compared to storing starchy seeds such as corn, rice, wheat, etc. since they contain a significant amount of protein (>22%) and starch (50%). Martins Filho *et al.*, (2001) found that there had been a decrease in vigour and viability starting at the 120th day of storage and after 210 days, which showed a void effect. The physiological quality assessment of soybean seeds—whose protein levels are higher than those of pigeon pea—provided a strong illustration of this affirmation. Peske *et al.*, (2006) claim that this behaviour is explained by a change in the seed's chemical composition. Since the same amino acids are present during this process, the metabolism of proteins promotes their partial breakdown, and alterations in chemical composition during degradation make it challenging to acquire seeds with high-capacity development and vigour. Rural diet norms were typically unattainable. According to their findings, pigeon pea provided 5% of the village's energy and 10% of its protein. The meal provided 21.7% of the body's total lysine requirements. These numbers are low and show that fewer people eat beans.

Management Strategies in Agriculture

Many strategies have been demonstrated to lower the virus incidence in pulse crops, such as planting at a certain time, using high seeding rates, closely spaced rows, early maturing cultivars, and virus-host-independent border plantings. Changing the planting date is a popular viral management technique that is strongly recommended for use in legume crops to avoid exposing plants to peak vector populations during their most vulnerable early growth stages. Six genotypes of lentils are

virus-resistant, typically referring to a plant variety or cultivar that has been genetically engineered or bred to resist infection by multiple viruses. In agriculture, viruses can cause significant damage to crops, leading to reduced yields and economic losses. Developing plants with resistance to multiple viruses can help mitigate these losses and improve crop productivity and sustainability. (Makkouk and Attar, 2003). According to reports, crop residues from the Brassicaceae family suppress the growth of soil-borne pathogens, which in turn lowers the frequency of plant diseases they cause (Sinha *et al.*, 2018). Glucosinolates (GSLs) degrade during the breakdown of crucifer residues to create sulphides, isothiocyanates (ITCs), thiocyanates, and nitrile compounds, each of which has fungistatic or antifungal effects.

To treat the infection brought on by various microorganisms, several chemicals are employed. Chemical usage is an expensive and impractical strategy. Crop rotation and crop residue burial are two techniques that help lessen the spread of diseases, which in turn minimise yield losses. The techniques are both economically and environmentally advantageous. Pigeon pea diseases, insects, and pests are treated with the chemicals Matalaxyl, Mancozeb, Thiram, Keptan, Carbendazim, and Zineb. However, occasionally, botanical treatments (plant extracts—leaf powder, rhizome powder, and oil) are used in place of chemical treatments. Seed treatment with plant extract is a possibility in agriculture, but it has a slow effect and can't be utilized for lengthy periods. When used as a seed treatment agent, plant extract (essential seed oils such as mustard oil, neem oil, and groundnut oil) is both environmentally friendly and beneficial to bacteria. Additionally, the fact that it is safe for mammals and effective against a range of fungal diseases reduces the risk associated with application. (Shuping *et al.*, 2017). These treatments are used to prevent the spread of disease and insect pests both in the field and during storage.

CONCLUSION

From the above study, it can be concluded that Pigeon pea is the most dominant pulse of India in terms of production, storage, consumption, and management. If we examine the production and seed availability, the situation seems to be very critical because most of the districts of Eastern Uttar Pradesh fall below the standard recommendation and are standing on the threshold of nutritional insecurity. The results of the current study should assist the pulse industry and regulatory bodies in selecting the right pulse and treatment for efficient future use of these materials. It has also been noted that the type of pulse, its treatment (soaking, germination, processing, storage, and cooking), and their interaction had significant effects on the levels of all enzyme inhibitors (a-amylase, trypsin, and many others) in peas (pigeon pea). So, we need to proceed with the application and technique to control the damage of pigeon pea production and seed storage processing for the best in future research perspectives.

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CONFLICTS OF INTEREST STATEMENT

We have no conflicts of interest to disclose. The authors declare that they have no conflicts of interest. The research was fully done independently, not no financial support involved.

AUTHOR CONTRIBUTION

Contributed to the conception and design of the analysis paper. Contributed to the data collection. Data and analysis tools were used to write the analyzed paper. Also evaluated the paper and then suggested publishing it in this journal.

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