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Review Article

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Genetic resources of underutilized fruits of arid and semi-arid zones: A review

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ABSTRACT

Indian subcontinent is one of the biodiversity regions in the world. These are three bio diversity hotspots namely Northern Eastern Hill region, North western Himalayan region and Western Ghats ate situated in this region. Apart from these three hotspots, several other regions particularly the semi-arid and arid regions also have rich in diversity of plant and animal. The low and erratic rainfall, high evapo-transpiration, extreme temperature regimes, poor soil conditions of these regions helped to evolve several plant species which can grow well under stressful edaphic and environmental conditions. These perennial plant species have played a major role in the food sustainability and livelihood of these regions. Traditionally most of these species were collected from the forest. The recent awareness about potential of ecologically fragile lands for cultivation of fruit trees has not only opened up scope for providing economic sustainability for the natives, especially small farmers, but also for bringing new areas under fruit production. The underutilized fruit crops such as *bordi* (*Ziziphus rotundifolia*), *jharber* (*Z. nummularia*), lasoda (*Cordia myxa*), *kair* (*Capparis decidua*), phalsa (*Grewia subinaequalis*), *gangana* (*Grewia tenax*), bael (*Aegle marmelos*), jamun (*Syzygium cuminii*), *pilu* (*Salvadora oleoides and S. persica),* karonda (*Carissa carandas*), wood apple (*Feronia limonia*), mulberry (*Morus* spp.), manila tamarind (*Pithocelobium dulce*), etc. are found in these regions. A vast diversity of these species exists in the region. The genetic resources of these fruits are rapidly declining due to climate change, urbanization and change in farming systems. There is need to conserve these genetic resources for their utilization for crop improvement programme and future uses. Several attempts have been made by research organizations to collect, conserve and utilize the genetic resources of these underutilized fruit species. Several promising varieties and lines have been identified for enhancement of production, and productivity of these crops. The status of plant genetic resources of some of the important underutilized fruit species of semi-arid and arid regions have been compiled in the review paper.

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Introduction

In India, arid and semi-arid regions cover approximately 15.8% and 37% respectively, which is roughly half of the total geographical area (about 3,287,263 km^2). The arid regions of Rajasthan, Gujarat, Punjab and Haryana while the semi-arid region is spread over a large tract of central India which includes part of Madhya Pradesh, Maharashtra, Karnataka, Telangana, Tamil Nadu, Odisha and Andhra Pradesh. The underutilized fruits may be categorized in two groups i.e. indigenous and exotic. India has a rich and varied heritage of biodiversity, encompassing a wide spectrum of habitats from tropical rainforests to alpine vegetation and from temperate forests to coastal wetlands. Out of 18 biodiversity hotspots identified in the world, four hotspots, i.e. Western Ghats, Eastern Himalayas, Western Himalayas, and Nicobar Islands, are in India.

Several fruit plant species have originated in the Indian subcontinent. India is the centre of origin of bael, aonla, ber, jamun, mahua, phalsa, lasoda, karonda, wood apple and several other wild fruits. Some of these fruits have gained popularity in the past few decades but the majority are still not grown in large area. Several minor fruits such as *Annona* spp., manila tamarind, prickly pear, dragon fruit etc. were introduced during last few centuries. Some of adopted to the climatic conditions of India and have become major fruits. The genetic resources of indigenous species are under threat due to urbanization, changes of farming system and livelihood patterns. The conservation and utilization of genetic resources of these crops are essential to enhance productivity, promote commercialization, and develop climate-resilient horticultural systems (Meghwal and Singh, 2024).

Conservation strategies include both *in-situ* and *ex-situ* approaches. In-situ conservation ensures theprotection of genetic diversity within natural ecosystems and traditional farming systems, whereas *ex-situ* conservation involves the conserving of germplasm in seed banks, field gene banks, and cryopreservation facilities. Advances in molecular characterization techniques have further strengthened efforts to identify and preserve elite germplasm, facilitating breeding programs aimed at improving fruit quality, yield, and stress tolerance. With increasing concerns about climate change and desertification, the role of arid and semi-arid fruit crops in sustainable agriculture is gaining attention. Systematic research, farmer participation, and policy support are crucial to harnessing the full potential of these crops for future food security and environmental resilience.

Efforts led by institutions such as the ICAR-NBPGR, ICAR-CIAH and agricultural universities focus on germplasm collection, characterization, and conservation to safeguard the genetic diversity of these crops. Most of ICAR institutes and agricultural universities etc. are involved in the collection, evaluation and utilization of fruit genetic resources. Being a National Active Germplasm Site (NAGS) for arid fruits, the ICAR-CIAH, Bikaner, Rajasthan, is maintaining the largest repository of the germplasm of arid and semi-arid regions. NRC for Pomegranate, Solapur has a large collection of pomegranates, while the ICAR-IIHR is maintaining a large germplasm of Annona, pomegranate, jamun, wood apple and kaith. The crop-wise status of collection, conservation, and utilization of germplasm of some important fruit crops of the arid and semi-arid zone is described as follows.

Bael (*Aegle marmelos* (L.) Correa)

Bael occupies an important place among the indigenous fruits of India. It has been known in India since prehistoric times. It is called *Bilva* or *Sriphal* or *Shivadruma* in Sanskrit and is considered auspicious, sacred, and the emblem of prosperity. The history of the bael has been traced to Vedic times (2000 BC-800 BC in *Yajurveda* and in Buddhist and Jain literature (800 BC-325 BC). It belongs to the family Rutaceae. It is also known as Bengal-quince, golden apple, and stone apple. The chromosome number is x=9 and 2n=36.

There are no detailed cytogenetic studies on bael, however, few reports from Punjab plains, Shivalik Hills and Panchmadi Hills revealed the existence of diploid (2n=8) and tetraploid cytotypes (2n=36). Bael is native to Indian subcontinent and its origin is the Eastern Ghats and central India. It is mainly found growing in tropical and subtropical regions. The tree is also found as a wild, in the lower ranges of the Himalayas up to an elevation of 1000 m. It is found growing in neighbouring countries like Nepal, Sri Lanka, Pakistan, Bangladesh, and most of the Southeast Asian countries, but is cultivated only in India.

Genetic resources

The genus *Aegle* is one of the monotypic genera of the orange subfamily with deciduous leaves. One more species *A. decandra* Fern Vill. was reported under the genus *Aegle* according to World Checklist of species of plants (WCSP), global species resources. *A. decandra* is native to the Philippines. The rich diversity of bael present in India in cultivated and uncultivated areas has been collected and maintained. However, genetic erosion of these resources is high due to severe deforestation, natural calamities and other land use changes that are occurring in the country at an unprecedented rate, therefore, its conservation has become necessary. Naturally growing bael trees are found in U.P, Bihar, Jharkhand, M.P., Orissa, West Bengal and Chhattisgarh. In these areas, great diversity could be observed which needs to be conserved *in-situ* or be collected, conserved and exploited. In Uttar Pradesh, Ayodhya, Sultanpur, Gonda, Jaunpur, Deoria, Pratapgarh, Allahabad, Varanasi, Mirzapur, Etawah, Mathura and Agra are the districts where many improved types are growing or planted in backyards (Pandey *et al*., 2013).

Rai and Dwivedi (1992) and Vishal Nath *et al*. (2003) reported a wide range of bael genetic diversity in Northern and Eastern Central India. Apart from the morphological characters, wide variation exists for traits such as fruit shape and size; bearing habit; pulp colour, texture, fibre content, sugar content, mucilage content; number of seeds per fruit, gumlocules; thickness of pericarp, etc. Among the local types, Ayodhya, Kagzi Etawah, Kagzi Gonda, Sivan Large, and Mirzapuri are popular in UP due to their good yield potential and fruit quality. The bael genotypes available in Karnataka, Andhra Pradesh, and Telangana are different from the genotypes available in North Indian plains. These have smaller leaves and leaflets. The fruits are smaller and non-edible because of higher saponin content (Tripathi *et al*., 2017).

Collection

In India, there are two prominent types of bael. One is the small-fruited type having acrid pulp and many seeds, high mucilage and fibre content and the second is the large-fruited type with a thin shell, few seeds, less fibre and mucilage and sweet pulp. Bael germplasm is collected and conserved by ANDUA&T, Ayodhya; GBPUA&T, Pantnagar; ICAR-CISH, Lucknow; ICAR-CIAH, Bikaner; ICAR-CAZRI, Jodhpur; ICAR-NBPGR-Regional Station, Jodhpur; ICAR-IIHR, Bengaluru. The collections from Bihar, Jharkhand are conserved at ICAR-NBPGR-RS, Jharkhand (Dhakar *et al*., 2019). ICAR-IIHR, Bengaluru explored Karnataka, Andhra Pradesh, Telangana and collected more than 100 samples (Tripathi *et al*., 2017).). The bael germplasm is also collected at several other research stations. There may be many duplicates in the germplasm at different stations as many samples were collected from secondary sources. The available bael accessions are conserved at the field gene banks of the above-mentioned research centres.

Conservation

Bael germplasm is conserved using *in-situ* and *ex-situ* approaches. The bael accessions are conserved in *ex-situ* at the field gene banks of at several research institutes (Table 1). In efforts of conservation germplasm under gene bank under laboratory conditions at low temperature is also is in progress. The seed of bael are intermediate type and can be stored for 24-36 months at ambient temperature (24-36°C). The bael seeds can be cryopreserved and stored for a long time. Bael seed loses most of its viability (germination 1.07%) when the critical seed moisture level falls to 4.4%. The loss of viability due to exposure of liquid nitrogen was 11.60%. The viability of seed was 70% and 65.5%before and after cryo-conservation, respectively (Malik *et al*., 2010). The seeds show chilling sensitivity and most seeds lost viability after 12 months of storage at -20^{O}C.

Only a few studies have reported on the collection and maintenance of bael germplasm in Sri Lanka, Pakistan, and Bangladesh. The collections of Pakistan and Bangladesh are genetically similar to the collections available in Northern India.

Table 1. Bael germplasm maintained at different research centres

Name of the organization	Accessions
Acharya Narendra Dev University of Agriculture & Technology, Ayodhya, Uttar Pradesh	22
Govind Ballabh Pant University of Agriculture & Technology, Pantnagar, Uttarakhand	10
ICAR-Central Institute for Subtropical Horticulture, Lucknow, Uttar Pradesh	22
ICAR-Central Institute for Arid Horticulture, Bikaner, Rajasthan	16
Dryland Agricultural Research Station, Anantapur, Andhra Pradesh	12
Regional Research Station, Aruppukottai, Tamil Nadu	05
Dryland Agricultural Research Station, Sardarkrushinagar, Gujarat	12
ICAR-National Bureau of Plant Genetic Resources, New Delhi	05
Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra	06
ICAR-National Bureau of Plant Genetic Resources, Regional Station, Thrissur, Kerala	57
ICAR-Indian Institute of Horticultural Research, Bengaluru	117
ICAR-NBPGR, RS, Ranchi	17
ICAR-CIAH, CHES, Godhra	222

Evaluation

Rai *et al.* (1991) reported on bael variability available in India observed at different locations. Lal (2002) evaluated

12 genotypes collected from Jaipur, Rajasthan and found that 8 genotypes produced fruits of excellent quality under semi-arid conditions, and two genotypes were identified for further testing. Extensive characterization was done by Jaiswal and Mishra (1998). The wild and cultivated trees growing at the above-mentioned places were reported to be diploid with normal meiosis with 92-98% pollen fertility. The trees possessing large leaves and fruits were found to be tetraploid. In addition to tree morphological characters, wide variability was found in fruit size and shape, bearing habit, flesh colour, texture, fibre content, sugar content, mucilage content, etc, in different parts of the country (Singh *et al.*, 2011; Nath *et al.*, 2003). In the Jaunpur area of UP, among the very old naturally growing bael trees with many seeds, gum locules and thick pericarp were found (Misra *et al.*, 2000). Some promising lines have been identified, but still need to be tested rigorously (Pareek and Nath, 1996; Vishal Nath *et al.,* 2003).

Bael collections made at ICAR-NBPGR were characterized for various physicochemical characters and the heaviest fruits with the highest TSS were recorded for accession IC546120, followed by those in IC54613.In West Bengal, collection and evaluation of over 1200 bael trees were initiated in 1994 for various traits such as yield, fruit weight, fruit shape etc., and six genotypes were identified as superior clones and are being conserved at the Faculty of Horticulture Research Station, Kalyani (Mitra *et al.*, 2010). Tripathi *et al.* (2017) evaluated 115 accessions of bael collected from Karnataka, Andhra Pradesh, Telangana, Maharashtra and North India. The growth habit ranged from spreading to upright. Overall, accessions collected from Karnataka and Telangana had smaller fruits and a more soapy flavour and taste but were found free from cracking and even fruit borer. The latter need more studies to confirm so that these may be used in the programme to improve these traits. Chaturvedi *et al.* (2023) evaluated 24 bael genotypes from two agroecological zones of India using morphological (13 quantitative traits), biochemical (9 attributes), and molecular (10 SRAP primers) characterization. Fruit and pulp weights varied from 79.0 to 1478.8 g and 15.0 to 894.3 g, with mean values of 448.67 g and 233.3 g, respectively. The fruit pulp exhibited high phenol (11.65–24.38 mg GAE/g fw) and flavonoid (12.32–74.63 mg CE/g fw) contents, indicating notable antioxidant potential.

Five elite bael accessions were evaluated at Fruit Research Station in Sri Lanka and considerable variation was observed for the variation of the fruit size, pulp, organoleptic preferences, etc. and fruits from Rambukkana and Polonnaruwa-Supun lines were found to be the most preferred (Pathirana *et al*., 2020). Presently the selection of the selected genotypes is the only method used to develop the varieties. The hybridization and mutation breeding may be used to develop breeding lines and varieties with desirable traits in future. The present varieties are a selection from the landraces or seedlings progenies.

Varietal development

Elite selections have been made at ANDUA&T, Ayodhya (NB-4, 5, 7, 9, 16, 17); GBPUA&T, Pantnagar, ICAR-CIAH, Bikaner and CHES(CIAH), Godhra (Goma Yashi, Thar Divya, Thar Neelkanth, Thar Prakriti), ICAR-CISH, Lucknow (CISH B-1 & 2) which are becoming popular for commercial cultivation. Other institutes like FSRCHPR, Ranchi one genotype Swarna Vasudha and Dhara Road from CAZRI, Jodhpur and GB PAUT viz., Pant Nagar promising one are Pant Aparna, Pant Shivani, Pant Sujata, Pant Urvashi released for commercial orcharding.

Kaith (*Feronia Limonia L. syn. Limonia acidissima* L, *Limonia elephantum* (Correa), *Schinus limonia* L.

Wood apple (kaith) is adrought-resistantfruit tree species. It is known as *kathbel* in Bengali, *kothu* in Gujarati, *beldahannu* in Kannada, *kavit* in Marathi, *Vilaljam* in Tamil and Malayalam, *Kaith*, *katbel* in Hindi, and *Kapittha,Dadhiphal* in Sanskrit, wood apple/curd fruit in English. *Kaith* is a multipurpose tree species, valued for its nutritious edible fruits, gum, wood, and alkaloids. It is said to have many medicinal properties. The fruit pulp is sour-sweet in taste and full of small seeds. It is rich in nutrients suchas carbohydrate, protein, fat, fibre, vitamins (A, B_1, B_2, B_3 and C) and minerals (iron, calcium, phosphorus, zinc, manganese). It belongs to the sub-family Aurantioideae of the family Rutaceae. Kaith is a deciduous tree which grows up to 20 m high.

Kaith is native to Indian subcontinent. It is also found growing in Pakistan, Bangladesh, certain parts of Sri Lanka, Pakistan, Thailand, Malaysia, Cambodia and some other countries of Southeast Asia. In India, it is grown in Maharashtra, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Karnataka, Telangana, Rajasthan and Gujarat. It grows on barren lands, bunds of field, and the forest areas. The fruits are collected from these trees and sold in the market. The fruits are available in the market from October to March, sometimes up to June.

Genetic resources

Feronia is a neglected crop, and systematic efforts to collect of Feronia are yet to be taken. Isolated efforts were made at several institutes and universities to collect Feronia. Several types of Feronia are found in wild and in cultivated land in Karnataka, Maharashtra and Madhya Pradesh. As *Feronia* is monogenic, there are no related species.

Collection

Most of the trees are of seed origin and exhibit considerable variation which can be used for making selection of superior types. There are two forms - one with large, sweetish fruits and the other with small, acidic fruits. ICAR-IIHR, Bengaluru maintaining 16 accessions and ICAR-CIAH, CHES, Godhra is maintaining 16 accessions. At BCKV, Kalyani 07 accessions are being maintained (Ghosh *et al.*, 2012).

Conservation

Very little work is done on Feronia conservation, with only a few accessions maintained in field gene banks at a few institutes. As wood apple seed can only be stored for about 90 days without serious loss of viability. Since there have been no explorations/ surveys, neither genetically diverse samples nor elite material has been conserved. This species has been neglected and has not received the attention it deserves, mainly due to difficulties in conducting research, e.g., their large size, prolonged juvenility, long life cycles, irregular flowering, and lack of standardized cultivation practices

Evaluation

Precocity in bearing, less spine intensity, earliness, regular bearing, uniform maturity, the dwarf stature, large fruit with more pulp and fewer seeds are some traits. Two types of kaith, i.e., one with larger fruits sweeter in taste and another smaller with acidic fruits, are found in all the growing areas. Since this is a monogenic species, the variability is less compared to other fruit species of family Rutaceae. As noted earlier, very few efforts have been made to collect kaith genetic resources from different regions of the country. At ICAR-IIHR, Bengaluru, more than 16 collections were made from Karnataka, Telangana, and Andhra Pradesh. Among them, two collections were found superior to others by being high-yielding, regular-bearing, large-fruited, with higher TSS (>18°Brix), brown colour pulp, and sour-sweet taste (Tripathi, 2020). Ghosh *et al.* (2012) collected and characterised seven samples wood apple, trees with varied ages (13 and 70 years) for different traits viz. yield (650 to 1085 kg/plant), fruit weight (130 to 225g), pulp percentage (42.9 to 60.6%), T.S.S. (15.0 to 18.4°Brix), acidity (1.7 to 4.6%) and total sugar content (5.1 and 14.3%).

CHES, Godhra was evaluated for traits like precocity in bearing, less spine intensity, earliness, regular bearing, and dwarf stature of the tree. The fruit have strong aroma. The fruit weight ranged between 145.52g to 431.23g (Yadav *et al.*, 2018). In wood apple, *in-situ* evaluation of accessions from Telangana revealed that the accessions identified with desired fruit traits include AS/SB-1 (Fruit weight >250 g), AS/SB-8, AS/SB-13, AS/SB-19 (>65% pulp recovery), AS/SB-8 (high TSS 20.8°Brix) and AS/SB-7 (low acidity of 2.28%). Based on yield and fruit qualities, superior wood apple tree (CKBR-1) from Karikere in Chitradurga district was identified from field of a farmer. The tree is nearly free of thorns, bears large fruits (350 g) with high pulp recovery (62%), TSS (19°Brix) and moderate acidity (2.87%). Fruiting occurs during February-June. Average yield is 300 kg per tree per year. The source of resistance to abiotic and abiotic stress has not been identified. There is a need to select elite lines that may be used as parents for future improvement programmes. Presently, the selection of the genotypes from the variability in forests and stray land is the only method that can be used to develop the varieties.

Varietal development

Some elite lines have been collected and multiplied at some organization. A few varieties have been identified, including Yellora by VNMKV, Parbhani (MS), Thar Gaurav and Thar Prabha by ICAR-CIAH, CHES, Vejalpur, PDKV Pratap by PDKV, Akola (MS) and PKM-1 from TNAU, Periyakulam.

Karonda (*Carissa carandas*)

Karonda is native to India and occurring throughout country. It grows well arid tropics and subtropics and produces attractive coloured edible fruits. It also grows successfully on marginal and wastelands. It thrives well under rain-fed crop conditions and needs hardly any care and gives satisfactory fruit yield with the minimum management. It is also used as live fencing around the orchards. Ripe fruits are sub-acidic to sweet with peculiar aroma. The fruits are eaten as a dessert when ripe. Mature fruits contain a high amount of pectin and are used for the preparation of different products such as jelly, jam, squash, sauce, syrup, etc. *C. carandas* (2n=22) belongs to family Apocynaceae. It is a large evergreen shrub with a short stem grows to a height of 3-6 meters.

C. *carandas* and *C. spinarum* are native to India while *C. grandiflora* is native to South Africa. *C. carandas* is also grown in Sri Lanka, Myanmar, Thailand and Peninsular Malaysia. In India, it is found wild in the Western Ghats, Konkan area of Maharashtra and throughout the semi-arid regions. It is usually found in home gardens, as a hedge along farmer's fields and orchards and grown for commercial purpose. *Carissa* species is of socio-economic importance in the tribal areas of Gujarat, Maharashtra, Rajasthan, and Madhya Pradesh.

Genetic resources

It is found growing in Maharashtra, Bihar, West Bengal, Chhattisgarh, Orissa, Gujarat, Madhya Pradesh, Rajasthan and in the Western Ghats Karonda occurs growing naturally in several areas. In Maharashtra, it is cultivated scattered in submontane areas like Kolhapur, Ratnagiri and Pune district. It grows wild in most South Asian countries like in the lowland rain forests of Sri Lanka. Although it grows throughout India, the maximum variability is found in the states of Maharashtra, Bihar, West Bengal, Chhattisgarh, Orissa, Gujarat, Madhya Pradesh, Rajasthan and in the Western Ghats. Aravalli Hills of Haryana and Rajasthan (mainly the Mt. Abu), Chittorgarh and Sirohi districts are rich in karonda diversity.

It has been widely collected from Maharashtra; 212 collections have been made from Kolhapur (Sawant *et al*., 2002) and are maintained at the College of Agriculture, Kolhapur. A total of 111 samples were collected from 45 locations in western Maharashtra, Marathwada, and Goa, which are classified based on fruit characters. At ICAR-NBPGR, germplasm of *C. congesta* and *C. spinarum* has been collected from Rajasthan, Gujarat, and Madhya Pradesh. *C. grandiflora,* which maintained in the field gene bank at the Regional Research Station, PAU, Abohar, was also added to the ICAR-NBPGR gene bank.

The genus Carissa has nearly 30 species originating in South Africa, Australia, tropical Asia and Malaysia. Different species of Carissa are grown for their small berry-like edible fruits and as closely branched spinous hedges. Some species are also cultivated for ornamental purposes. Apart from *C. carandas*, other important species are *C. spinarum*L*, C. inermis* Vahl.*, C. suavissima* Bed.*, C.acuminate* DC*, C. bispinosa* Desf., *C. congesta* Wight*, C. edulis* Forssk.*, C. grandiflora* and C. *macrophylla* Wall. ex G. Don. These are spread over subtropical and tropical Asia and Africa. Most of them have edible fruits that are used by the native people.

Collection

Germplasm of karonda and its wild species are being maintained at various field gene banks at MPKV Rahuri, RS Kolhapur; ICAR-CAZRI, Jodhpur; ICAR-CISH, Lucknow; ICAR-CIAH, Bikaner; ANDUA&T, Ayodhya; CCSHAU, Regional Research Station, Bawal; ICAR-NBPGR Regional Station, Jodhpur; CHES (ICAR-IIHR), Chettalli and GBPUA&T, Pantnagar (Table 2).

Table 2. Karonda germplasm at different locations

Institute	Accessions
ICAR-CIAH, Bikaner	8
ICAR-CIAH, CHES, Godhra	40
ICAR-IIHR, CHES, Chettalli	31
MPKV, Rahuri, RS, Kolhapur	212
CCS HAU, RRS, Bawal	4
ICAR-CISH, Lucknow	25

Conservation

In-situ conservation of karonda has been done at various locations. Although seeds are the major source of propagation, they can be multiplied to someextent by rooting cuttings and layering. Thus, both sexually and vegetatively propagated plants are conserved in field gene banks. However, seeds have short viability and should be sown soon after extraction from fruits. The studies conducted at ICAR-NBPGR demonstrated karonda's intermediate nature of seed. Fresh seeds exhibited 18.4% moisture and 72% germination and dropped by 50% in 3 months. Seeds showed slight desiccation sensitivity and high freezing tolerance as on desiccation to 9% moisture and 12% decline in viability was recorded. Seeds desiccated to 6-8% moisture showed 65-70% germination after LN exposure. Fourteen accessions of *Carissa* spp. (9 of *C. carandas*, 1 each of *C. edulis* and *C. grandiflora,* and 3 of *C. spinarum*) are in cryo-storage at ICAR-NBPGR, New Delhi (Malik *et al.*, 2010).

Evaluation

The major concerns are smaller fruit size, thorniness, high latex, acidity, low TSS, cracking and more number of seeds per fruit. High yield potential, big-sized fruits with attractive skin colour higher pulp content, a smaller number of seeds, high TSS with low in acidity, dwarf stature with less spine intensity, resistance for major diseases and pests are desirable traits. A survey of karonda in eastern Uttar Pradesh identified 4 types of fruit, viz. green, white with a pink blush, green with purple blush and maroon (Kumar and Singh, 1993). Average fruit weight ranged from 1.6 to 4.7 g and an average number of seeds per fruit from 5 to 11. TSS ranged from 3 to 4.5%, ascorbic acid from 10.26 to 17.94 mg/100 g, reducing sugars from 0.93 to 2.4% and non-reducing sugars from 0.57 to 1.33%. Mishra *et al.* (2007) developed three varieties by selection viz., Pant Manohar, Pant Sudarshan, and Pant Suvarna. At ICAR-CAZRI, Jodhpur, collected a wide range of samples of *Carissa* in 2000-2001 and three genotypes were identified to be the high yielding and to be released shortly (Anonymous, 2011).

Sixteen distinct karonda genotypes were identified from the germplasm collected from western Maharashtra. At MPKV, Rahuri four promising genotypes were identified (Karale *et al*., 1989; Karale *et al*., 1990)). Singh *et al.* (1999) identified 4 genotypes of karonda based on the colour of the fruits and grouped in to, green, green with purple blush, white with pink blush and maroon. Tripathi *et al.* (2014) evaluated 45 karonda accessions collected from the Western Ghats and some parts of South India. The number of fruits ranged from 84 to 3540 fruits/ plant. The yield ranged from 0.93 kg/tree to 69.50 kg/ plant. The highest yield was recorded in K-I-2 (69.56 kg). The fruit weight was highest in K -I-3 (21.69 g). Pulp percent ranged from 66.41 to 92.58 per cent. The TSS varied from 11.6° Brix in K-I-8 to 18.9°Brix in K-V-4. These superior lines have big size fruit (12- 16g), few seeds and higher TSS.

Varietal development

Elite selections have been made at GBPUA&T, Pantnagar (Pant Suvarna, Pant Manohar, Pant Sudarshan); BSKKVV, Dapoli (Konkan Bold), ICAR-CAZRI, Jodhpur (Maru Gaurav), ICAR-IIHR, CHES-Chettalli (CHES- K-II-7&CHES- K- V-6) and CIAH, Bikaner (Thar Kamal) which are gaining popularity for commercial cultivation. The varieties and promising line developed through selection are, CHES-K–2, CZK-2011, CZK-2022, CZK-2031 CISH Kr-11, CHESC-K-2-7 and CHESC-K-35.

Kair (*Capparis decidua* (Forssk.) Edgew)

Kair, Caperberry, Bare Caper is an important indigenous multipurpose shrub of a hot arid ecosystem with the ability to survive in various unattended and unprotected habitats (Singh *et al*., 2005). It is found growing in arid and semi-arid tracts. *Kair* is found growing along farm boundaries, pastures and wasteland and can survive in various habitats. It produces edible fruits which are relished by the local population. The fruits are rich in carbohydrates, proteins and minerals. The cured dried fruits are used in vegetable preparations and for pickling. The species play ecological roles in providing vegetative cover, improving soil fertility, preventing soil erosion and promote biodiversity in addition to its economic significance.

It belongs to family Capparaceae. *Kair* is a straggling glabrous shrub with zigzagging green branches (phylloclade) with a pair of straight spines. Exact origin of *kair* is unknown but it is distributed naturally in a wide area comprising of India, Iran, Jordan, Mauritania, Chad, Egypt, Ethiopia, Niger, Nigeria, Pakistan, Senegal, Somalia, South Africa and Sudan, the area of its natural distribution. Ker grows wild and unattended throughout India's arid north-west regions. In India, it is mostly found in Rajasthan and Gujarat (Singh and Singh, 2011). It is a source of income to people in the drier regions of Rajasthan and Gujarat. Several thousand tonnes of fruits are produced in the Jodhpur and Bikaner districts of Rajasthan (Chandra *et al*., 1994).

Genetic resources

The genetic variability is spread over dry arid regions of western India particularly in drier areas of Rajasthan and Gujarat in India and in other countries of its natural distribution. Natural population exhibits marked variation in plant types, spines, canopy (spread and compactness), flowering (time of flowering, the colour of flower), and fruiting (size and colour of fruits) characters. Two distinct plant types were observed, a shrub with large canopy and small tree form having more than 5 m height. Flowers are light red to scarlet red, and occasionally few plants have yellow flowers. The size and colour of mature fruits varied considerably. The collected accessions exhibit wide range of variability for fruit diameter, fruit weight, number of seeds per fruit, test weight and canopy characteristics. There are several species in the genus *Capparis*, namely *C. spinosa, C. orientalis, C. sicula, C. aegyptia, C. ovate* etc., which are found in Spain, Morocco, Syria, etc. Amplified Fragment Length Polymorphism (AFLP) revealed low genetic distance among *Capparis* species.

Collection

Various studies carried out on natural populations of *C. decidua* indicate that it possesses considerable genetic diversity (Abdel-Mawgood *et al*., 2005; Singh *et al*., 2007; Vyas *et al*., 2009) but its systematic utilization in genetic improvement has been very limited. The collection of *kair* variability in various hot and drier regions of Gujarat, Rajasthan and Haryana are being taken at CAZARI, Jodhpur; CIAH, Bikaner; CCS HAU RRS, Bawal and ICAR-NBPGR RS, Jodhpur.

Conservation

Conservation of *kair* germplasm is presently being undertaken using *ex-situ* field gene banks at ICAR-CAZRI, Jodhpur (20 accessions), CIAH, Bikaner (65 accessions) CCS HAU RRS, Bawal (57 accessions) and ICAR-NBPGR RS Jodhpur (22 accessions). Micro propagation of *kair* has been successfully reported by with 3-5 shoots per explants using *in-vitro* culture of nodal explants. Germination and seedling growth showed significant variations among accessions. The germination ranged 41.6–93.4 % and survival varied from 44.2 to 76.8%. Total 88 accessions of *kair* are maintained at cryo-storage of ICAR-NBPGR, New Delhi (Malik *et al*., 2010). Ahlawat *et al.* (2018) reported that synthetic seeds of *Capparis* was stored for 30 days at 4°C and 8°C and moisture content 69.7% and 50.9% respectively, which was similar to the highest germination. The encapsulated shoot tips of *Capparis decidua* showed maximum regrowth frequency on media MSA and responded with almost 100% conversion to plantlets as compared to the nodal segment.

Evaluation

Mahla and Singh (2013) collected and characterized 45 collections of *kair* from Western Rajasthan (Bikaner, Nagaur, Jodhpur, Barmer and Jaisalmer districts) and found ample variation for fruit diameter (11.42-22.63 mm), fruit weight (1.18-7.23 g), seeds per fruit (5.2-27.8) and test weight (14.6-26.9 g). Bigger fruit size, fewer seeds are the desirable traits. Selection of elite lines from the wild and uncultivated land is the only option till now.

Varietal development

There are no released varieties of *kair*. There are some promising lines identified by the institutes. The area under cultivation of *kair* is very limited and most of the produce comes from forest.

Lasoda (*Cordia myxa* Roxb.)

Cordia myxa Roxb. (Indian cherry, Lasoda, Goonda) is a large evergreen tree with a dense crown, which can grow up to 12 metres. It is a multi-purpose tree and uses include - food, medicine and source of wood, fibre, etc. It is originated in the Indian subcontinent but is also cultivated in western African countries for its edible and medicinal fruits. The fruit makes an excellent pickle (Tripathi, 2020). The ripe fruit is eaten by children despite gum-like substances when ripe. It belongs to family Boraginaceae. The other important species are *C. gharaf* (goondi), *C. rothii, C. macleodii, C. vestita* and *C. wallichii. Cordia myxa* originated in the sub-Himalayan region extending through the forests of India, Nepal and Myanmar and can be found growing up to 1,500 meters MSL. It is distributed throughout the country mainly in warmer parts of the country. It is mostly found as wild and only occasionally as cultivated. *C. myxa* found growing home gardens, backyards and farmers' fields as an isolated tree or a few in numbers. It is also found in Taiwan, Thailand, Malaysia, China, Polynesia and Australia. In India, lasora grows in moist and dry forests of Rajasthan, Punjab, Maharashtra, parts of the sub-Himalayan tract and the Western Ghats. It prefers ravines and valleys.

Genetic resources

Great variation exists in natural population with respect to morphological characters particularly plant height, spread, leaf size, fruit size; fruiting behaviour; fruit characteristics like colour, pulp content, pickling quality, seed, pulp ratio, etc. However, it has neither been systematically collected from areas of its natural distribution nor there have been any efforts to exploit it. More recently, some efforts have been made by ICAR-NBPGR Regional Station, Jodhpur and ICAR-CIAH, Bikaner to identify some big fruited types with high productivity. At CCS HAU, Hisar, different genotype was evaluated by Saini *et al.* (2002) and they reported variability in plant height and spread. High genotypic coefficient of variation and phenotypic coefficient of variation for fruit weight and leaf size together with high heritability and genetic advance has been recorded by Samadia (2007). Pulp: stone ratio had a significant positive correlation with most of the parameters except several fruits per cyme and stone thickness, and it had a negatively significant correlation with several flowers per cyme (Nagar *et al.*, 2013).
Kaushik and Dwivedi (2004) reported a wide range of diversity in morphological and quality characters in 45 collections of lasoda from Haryana. In general, two types of plants viz., large-fruited and small-fruited are found growing and are sold by local people. Large fruited cultivars have an average fruit weight of 8.55 g, whereas small-fruited cultivars have fruit weight of 3.0 g. In the case of large-fruited cultivars, fruit have comparatively more pulp thickness and therefore are suitable for consumption. Large fruited types in Gujarat also recognized as 'Paras Gonda', is a general term for any fruit variety with big size fruits. Similarly, in Rajasthan 'Puskar Local' is big with good fruit shape. At CIAH, Bikaner under *ex-situ* conservation, 65 types of lasoda have been collected and planted under field conditions to identify promising types.
Sivlingam *et al.* (2012) reported that there is much variation in fruits morphological character as well as molecular observations. The genus *Cordia* has about 250 species majority of which occurs in the New World. The other species in the genus *Cordia* are *C. gharaf* (Forsk.) Ehrenb & Asch. Syn. *C. rothii* Roem. & Schult.), *C. macleodi* Hook. F. & Thomas. and *C. Sebastian* L. Gonda exists in two forms, namely small-fruited and large-fruited types. The primary differences between them lie in the size of the fruits and leaves (Meghwal and Singh, 2016).

Collection

Genetic diversity of *Cordia* species, especially *C. myxa,* has been collected by ICAR-NBPGR from Rajasthan, Haryana, Gujarat, Madhya Pradesh, Himachal Pradesh and Uttar Pradesh and 134 accessions of various *Cordia* species have been collected. Besides, 45 accessions of elite germplasm have been collected by ICAR-NBPGR in collaboration with CCSHAU, RRS, Bawal from Rewari, Mahendragarh and Bhiwani districts of Haryana and germplasm was established at field gene bank at CCSHAU, RRS, Bawal and ICAR-NBPGR, Regional Station, Jodhpur. ICAR-NBPGR collected 57 accessions comprising of *C. myxa, C. crenata and C. rothii* from six states of India High genotypic coefficient of variation and phenotypic coefficient of variation for fruit weight and leaf size, representing sizable diversity in fruit weight, shape, size, surface feature, pulp content, seed size, weight and shape. One promising accession with bold and shiny fruits and prolific bearing was identified by local farmers near Kotputli, Rajasthan. ICAR-CAZRI, Jodhpur collected 13 accessions during 2000-04 from different parts of Rajasthan and Gujarat and evaluated and vide variation in fruit size, shape, yield, and pulp: stone ratio (Anonymous, 2011). Saini *et al.* (2002) collected 27 promising genotypes were collected and planted in Haryana. ICAR-NBPGR, in collaboration with CCSHAU. RRS, Bawal collected 45 accessions. Germplasm was collected from Rewari, Mahendragarh and Bhiwani districts of Haryana and planted in the field gene bank at CCSHAU, RRS, Bawal and ICAR-NBPGR-RS, Jodhpur. Few collections of lasoda have been made from Karnataka at ICAR-IIHR, Bengaluru.

Conservation

Germplasm of lasoda is being conserved in the field gene banksat CCSHAU, RRS, Bawal (30); ICAR-CIAH, Bikaner (65); ICAR-NBPGR Regional Station, Jodhpur (73) and ICAR-IIHR, Bengaluru (17). Detailed studies conducted at ICAR-NBPGR showed that seeds are shed at about 25% moisture and exhibit high germinability (94%). Seeds exhibit desiccation tolerance to some extent, but appeared to be sensitive to freezing, but at a 6 - 8% moisture content, high recovery rate was observed. Based on these results, seeds of *C. myxa* (24 accessions), *C. crenata* (3), *C. obliqua* (1) and *C. rothii* (9) have been cryo-stored at ICAR-NBPGR, New Delhi (Malik *et al*, 2010).

Evaluation

Singh *et al*. (1999) identified two types of lasoda based on fruit maturity - one early type with small and turnip shaped fruits and the other late type with large spherical fruits. At ICAR-CAZRI, Jodhpur two elite genotypes i.e. CAZRIG2021 and CAZRIG2025 were identified based on fruit size, shape, yield, and pulp: stone ratio and other desirable attributes (Anonymous, 2011). Kaushik and Dwivedi (2004) recorded variability in fruit length (1.34-2.96 cm), fruit breadth (1.84-3.34 cm), fruit weight (11.6-25 g) TSS (8.5-28%) and seed weight(0.22-0.85 g). At ICAR-NBPGR a total of 24 accessions were characterized for traits such as fruit shape (ovoid to oval), fruit length (1.4-12.72 cm), fruit width (1.29-2.92 cm), fruit weight (1.12-9.82 g), pulp thickness (0.23- 0.56 cm), and seed weight (0.21-1.26 g). Among these, seven were found better in terms of large fruits, higher TSS, pulp thickness and smaller seeds. Similar studies have been reported by Bhatnagar, 2018; Bhatnagar *et al.,* 2015; Hare Krishna *et al*., 2019 and Tripathi *et al*., 2020.

Varietal development

Few elites' lines have been identified by some institutes viz. Thar Bold has been released by ICAR-CIAH, Bikaner, Maru Samrudhi by ICAR-CAZRI, Jodhpur and Karan Lasoda from SKN AU, Jobner (Rajasthan).

Phalsa (*Grewia subinaequalis* DC)

Phalsa is a shrub or small tree used in the Indian subcontinent since the Vedic period. The ripe fruits are consumed fresh or made into refreshing drink during summer. Phalsa fruit has a short shelf life suitable only for marketing locally. It is cultivated on a commercial scale mainly in the northern and the west India states of India. Phalsa is known by a different name in different Indian languages such as *dhamin*, *parusha*, and *shukri* in Hindi (Tripathi, 2009). Phalsa fruits are rich carbohydrate (6.8to 25.8%), sugar and acid (0.42 to 2.5%) and very little protein and fat. Phalsa belongs to family Malvaceae. The closest relative of phalsa is *Grewia elastica* var. *vastita,* which is generally found in small hillocks and valleys. Apart from these two species, there are around 150 species in the genus *Grewia.* The important ones are *G. glabra, G. micrococas, G. optiva, G. tilifolia,* and *G. belosa.* Phalsa is found wildly growing in UP, Rajasthan, Punjab, Haryana, Madhya Pradesh, West Bengal and parts of south India. The cultivation of phalsa is limited to a very small scale (may be around 1000in Punjab, Haryana, Rajasthan, and Gujarat and UP. Apart from India, it is cultivated in Pakistan, Nepal, Bangladesh, Laos, Sri Lanka, Thailand, the Philippines, Vietnam and on experimental basis in some provinces of the United States of America.

Genetic resources

There are local varieties grown in different growing regions. In Hisar area of Haryana, two local varieties i.e., tall and short are grown. The dwarf variety is more productive than the tall one. The dwarf variety has higher total sugars and non–reducing sugars that the tall variety which also has more reducing sugars. In Kanpur area two varieties namely, Local and Sharbati are grown. Not much variability is reported in phalsa due to the self-pollination. Some species belonging to genus *Grewia* are *G. asiatica* L., *G. damine* Gaertn., *G. elastica* Royle, *G. glabra* Blume, *G. helicterifolia* Wall., *Grewia microcos* L., *G. optiva* J. R. Drumm. ex Burret, *G. sapida* Roxb., *G. tenax* (Forssk.) Fiori and *G. villosa* Willd.

G. tenax is highly drought resistant and occurs in the driest savannas at desert margins and regions of higher rainfall, where it grows in thickets on termite mounds in otherwise seasonally flooded country. *G. tenax* is available in all seasons in semi desert areas and has potential as forage sources for honeybee and some other insects (Sharma and Patni, 2012). Other species which are found in drier parts of tropical Africa are *G. flavescens, G. villosa, G. bocolour, G. ferruginea, G. louisii, G. monticola, G. plagiophylla, G. pinnatifida* and *G. microthyrsa*. These may be a source of drought resistance.

Collection

Phalsa germplasm has been collected from various parts of India such as Rajasthan, Haryana, Gujarat, Maharashtra and Andhra Pradesh, by ICAR-NBPGR, New Delhi; CCSHAU, Hisar; CCSHAU, RRS, Bawal and ICAR-CIAH, Bikaner. Thirty-six accessions belonging to 6 economically important species namely *G. hirsute*, *G. oppositifolia*, *G. tiliaefolia*, *G. rothii*, *G. orantalis* and *G. subinaequalis* have been collected at CCSHAU, RRS, Bawal. Sivraj and Pandravada (1997) reported seventy-eight accessions of phalsa (*Grewia asiatica* L.) were collected from parts of Andhra Pradesh. Considerable variability in fruit and plant morphological characteristics is recorded. Ranga Reddy, Mahbubnagar and Medak districts have a larger area under phalsa in comparison to other areas. Few promising lines for various traits were also collected.

Conservation

Phalsa germplasm is being conserved in the field gene bank at CCSHAU. RRS, Bawal (31), ICAR-CIAH, Bikaner (6), ICAR-CIAH, CHES, Godhra (2) and IIHR, Bengaluru (1). Basic studies on seed physiology and storage undertaken at ICAR-NBPGR, New Delhi indicate that seed viability is lost after 90-100 days of storage (Chandra *et al.*, 1994). It was also found that seeds showed 50% viability after 4 months of storage at ambient conditions. Seeds were desiccation sensitive as at critical moisture content showed a 23% loss in viability. Intermediate seed storage behaviour has been concluded as seeds survived LN exposure with 500/0 viability. A total of 15 accessions of *Grewia* species have been cryo-stored in the cryogene bank (Malik *et al.*, 2010)

Evaluation

There are local regional favourites land races grown in different regions. Some growers have given names like'Local' and 'Sharbati' to different phalsa types (Dhawan *et al.*, 1993). Two distinct types, i.e., Tall and Dwarf were recognized at Haryana Agriculture University, Hisar. These two types differ in their plant height, fruit yield and other morphological parameters such as leaf size, fruit size and fruit weight. These two types did not show any marked variation in their fruit weight, edible portion, seed weight and juice yield. The tall type had a higher content of reducing sugars whereas total and non-reducing sugars were higher in dwarf type. However, glucose was observed only in the tall type (Dhawan *et al.*, 1993).

Varietal development

Most of the genotypes grown are of local types. Some promising one like 'Thar Pragati 'has been identified for cultivation by ICAR-CIAH, Bikaner.

Tamarind (*Tamarindus indica* L.)

Tamarind belongs to the family Fabaceae. It is one of the most widespread trees of the Indian subcontinent. It is a large evergreen tree with an exceptionally beautiful spreading crown and cultivated throughout the India, except in the Himalayas and western dry tracts. Tamarind is a multipurpose plant. The pulp of the fruit has been used as a spice in India, especially in the southern part of India, for a long time. Almost all parts of the tree are used in the food, chemical, pharmaceutical or textile industries, or as fodder, timber and fuel. It is grown throughout India and vast diversity is available in the states of Maharashtra, Andhra Pradesh, Chhattisgarh, Tamil Nadu, Gujarat, Rajasthan and the north-eastern states and naturalized in several regions. In the American continent, commercial plantations were reported in Belize, Central American countries and in northeast Brazil (Sharma and Bharadwaj, 1997). Although it is grown in many countries, tamarind is grown as a plantation only in a few countries such as India and Thailand.

Genetic resources

Tamarind is a semi-domesticated species, and has long been planted in many areas in tropics. In Indian subcontinent is present both in wild and cultivated areas, and the later, although ill-defined, could be considered as landraces. There is large variability in morphological and fruiting characters. The selection from the land races has resulted in the identification of distinct varieties varying in the taste of the pulp (sour, sweet, or bitter) and size of the pod (long or short).

Diallo *et al.* (2007) defined that there are three major groups of tamarind populations in West Africa, East Africa, and Cameroon. They have also demonstrated that, although self-pollination is common in tamarind, most often there is pre-zygotic self-incompatibility and cross-pollination is common leading to expression of high genetic variability. Tamarind is a monogenic species so there are no possibilities of out crossing with other species. There are several types of tamarind available in the forest and uncultivated areas. Being a cross-pollinated crop, large viability in the wild population has been reported from India and African countries. The large variation in tree growth, canopy size, flowering pattern, fruit productivity, pulp colour and sweetness exist in tamarind. Based on the pulp colour tamarind has been delineated as red tamarind and brown tamarind.

Collection

Systematic collections and evaluation of tamarind germplasm from India have not been taken up. However, 248 samples were collected by various organizations mainly from the states of Bihar, Jharkhand. Gujarat, Tamil Nadu, Andhra Pradesh, Madhya Pradesh, Kerala, Karnataka, West Bengal and north-eastern states. The attention hasbeen given to this crop under-the ICAR network project on underutilized fruits and some promising collections have been made by ICAR-CISH, Lucknow (5 accessions) and CHES (CIAH), Godhra from Uttar Pradesh, Madhya Pradesh and Gujarat.

Variability of tamarind has also been collected from Maharashtra, Karnataka, Andhra Pradesh and Chhattisgarh by State Agricultural Universities and State Forest Departments. ICAR-NBPGR, New Delhi collected 9 diverse germplasm collections from various states. The wide variation is recorded in the species due to its out crossing ability. ICAR-IIHR, Bengaluru, more than 100 collections were made from Karnataka, Maharashtra, Chhattisgarh, Odisha, Jharkhand, Assam, Tamil Nadu and some sweet types have been identified and collected (Kanupriya, 2023).

Conservation

Germplasm of Tamarind is being maintained at several state Agricultural Universities and state forest departments viz. UAS, Dharwad (19 accessions), Marathwada Agricultural University, Parbhani (3), Aurangabad, Maharashtra (351), Pune, Maharashtra (118), Horticulture College and Research Institute, Periyakulam, Tamil Nadu (85), TNAU, Research Station, Tupukotti (26), ANGARU, Research Station, Anantapur (15), ICAR-CIAH, CHES, Godhra, ICAR-IIHR, Bengaluru (>100) and Belgaum, Karnataka (40). Besides, several promising accessions are being conserved by the Forest Department, Karnataka (220 plus trees), and Forest Department, Tamil Nadu (328 plus trees).

Lot of collections of tamarind genotypes have been made throughout the tropics. There is an estimate that there are 19327 genotypes worldwide. Studies on seed physiology, storage behaviour and cryopreservation of tamarind seeds have been undertaken at ICAR-NBPGR, New Delhi. Seeds are orthodox as they showed complete desiccation and freezing sensitivity and seeds showed up to 50% viability by 18 months storage. Freshly shed seeds showed 35% moisture with high viability of 97%. Seeds retrieved from liquid nitrogen showed high viability of 94%. Total 10 accessions of tamarind have been cryo-stored at ICAR-NBPGR, New Delhi (Malik *et al*, 2010).

Evaluation

Considerable variation in tree growth, canopy size, flowering pattern, fruit productivity, pulp colour and sweetness exist in tamarind. Based on the pulp colour tamarind has been classified as red tamarind and brown tamarind. The red pulp colour in unripe fruits is due to the presence of anthocyanin in cell vacuoles which is a natural water-soluble, non-toxic pigment and there is considerable potential of red tamarind as a bio colourant in food processing. Ten tamarind accessions were evaluated at TNAU, Research Station, Arupukottai. Reproductive biology and breeding system have been studied in 5 clones of tamarind at IFGTB, Coimbatore. Variability in morphological and physicochemical characters has been observed in the germplasm collected from Maharashtra (Keskar *et al*., 1989), Karnataka, Andhra Pradesh (Mastan *et al*., 1997) and Chhattisgarh. State Silvicultural Division, Tirupati (AP) identified 52 high yielding genotypes of tamarind based on morphological and physicochemical characters of fruits. A red-fleshed tamarind tree having sweet pulp (TSS>85%) have been reported in village Faraskot, Dantewada, Bastar district of Chhattisgarh.

Germplasm collected at ICAR-NBPGR, New Delhi have been characterised for some fruit and seed characters. The fruit length x width varied from 7.50 cm x 1.76 cm to 11.13 cm x 5.94 cm. The total fruit weight showed variation ranging from 6.4 to 12.93 g. Seed length x width varied from 0.93 cm x 1.02 cm to 1.43 cm x 2.20 cm. The seed weight ranged from 0.5 to 0.76 g. Mayavel *et al.* (2018) evaluated 21 genotypes of red tamarind collected from different parts of Tamil Nadu, Puducherry, Karnataka and Andhra Pradesh. The wide variation was recorded for length of inflorescence (13.32 cm and 5.20 cm), number of flowers/ inflorescence (27.15 and 10.86), yield/ tree (40.26 kg and 14.56 kg), fruit length (12.02 cm and 4.96 cm), fruit breadth (3.15 cm and 1.32 cm), fruit weight (13.94 g and 4.89 g), pulp weight (7.99 g and 2.50 g), number of seeds (8.10 and 3.92), seed weight (7.86 g and 1.93 g) and anthocyanin content (246.94 mg/L and 123.06 mg/L).

Agasimani *et al.* (2019) assessed thirty-one tamarind genotypes in six districts (Belagavi, Dharwad, Gadag, Bellary, Chitradurga and Gulbarga). A high degree of variation was observed for tree height, trunk diameter, the spread of the tree east to west, the spread of the tree north to south, crown size, pod length, pod thickness, pod weight, pulp weight, number of seeds per pod, seed weight per pod, shell weight per pod, vein weight per pod, pulp per cent, seed per cent, shell per cent, vein per cent, tamarind pod yield and tartaric acid content.

Varietal development

Several varieties have been developed through selection from germplasm collected across different states. Fruit Research Station, Aurangabad of Marathwada Agricultural University, Parbhani, Maharashtra released three varieties of tamarind namely Pratisthan, Yogeshwari and Selection No.263. PKM-l was released from Horticulture College and Research Institute, Periyakulam. Urigam- 1 was released by Department of Horticulture, Tamil Nadu. Two selections DTS 1 and DTS 2 have been identified by College of Horticulture, Arbhavi, Dharwad. ICAR-CIAH-CHES, Vejalpur also identified promising genotype Goma Prateek and Thar Rashmi and FRS, Ananathapuram also released Anantha Rudhira & Thettu Amblika. PDKV, Akola (MS) also released variety as Akola Smruti (AKT-10) and farmer's variety Lakshmana identified for release from ICAR-IIHR, Bangaluru. Makham Waan, Secthong, Tamarind sweet types are varieties from Thailand.

Aonla (*Emblica officinalis*)

The Indian gooseberry (*Emblica officinalis*), commonly known as aonla, is a valuable minor fruit crop native to India. It thrives in a wide range of soil types and climatic conditions across the country. Extensive research over the past two decades has led to the development of more than 30 improved varieties, allowing for commercial cultivation in several regions. Aonla has demonstrated its adaptability to arid and semi-arid ecosystems, where it proves to be a hardy, highly productive, and economically viable fruit crop, even under drought-prone and saline conditions. However, due to its highly acidic and astringent taste, fresh consumption is limited. Aonla is sensitivity to frost in cold climates, especially in hot arid regions.

Genetic resources

In India, the natural distribution of wild aonla is found on the Himalayas, Chota Nagpur, Bihar, Orissa, West Bengal, North Circars, Deccan, Karnataka and in Western Ghats (Rawat and Uniyal 2003). It has been naturalized in great profusion in North Eastern India. The genus *Phyllanthus* comprises about 350 or even 500 species; mostly shrubs, few herbs and trees. *Phyllanthus emblica* Linn. has now been placed under *Emblica officinalis* Gaertn. Of the related species *Phyllanthus acidus* Skeel., syn. *P. distichus* Muella, popularly known as otaheite gooseberry, star gooseberry or country gooseberry, is mostly grown for ornamental purpose, whereas wild species *Emblica fischerry* Gamble., syn. *P. fischerry* found in the forest of south India, bears fruits suitable for pickle making (Srivastava *et al.*, 1997).

In western and eastern Ghats, three species namely *Phyllanthus emblica*, *P. indofisheri* and *P. acidus*are of common occurrence. The wild aonla germplasm is mostly confined in the mixed forests with sloppy topography and sometimes even difficult to approach. A rich genetic diversity of aonla exists in north-eastern region of India, particularly in lower Assam, Maghalaya (Khasi and Garo hills), Mizoram and Tripura. The natural population of aonla in west Khasi hills (Nongkhyllum, Rajaju, Khonjoy area) of Meghalaya warrants *in-situ* conservation, which may even be declared as gene sanctuary for this species (Pathak, 2003). Mizoram (forests of Kolasib, Thingdawl and Champhai), the homeland of wild aonla and star gooseberry (*Phyllanthus acidus*), which has potential as dwarfing rootstock for aonla. Madhya Pradesh forests also have rich diversity of aonla in Sheopur, Betul, Balaghat, Satna, Sidhi, and Panna districts.

The important sites in Jharkhand are Lali Forest near Ranchi, Dalma range of Jamshedpur, Theo Ghat Forest of West Singhbhoom, Tiamara valley area between Ranchi and Jamshedpur, Ramgarh area of Hazaribagh, Parasnath hills of Giridееh, Kodemera and Jaomi areas of Bihar border, Simdega and Netarhat forest areas of Gumla, Belta forest of Daltonganj, Palamu and Garhwa of Jharkhand and adjoining areas of Sarguja and Ambikapur districts of Chhatisgarh. The Belta forest (Daltonganj), Netarhat range in Gumla and Dalma range of Jamshedpur has comparatively high plant population of aonla in the natural habitat. A wild strain of aonla grows in the Himalayas up to an altitude of 1600 msl even at places which experience mild snowfall during winter months, displaying cold tolerance.

Collection

Wide variability in aonla has been reported from Uttar Pradesh, Uttarakhand, Bihar, Chhattisgarh, Gujarat, Jharkhand, Madhya Pradesh, Maharashtra, Rajasthan, Himachal Pradesh and North Eastern region of India (Singh *et al.*, 2016). An extensive survey was made to identify and collect the elite genotypes at different altitude to determine variability for physical and biochemical traits and find out the promising genotypes having good fruit quality from different regions of the north-eastern region of India, i.e. Manipur, Meghalaya, Asom and Nagaland (Singh *et al.*, 2016). In Uttar Pradesh, its cultivation is more common in Pratapgarh, Varanasi, Sultanpur, Azamgarh, Jaunpur, Rai Bareilly, Agra and Bareilly. Of which, Pratapgarh is a leading district of aonla cultivation on commercial scale throughout the country (Pathak *et al.*, 1993).

Aonla cultivars were characterized and evaluated using aonla descriptors developed at ANDUA&T, Ayodhya that revealed a broad range of variability for different characters. Four promising accessions were identified characterized 33 genotypes of aonla collected from Uttar Pradesh (Rai *et al.*, 1993) based on the horticultural traits. Singh *et al.* (2016a) surveyed the north east states viz., Meghalaya, Manipur and Nagaland and identified three elite genotypes based on the desirable horticultural traits. Owing to predominance of seedling propagation, India holds rich genetic diversity in cultivated and their wild relatives of aonla.

Genetic erosion status of these resources is constantly high due to severe deforestation, urbanization, natural calamities and adoption of a few popular cultivars in the selected pockets. However, enormous variability in aonla still remains unexploited and awaits proper attention on exploration, collection and maintenance to conserve genetic diversity available in the nature. The desirable traits for germplasm collection include large fruit size, low fiber content, and resistance to frost, rust, internal fruit necrosis and insect-pests. Many of the present-day varieties have been developed from these collections as chance seedlings of these genotypes.

Conservation

Currently the genetic diversity of aonla is conserved by *ex-situ* in field gene banks of ICAR institutes and State agricultural universities (Table 3). *Ex-situ* and *in-situ* conservation strategies require a large area, a huge effort for maintenance. Therefore, biotechnological approaches such as *in-vitro* conservation and cryogenic storage (-196°C liquid nitrogen) can help for long term storage of germplasms.

Table 3. Status of national germplasm banks of aonla

ICAR Institute/ SAU	Accessions
ANDUA&T, Ayodhya	22
ANGARAU RRS, Anathapuram	15
ICAR-CIAH, CHES, Godhra, Gujarat	18
TNAU RRS, Aruppukottai	15
ICAR-CISH, Lucknow	12
ICAR-IIHR, Bengaluru	12
SDAU, SK Nagar	12
MPKV, Rahuri	8
CCS HAU RRS, Bawal	6

Characterization and evaluation

Assessing genetic variability for varietal enhancement necessitates a comprehensive capture of both quantifiable and non-quantifiable morphological characteristics. The Aonla germplasm showcases notable variability in morphological traits, growth, flower, bark, and fruit characteristics, reflecting the diversity across its tree (Singh *et al.*, 2024). The characterization of aonla germplasm for tree, foliage, fruit and stone attributes under semi-arid ecosystem of Haryana (Singh *et al.*, 2022). Among the 11 genotypes characterized, CISH-A-33 and CISH-A-31 exhibited superior fruit yield per plant (Pandey *et al.*, 2025).

The cultivars of aonla, viz. Banarasi, Chakaiya, Neelam, Francis, Kanchan and Desi were evaluated for growth, yield and quality parameters under lower Shivalik foothills of Himalayas. Neelam cultivar of aonla is most superior under the rainfed conditions (Bakshi *et al.*, 2015). The variety Krishna was found superior compared to other varieties for fruit characters and ascorbic acid content under Bengaluru Conditions (Chiranjeevi *et al.*, 2015). Tripathi *et al.* (2016) found that the fruit yield was highest in cv. Chakaiya (26.78 kg/ plant) and cv. Krishna (26.34 kg) under humid tropical conditions of Chettalli (Karnataka). Rozar *et al.* (2024) evaluated 84 wild aonla genotypes for morphological, physical, and biochemical characteristics from Mizoram, Meghalaya, and Tripura states of Northeastern India.

Varietal development

Three varieties of aonla viz Chakaiya, Francis and Banarsi were popular before 1980. Later on, several varieties of aonla have been developed through selection. These includes NA-4 (Krishna), NA-5 (Kanchan), NA-6 (Amrit), NA-7 (Neelum), NA-9, and NA-10 (Balwant) from ANDUA&T, Ayodhya, as well as Anand Aonla-1 from AAU, Anand, Aonla-2 from ICAR-CISH, Lucknow, Goma Aishwariya from ICAR-CIAH, CHES, Godhra, BSR-1 (Bavanisagar) from TNAU, Coimbatore. These varieties are high yielding with bigger size fruits.

Dragon fruit (*Hylocereus* spp.)

Dragon fruit (*Hylocereus undatus*), also known as the Kamalam, "Wondrous Fruit" of the 21st century or strawberry pear belongs to the cactus family (Cactaceae). It originates from Central and South America, particularly in countries like Mexico, Guatemala, Nicaragua, Costa Rica, and El Salvador. Over time, it has successfully adapted to various tropical and subtropical regions, including Southeast Asia, India, and Africa. This fruit comes from the *Hylocereus* genus, which consists of around 14 species of climbing cacti. Closely related to *Selenicereus* and *Epiphyllum*, these plants share characteristics such as growing on trees or rocks, blooming at night with large, fragrant flowers, and producing fleshy fruits filled with tiny seeds.

The main cultivated varieties include *Hylocereus undatus* (white-fleshed), *Hylocereus costaricensis* (red-fleshed), and *Selenicereus megalanthus* (yellow). It has successfully spread to various tropical and subtropical regions worldwide, including Southeast Asia, the Indian subcontinent, and parts of Africa and has emerged as a fruit of significant global interest in recent years. In recent years, the cultivation of dragon fruit has expanded significantly, driven by increasing demand in both local and international markets. It is a hub for many underutilized horticultural crops which may not know to other parts of the country. Most of the lands in this region is virgin and remain unexploited which may be used up for cultivation of different crops which are emerging lately in these areas.

Genetic resources

Pitaya (Dragon-fruit) originated from Latin America. Since the early 1990s, when introduced to China, it has been widely cultivated in China and has become economically important fruit crop. The majority of germplasm accessions are white or red pulp types. The estimations of genetic diversity and relationships are important for evaluating, conserving and utilizing plant resources and for determining uniqueness and distinctness of genotypes. Traditionally, the methods for pitaya cultivar identification have based on morphological traits. Variation in chromosome number (polyploidy), is considered a significant phylogenetic feature in the evolution of the *Cactaceae* family (Cota and Philbrick 1994). Cytogenetic research revealed that the chromosome number in the *Cactaceae* family has a base number of n = 11 (Gibson and Nobel 1986).

Within the genus *Hylocereus*, including species such as *S.undatus, S. monacanthus, and S. costaricensis*, they are diploid (2n = 2x = 22), whereas *S. megalanthus*is allotetraploid (2n = 4x = 44), due to natural hybridization (Lichtenzveig *et al*., 2000; Tel-Zur *et al.,* 2005). The basic chromosome number is x = 11 for both diploids and tetraploids (Ross, 1981). In a study by Tel- Zur *et al*. (2003), chromosome doubling was induced in vine cacti hybrids through reciprocal crosses between *S. megalanthus* (4x) and *Selenicereus* spp., specifically *S. undatus and S. monacanthus.* Surprisingly, viable hexaploids and 6x-aneuploid hybrids were obtained instead of the expected triploids when crossing *S. megalanthus* with *S. undatus*. The uniform pollen grain diameter of *H. undatus* indicated a low frequency of unreduced gametes, whereas *S. megalanthus* pollen exhibited variation, suggesting the occurrence of unreduced gametes.

Collection

In India currently there are 56 germplasm collections in ICAR-IIHR, Hirehalli, out of which 36 are exotic. Some of the dragon fruit germplasm collections are listed below in Table 4 (Yadav *et al*., 2025).

Table 4. Dragon fruit germplasm maintained at different centres

Institute	Accessions
ICAR-IIHR, CHES, Chettalli	04
ICAR-IIHR, CHES, Hirehalli, Tumakuru, Karnataka	56
ICAR-IIHR, CHES, Bhubaneswar	03

Conservation

Breeders and farmers need access to the wildest possible pool of genetic resources, either collected from the wild or from the farmers. Gene bank plays an important role because they can act as a centralized storage facility of diversity. In Belgium they have successfully developed *in-vitro* cultured plant material by help of sterile stock provided by Botanical Garden. The materials were being maintained in plant growth room at 26°C under 16/8h light/ dark regime. Then have executed *in-vitro* initiation for long term conservation via cryopreservation. Cactaceae family initial study for post-cryopreservation regeneration rates resulted between 0 and 90%. Dragon fruit seeds were being stored at room temperature, in refrigerator at 7°C and freezer at -20°C which resulted in >90% germination rate (Wilms and Panis, 2023).

Evaluation

About 18 species in the genus Hylocereus were found in West Indies, Mexico, Central America and northern South America evaluation of Hylocereus genus led to the conclusion that most of the species were having 3-angled stems with 2 to 6 brown coloured spines seated on the areoles which were 2 to 6 cm apart on the vines. Rahmawati and Mahajoeno (2009) reported a study of variations of dragon fruit based on morphology, isozyme, and vitamin C content in the area of Pasuruan (East Java), Sukoharjo, and Klaten (Central Java), and Bantul sub-districts (Yogyakarta). Tran *et al.* (2015) reported a study on pollination methods on fruit set and fruit characters in several Pitaya clones, which aimed to improve pollination efficiency, fruit quality, and yield by determining pollination agro-management requirements.

The species *H. polyrhizus* and *H. costaricensis* were differentiated based on their stem and fruit characters, even though both the species had a pink skin. Tran *et al.* (2015) evaluated 30 dragon fruit germplasm in which Damao 9, D 4, D 13 observed better fruiting and flowering quality. Rifat *et al*. (2019) evaluated variability of 15 genotypes of dragon fruit which were collected from Thailand and Vietnam. Sarker *et al*. (2022) evaluated 3 different germplasm collected from Bangladesh and found 2 genotypes produced excellent quality fruits and other genotype was said to need further testing. Sethunath and Bhaskar (2024) evaluated the variability among the dragon fruit (*Hylocereus* spp.) genotypes in 4 different districts of Kerala.

Varietal development

There are three major types' viz. red colour fruit with white colour flesh, red colour fruit with red colour flesh and yellow colour fruit with white colour flesh. The systematic work of dragon fruit improvement was initiated at ICAR- IIHR, Bengaluru. Four varieties *viz.*, CHESH-D1, CHESH-D2, CHESH-D3, CHESH-DE (mutant) were identified (Karunakaran *et al*., 2024).

Jamun (*Syzygium cumini*)

Jamun (*Syzygium cuminii* Skeels) belongs to the family Myrtaceae. It is native to Indian subcontinent and has grown naturally since time immemorial. Itis found in all parts of our subcontinent as well as countries of Southeast Asia and Eastern Africa. In India, it is grown widely all over the country except higher hills. The most commonly found variety of jamun is often oblong and has a deep purple to bluish colour. The pulp of the fruit is grey or pink and has a seed in the centre. The fruit is acidic and astringent in nature, with a sweet taste. Lot of variation exists in respect of growth and fruit characters.

Genetic resources

As majority of jamun trees are of seedling origin, and they show tremendous variation in their morphology and physico-chemical attributes. The extent of variability increases when this highly cross-pollinated plant multiplied through seed. Singh and Singh (2012) assessed the variability in terms of flowering, fruiting and fruit traits under Gujarat conditions. Regional Fruit Research Station, Ventura, Maharashtra maintains a rich germplam and one promising germplasm has been released in the name as "Konkan Bahadoli" which is having bold fruits, small seeds, heavy and cluster bearing habit (Salvi, 2006). Still, many types differing in economic traits need to be surveyed, collected and maintained. Genotypes with extended fruiting period have to be identified as a priority one as this fruit is now available only for very limited weeks in nature.

Seedless Jamun is also available at TNAU and IIHR (Tripathi *et al.*, 2020) but its limitations are small in size and instability in selflessness due to its chimer nature. Diversity exists in respect of vegetative growth, aspects of spread, leaf shape and fruiting habit and maturity (June - August). However, very little work has been carried out to understand and exploit the genetic resources of jamun. The crop is facing severe threat of genetic erosion as a result of urbanization and intensive agriculture. The genetic diversity of the related wild *Syzygium* spp. is of particular value in search for sources of resistance to races/pathotypes of fungi, bacteria, viruses and nematodes besides winter hardiness and resistance to drought and salinity.

Table 5. Jamun collections maintained at different centres

Name of center	Source	Total collection
ICAR-CISH, Lucknow	Uttar Pradesh, Bihar, Haryana, Gujarat, Maharashtra, Tamil Nadu and Karnataka	40
ICAR-IIHR, CHES, Chettalli	Uttar Pradesh, Haryana, Gujarat, Tamil Nadu and Karnataka	30
ICAR-CIAH, CHES, Godhra	Uttar Pradesh, Bihar, Haryana, Gujarat, Tamil Nadu and Karnataka	50
ICAR-IIHR, Bengaluru	Uttar Pradesh,Bihar, Madhya Pradesh, Assam, Gujarat, Tamil Nadu and Karnataka	110

Collection

In India, there are several types of Jamun. The small-fruited type large-fruited type, seedless type, purple coloured, white coloured etc. Jamun germplasm is collected and conserved by ANDUA&T, Ayodhya; GBPUA&T, Pantnagar; ICAR-CISH, Lucknow; ICAR-CIAH, Bikaner; ICAR-CAZRI, Jodhpur; ICAR-NBPGR-Regional Station, Jodhpur; ICAR-IIHR, Bengaluru. The collections from Bihar, Jharkhand are conserved at ICAR-NBPGR-RS, Jharkhand (Dhakar *et al.*, 2019). ICAR-IIHR, Bengaluru explored Karnataka, Andhra Pradesh, Telangana and collected more than 100 accessions (Tripathi *et al.*, 2017). The Jamun germplasm is also collected at several other research stations. There may be many duplicates in the germplasm at different stations, as many samples were collected from secondary sources. The available jamun accessions are conserved at the field gene banks as given in Table 5.

Conservation

Jamun germplasm is conserved using *in-situ* and *ex-situ* approaches. The seed of Jamun are recalcitrant type and polyembryonic and cannot be stored for long time.

Being native to India, work on collection and evaluation is mainly confined to India, with a few studies reported from Sri Lanka, Pakistan, Bangladesh and South Eastern Asian countries.

Evaluation

A number of seedling strains with considerable variation available in respect of fruit shape, size, pulp colour, TSS, acidity and earliness particularly in Uttar Pradesh, Gujarat and Maharashtra, can offer good scope for selection of better varieties. It has been noted that F_1 hybrid from a cross between the Alba variety of water apple *(S. javanicum)* and rose apple *(S. jambos)* had prolific bearing with larger fruits than those of the parents. The fruits contained the fragrance and sweetness of rose apple. The majority of jamun trees available in India are of seedling origin. Owing to cross-pollination and seed propagation, there is enormous variability in respect of fruit morphology, fruit quality, maturity, and productivity. Explorations carried out, particularly in the eastern Uttar Pradesh, indicated considerable variability in respect of fruit shape (round, oval, oblong, perform), fruit base (flat, necked), fruit apex (flat, pointed), skin colour (deep purple, purple-pink, bluish-black, black), flesh colour (purple, purple-pink, white), fruit weight (5.77 - 19.73 g), fruit length (2.06-3.81cm), fruit diameter (1.94-2.98 cm), seed weight (0.141- 1.94 g), seed length (1.6-2.4 cm), seed diameter (0.8–1.3cm), pulp content (54.29–85.71%), TSS (4.5-17°Brix), acidity (0.524 - 0.832 %), pulp: seed ratio (3.03 - 46.38), moisture (84.5 - 86.4 %), total sugars (5.32 - 11.10 %) which need to be characterized for utilization in crop improvement.

Ashraf *et al.* (1987) reported that fruit shape varied from round to oblong and apex of fruits from flat to pointed.

They also observed great variability in physico-chemical characteristics, offering the possibility of selecting varieties suitable for fresh market and processing. Small seed size and high pulp content with better chemical parameters are considered ideal. Singh *et al.* (1999) evaluated eight accessions of jamun under Faizabad conditions and reported that oblong types had more fruit weight with relatively lesser seed weight. Among the locally available types in West Bengal, Selection No. 1 (oval shaped large fruit) and Selection No. 2 (cylindrical shaped medium sized fruit) proved better on the basis of yield and fruit quality attributes.

A survey in north Goa indicated a wide range variation in fruit weight (3.42-13.67 g), length (3.31-5.26 cm), girth (5.21-9.82 cm), pulp (58.57-84.55%), TSS (12.00-26.8°Brix), titratable acidity (0.59-1.63 %), total sugars (6.87-25.31 %) and sugar: acid ratio (15.39-27.92). Rekha *et al.* (2020) studied variation in the degree of polyembryony among the jamun accessions collected from different states. The collections of Jharkhand were found to produce higher number of single seedlings; whereas collections from Dharwad region are highly polyembryonic producing highest numbers of multiple seedlings. In another study, the morphological variability of 21 distinct jamun genotypes sourced from Bangalore Rural, Shivamogga, and Chikmagaluru districts in Karnataka were evaluated for 19 quantitative and 15 qualitative characteristics. The study highlighted the pivotal attribute of pulp percentage, ranging from 44.8% to 100%, with seedless varieties, specifically J13, J14, and J16, exhibiting the highest pulp percentage, and J18 the lowest.

Additionally, the entire fruit weight, varied widely from 0.74 g (J14) to 15.41 g (J4) and the revealed positive relationships between pulp weight and attributes like leaf length, tree spread, and seed width, while a negative correlation was observed with total soluble solids (Tripathi *et al.*, 2025). Sane *et al.* (2025) have reviewed the jamun diversity and its sustainable utilization. Jamun germplasm has been widely collected from different agroecological regions of India and is being maintained at government-funded institutes and agriculture universities across India. An intensive survey for utilization of the diversity available in jamun has resulted in a few promising high-yielding varieties. Nevertheless, a comprehensive and integrated taxonomical, morphological, biochemical, and molecular study will help in identifying actual diversity for better genetic resource management of this potential fruit crop (Sane *et al.*, 2025).

Varieties

Most of the jamun plantations are seedling trees. Some few superior varieties and lines have been identified for commercial orcharding namely Kokan Bahadoli from BSSKVV, Dapoli, Goma Priyanka and Thar Kranti from ICAR-CIAH, CHES, Godhra, Narendra Jamun-6 from NDAUT, Ayodhya, Rajendra Jamun -1 from Bihar Agriculture College, Bihar, CISH J-37 (Jamwant) and CISH J-42 from ICAR-CISH, Lucknow.

Mahua *(Madhuca longifolia* var. *latifolia/ Bassia latifolia*)

Mahua is an economically multipurpose tree. It belongs to the family Sapotaceae. The flowers, fruits, seeds and oil are used for various products. The flowers are a rich source of sugar and are used for the preparation of distilled liquor. Fruits are eaten raw or cooked. The fruit pulp can be used as a source of sugar for alcoholic fermentation. Seeds are a good source of oil. Mahua trees are found in almost all parts of India but commonly grow in eastern Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Maharashtra, Bihar, Jharkhand, Odisha, Andhra Pradesh, and Gujarat. The exact data on area and production of this fruit in India are not available. The production is mainly concentrated in the drier states and the produce is collected by the villagers and sold in the local market.

Genetic diversity

It is highly heterozygous, cross-pollinated fruit crop and as such seedlings exhibit a wide range of variations, which aids in the selection of the superior desirable genotypes. Due to cross pollination and predomination of seed propagation over a large period of time, it gives immense opportunity to locate elite trees having horticultural traits. A wide range of variability was observed in sweetness, acidity, size, shape and bearing habits in Mahua under Uttar Pradesh conditions (Singh *et al.*, 1999). Yadav *et al.* (2011) observed the variability in oil content and seed weight of 37 accessions of *mahua*. *Mahua* collected from different parts of Tamil Nadu, India, were assessed for seed weight and oil parameters, namely, kernel oil percent, palmitic acid, stearic acid, oleic acid, and linoleic acid. Maximum seed weight (340 g) was recorded in IC554535, and the least weight (100 g) was recorded in IC554545. Kernel oil ranged from a minimum of 44.4% in IC554535 to a maximum of 61.5% in IC556617.

Collection

Survey and collection of mahua germplasm have been carried out done almost all *Mahua* growing areas. Suryawanshi and Mokat (2020) collected 99 accessions of Mahua from the North Western Ghats for morphological and sugar analysis of flowers. It was revealed that accession ML01 has the highest amount of sugar (70.29 %) content compared to other accessions. Accession ML57 showed the highest amount of 100 flower weight. Twenty-four promising accessions have been identified, collected, multiplied and established in field gene bank for evaluation of growth and fruiting pattern at ICAR-CISH, Lucknow.

Conservation

Germplasm collection has been carried out by many institutes, and maintained at different institutes. A total of 272 mahua germplasm accessions are being maintained at different centers across India. The highest number of accessions (86) are conserved at CCS HAU, Hisar, followed by TFRI, Jabalpur and ICAR-NBPGR, Thrissur with 53 accessions each. ICAR-CIAH, Bikaner maintains 50 accessions, while ICAR-CISH, Lucknow holds 30 accessions.

Evaluation

A total of 99 accessions were collected for the morphological and sugar analysis of flowers. From the study, it was revealed that accession ML01 has the highest amount of sugar (70.29%) content compared to other accessions. Accession ML57 showed the highest amount of 100 flower weight. Singh *et al.* (2005) surveyed Panchmahal and adjoining areas to identify the elite genotypes of mahua. It was found that there was a wide variation among the genotypes for flowering time and yield. Peak period of flowering was earliest, in the first week of March. Dry flower yield ranged from 27-48 kg/plant being highest in MH 32. Fruit yield was found to be highest in MH 32 (98.00 kg/plant). The flower Juice was found to be highest (67.00 %) in MH 32. Total soluble solids, total sugar, reducing sugar, and vitamin C content of flowers were the highest in MH 32. The weight of the mahua fruit was found to be maximum in MH 34. The seed per cent was found to be maximum in MH 35 (42.91). The total soluble solids, total sugar, and vitamin C contents of the fruits were maximum in MH 32. The kernel percent varied from 74.13-82.68, with the highest in MH 24. The highest protein and mineral contents were recorded in MH 34. Fruit yield was found to be positively and significantly associated with flowers and fruits per fascicle, flower weight, and flower yield per plant.

For all traits studied in these genotypes, MH 32, MH 34, MH 35, MH 26, MH 27, MH 23, and MH 33 were found to be promising and would be exploited as potential parents to develop high-yielding stable genotypes.Twenty-four promising accessions were evaluated for growth and fruiting pattern at ICAR-CISH, Lucknow. The range of different parameters was flower weight (1.10 to 2.63 g), flower length (1.53 to 2.60 cm), diameter (1.46 to 1.90 cm), and TSS (14.53 to 26.0°B). The juice content in the accessions variedfrom 44.25 to 64.90%, and a few superior types were identified (Singh *et al.,* 2012).

Varietal development

Few elite lines have been developed at ANDUA&T, Ayodhya, Uttar Pradesh. These are NM 2, NM 4, NM 7, and NM 8. A variety TharMadhuwas released by CIAH, Bikaner.

Chironji (*Buchanania lanzan*)

Chironji belonging to the Anacardiaceae family, is native to the Indian subcontinent. It is highly adaptable to various soil and climate conditions and is naturally found in the arid and semi-arid forests of Jharkhand, Chhattisgarh, Madhya Pradesh, Rajasthan, Gujarat, and Uttar Pradesh. This medium-sized, sub-deciduous to evergreen plant features a straight trunk and coriaceous leaves. Chironji is a highly heterozygous and cross-pollinated species with a strong tendency for alternate bearing. Its fruits are edible both raw and roasted, with kernels rich in fats (59.0%), proteins (19.0–21.6%), carbohydrates (12.1%), fiber (3.8%), phosphorus (528.0 mg), calcium (279.0 mg), iron (8.5 mg), and vitamins (Khare, 2007). The plant has therapeutic potential to treat conditions such as snakebites, dysentery, diarrhoea, asthma, body inflammation, fever, ulcers, colds, and Alzheimer's. Additionally, it exhibits anti-diabetic and anti-hyper lipidemic properties (Patil and Rothe, 2017).

Varieties

Variety 'Thar Priya' has been identified by ICAR-CIAH, Bikaner. It has a semi-spreading growth habit, thick trunk, dense foliage and dropping branches, umbrella shape, and fruit ripening takes 50-65 days from fruit set. It is a comparatively dwarf, precocious bearer (4th year) and suitable for high density planting. It contains TSS 23.90^{o}Brix, 1.24% acidity, 13.06% total sugars, 6.67% reducing sugar, 48.70mg/100g vitamin C and 31.36% kernel protein. The fruit yield is 11.90 kg/tree.

Mulberry *(Morus alba* L.*)*

Mulberry, a member of the Moraceae family, is native to Southwest Asia. The genus *Morus* includes 24 species, of which 16 are deciduous, with *Morus alba, M. nigra*, and *M. rubra* being predominantly cultivated in commercial orchards. The commercial cultivation of mulberry is primarily focused on silk production and shelterbelts. The emphasis is not given on fruit characteristics. The mulberry fruits are nutritionally dense, containing vitamins, minerals, dietary fibre, sugars, amino acids, carotenoids, flavonoids, and phytosterols. These fruits are utilized as functional foods and pharmacological benefits.

Varieties

A huge diversity exists in the available germplasm pool of mulberry in India. Mulberry, being a perennial and outbreeding tree, exhibitsa high degree of heterozygosis.

There are very few elite lines, and variety was developed in mulberry for commercial fruit production. The promising selections of mulberry, intended for commercial fruit productionhave been identified at ICAR-CIAH, Bikaner, Rajasthan *viz.*, Thar Lohit (red fruited) and Thar Harit (white fruited). Thar Lohit was found to be the earliest forthe maturity period. It took 30-35 days to mature. It was found that mulberry genotype Thar Lohit was better than Thar Harit in terms of antioxidant attributes like polyphenol, flavanol, flavonoid and total antioxidant activity.

Annona (*Annona* spp.)

Edible fruits of the genus *Annona* are collectively known as *annonaceous* fruits. Genus *Annona* has 120 species, 6 of them having pomological significance and each one is unique in its taste, flavour, pulp colour and texture. Among these, custard-apple is the most popular one in India which has gained commercial significance in Maharashtra, Gujarat, Madhya Pradesh, Chhattisgarh, Telangana, Karnataka, Andhra Pradesh, Rajasthan, and Tamil Nadu. Others are cultivated on a limited scale, usually in gardens and homesteads. Other lesser-known edible Annona species include *A. reticulata* (Bullock's Heart), *A. diversifolia* (Ilama), and *A. muricata* (soursop). Custard-apple, atemoya, bullock's heart, and cherimoya are normally used as fresh fruits. In recent years, the Annona genus has gained attention as a promising drug candidate due to its remarkable anticancer, antitumor, and cytotoxic properties. The primary phytoconstituents identified in this genus include acetogenins and alkaloids.

Genetic resources

The fruits of Annona species vary in traits, such as size, taste, and texture, and are highly amenable to genetic manipulation, as they crossbreed easily. A total of 62 accessions of Annona species are conserved across different gene banks in India. The maximum number of accessions (29) are maintained at ICAR-IIHR, Bengaluru, followed by MPKV, Rahuri with 21 accessions. ICAR-CIAH, Bikaner conserves 9 accessions, while IIHR-CHES, Bhubaneswar maintains 3 accessions.

Collection

At ICAR-IIHR, sixteen varieties of custard apple (Balanagar, Raidurg, APK-1, Red Sitaphal, Mammoth, Barbados, Washington 07005, Washington 98797, Taiwan, NMK-1, Arka Neelachal Vikram, Phule Janki , Hyderabad Selection, Phule Purandar, Purandar Gold and Arka Sahan) three varieties of Atemoya (Island Gem, Pink's Mammoth and Bullock's Heart) and eight species of Annona - *Annona squamosa*, *Annona atemoya*, *Annona reticulata*, *Annona cherimola*, *Annona glabra, Annona muricata*, *Annona mucosa* and *Annona montana* are conserved in the field gene bank. Other centres conserving Annona germplasm are IIHR-CHES, Bhubaneswar, ICAR-CIAH, Bikaner, and MPKV, Rahuri.

Characterization and evaluation

Existence of variability in landraces indicates ample scope for improvement of annonas found adapted under sub-mountainous tracts of the Aravalli hills. (Bhatnagar *et al.*, 2012). A wide range of variability in physico-chemical attributes of custard apple genotypes showed the scope for superior plant selection based on these parameters (Yadav *et al.*, 2017). Islam *et al.* (1991) studied 27 custard apple genotypes for qualitative and quantitative characters and found considerable variation in landraces for parameters like fruit weight, size, edible portion, taste and TSS. Large genetic diversity is observed among Annonaceae species, although low genetic diversity within *A. muricata* populations had been recorded. Morphological variation of *A. muricata* were observed on a total of 315 samples collected from seven districts of three climatic zones and 133 samples collected from germplasm collections at three national research centres of Srilanka (Padmini *et al.*, 2013). Brisibe *et al.* (2017) characterized key phenotypic attributes and genetic diversity data from 42 representative accessions of the crop as a precursor to enhance a systematic varietal improvement and selection programme that would support conservation.

In the case of *Annona* species, the development of reliable chloroplast markers (rbcL and matK) is appropriate for the discrimination of the most important species of the genus (Larranaga and Hormaza, 2015). These specific markers based on matK and rbcL sequences were developed for 7 closely related *Annona* species of agronomic interest (*Annona cherimola, A. reticulata, A. squamosa, A. muricata, A. macroprophyllata, A. glabra*, and *A. purpurea*). The primers generated were validated in six additional species of the genus (*A. liebmanniana, A. longiflora, A. montana, A. senegalensis, A. emarginata* and *A. neosalicifolia*) and in an interspecific hybrid (*A. cherimola* x *A. squamosa*) as reported by Nerea Larranaga and José I. Hormaza, 2015.

Conservation

For conservation, *in-situ* efforts are sporadic and mostly limited to backyard gardens, focusing on species like soursop, custard apple, and sugar apple. The conservation and use of genetic resources of Annonaceae edible fruits were studied through a survey conducted in 2010 by the National Network of Annonaceae of the National Plant Genetic Resources. Conservation, characterization, and *ex-situ* collection of the genetic resources of custard apple are essential. *Ex-situ* conservation is practiced through gene banks or collections, but only for soursop, cherimoya, and llama, where limited accessions available. However, due to the non-orthodox nature of the seeds, long-term conservation remains a challenge. These conserved plant genetic resources can serve as sources for breeding approaches aimed at improving yield, quality, nutritional value, and resistance to abiotic stresses, thus ensuring livelihood and health security (Sushmitha and Sakthivel, 2023).

Varietal development

Custard apple varieties are broadly grouped based on external fruit color into green, red, and yellow custard apples. Most of the commercial cultivars released in India and abroad were developed from open-pollinated progenies and chance seedlings. These are 'Mammoth', 'Green Sitaphal', 'Red Sitaphal', 'Balanagar', 'Barbados, 'Islander', Red Israel', Washington P1107-005, Washington P198797, British Guinea and Brandy (Rymbai *et al.*, 2014). The hybridization efforts are ongoing in custard apple at ICAR-IIHR, Bengaluru and MPKV, Rahuri, where several promising hybrids, including Hybrid No. 6, Hybrid No. 13, and Hybrid No. 22 have been identified. Some of the famer's varieties such NMK, Saraswati is also popular among the growers.

Ber (*Ziziphus mauritiana* Lamk.)

The Indian jujube, Ber, belongs to the family Rhamnaceae. This fast-growing tree features a spreading canopy, a short bole, and slender, downy branches with paired brown spines and known for its drought-hardiness, the ber tree thrives in arid and semi-arid regions due to its deep taproot system and xerophytic adaptations, such as leaf shedding during peak summer to reduce transpiration, waxy and hairy leaves, and thick bark.

Genetic resources

The diversity in ber is widespread across various growing regions of India, particularly in dry and arid areas. This diversity presents significant opportunities for improving key traits of the fruit, such as yield, quality, and resistance to environmental stresses. Maximum variability in ber is available in dry parts of country as well as desert.

Collection

A wide range of ber germplasm, including species, cultivars, and other varieties, has been collected from different research stations across the country and is being conserved in field gene banks at ICAR-CIAH, Bikaner, ICAR-NBPGR, RS Jodhpur, MPKV, Rahuri, CCS HAU, Hisar, ICAR-CAZRI, Jodhpur, PAU RS, Bahadurgarh, and SDAU, S.K. Nagar. Among these, ICAR-CIAH, Bikaner is maintaining the largest collection, with 318 accessions.

Varieties

Over 150 cultivars of ber are cultivated across India, many of which have been developed through selection methods in different regions. These varieties exhibit a wide range of characteristics, making them suitable for diverse agro-climatic conditions. The promising cultivar under commercial cultivations are Gola, Seb, Banarsi Karaka, Banarsi Pebandi, Kaithali, ZG-1, Sanaur-1, 2, 3, 4, Katha, Umran, Mundia, Chonchal, Illaichi, Rashmi, etc. (Shukla *et al.*, 2011). B.S.75-1 variety of *ber* has been developed from CCS HAU, RRS, Bawal which is resistant against fruit fly and powdery mildew.

Hybridization work is in progress at HAU, RRS, Bawal and highest fruit yield was obtained in Hybrid-1 (64.7 kg/tree) and incidence of powdery mildew was negligible followed by Hybrid-10 (63.7 kg per tree) (Anonymous, 2011). Narendra Ber Selection-1 has been released from ANDUA&T, Ayodhya and it is performing well under climatic conditions in Eastern UP (Anon, 2011). The new promising ber varieties such as Thar Sevika, Thar Bhubharajand Thar Malti were developed by CIAH, Bikaner for cultivation in arid conditions has been released (Shukla *et al.,* 2004).

Khirni (*Manilkara hexandra* L.)

Khirni also known as Rayan, is part of the Sapotaceae family and native to India. This evergreen, medium-sized, slow-growing fruit tree has a spreading canopy and thrives in arid, semi-arid, and tropical climates, often serving as an avenue tree or bonsai due to its dense foliage and compact growth habit. Khirni flowers in February–March, with fruits ripening by May–June. It is also used as rootstock for sapota owing to its drought and salinity tolerance. The tree's bark, seeds, and fruits are rich sources of tannins, oils, and vitamin A, respectively.

In India, this species is occasionally cultivated in backyards, homestead gardens, public parts as avenue tree and in farmers' fields near villages due to its economic importance as fruit tree having nutritional and medicinal properties. The production in India is mainly concentrated in the drier states and the produce is collected by the villagers and sold in the local market. Its cultivation may be spread to arid and semi-arid areas, resource poor areas and wastelands where other crops cannot be grown successfully.

Varieties

States of Rajasthan, Gujarat, Madhya Pradesh, Bihar, Jharkhand, Orissa, Andhra Pradesh and Maharashtra have rich diversity of khirni. Recently, an improved variety 'Thar Rituraj' has been developed by ICAR-CIAH, Bikaner, whichis semi-dwarf, precocious bearer (4th year), fruit ripens in 120-125 days from fruit set. It is suitable for table and processing purpose. The fruit yield is 10-16 kg/ plant.

Cactus pear (*Opuntia ficusindia* (L) Mill.)

Cactus pear is known as 'Prickly pear' or Cactus fig or Tuna. It belongs to the family Cactaceae. Genus *Opuntia* has nearly 300 species, out of them 12 species are grown for fruits, vegetables and fodder purposes. Being a succulent xerophytic plant, it is ideally suited to water-scarce dry zones of the world. It requires low energy inputs to provide food and fodder for humans and livestock. It is a most suitable plant for semi-arid and arid regions. In India, it is found in a wild state and under-utilized fruit. However, it is a National Crop of Mexico. The cactus pear is commercially cultivated in countries like the USA, Israel, Chile, Peru, Brazil, Bolivia, Argentina, Italy, Tunisia, the Middle East, and South Africa. It is a xerophytic spiny or spineless plant. It has a shallow, fibrous root system. Roots are developed when the areoles are in contact with soil. The plants have thick succulent stems called 'cladodes'. These cladodes or cactus stems have numerous areoles, which function like meristematic buds. The buds develop into new cladodes and fruits (aerial parts) and roots (underground parts) with the passage of time.

Genetic resources

There is no indigenously identified variety of cactus pear. However, as a part of an Indo-US collaborative research program on *Opuntia* in India, 33 *Opuntia* clones were introduced at Nimbkar Agricultural Research Institute at Phalton, India, in 1987. All these clones grew well under the semi-arid agroclimatic of western Maharashtra, and it is reported that some clones also produced fruits (Meghwal and Singh, 2016). In 1991, the Central Soil Salinity Research Institute, Karnal obtained five fruit, forage, and vegetable clones from Dr. Peter Felker's collection in Texas, USA. Again, in January 1997, 51 additional *Opuntia* clones were introduced from Texas A&M University-Kingsville at the ICAR-CIAH, Bikaner. Among them genotype 1269 performed better in terms of survival and cladode exceptions. Another germplasm exchange contained thorny and thornless varieties of red, orange, yellow, and lime-green fruits that ranged up to 200 g in fruit size. Forty-three exotic collections were introduced at ICAR-CAZRI, Jodhpur during 2010.

Evaluation

The evaluation of introduced germplasm at Jodhpur in Rajasthan and Bhuj in Gujarat has indicated the latter to be the better location for its growth. High summer temperature and dry atmosphere (low humidity) is not conducive for its optimum growth and therefore, its performance has not been very encouraging at Jodhpur.

Fig (*Ficus carica* L.)

Fig is one of the earliest cultivated deciduous fruit trees. It belongs to the family Moraceae. Although its precise origin remains uncertain, fig is believed to have originated in Western Asia and spread to northern India, with local varieties extensively cultivated in Mediterranean countries. The genus *Ficus* includes more than 700 species, mainly spread in the tropics. This fruit species seems to be evolved from *F. carica* var. *rupestris*, which spread throughout the Mediterranean Basin before being domesticated, with various simultaneous selection focuses in this area. The use of this plant by humans is ancestral, and there are archaeobotanical evidences that indicate the use of parthenocarpic fruits and the possible culture of fig 14,000 years ago, showing that fig was the first domesticated crop of the Neolithic Revolution. In India, fig cultivation is confined mostly to western parts of Maharashtra and Gujarat, Uttar Pradesh, Karnataka, and Tamil Nadu.

Varieties

Poona Fig is the most popular cultivar in our country. A mature Poona Fig tree yields 25–30 kg of fruit per plant after five years of growth, with an average fruit weight of 30–60 g and TSS content of 18–20°Brix.

Dinkar: It is an improvement over cv. Daulatabad for yield and quality. It is a recently identified variety, which resemble Poona Fig variety in fruit characteristics.

Deanna: Produces medium to large golden-yellow fruits with strawberry pulp, suitable for dried fig production. The fruits are large (up to 46.64 g), with high TSS (21.20°Brix) and low acidity (0.15%), ensuring superior colour, flavour, and texture in processed products.

Excel: It develops smaller canopies, making them ideal for high-density planting.

Conadria (synonyms: Adriatic Hybrid, Verdone Hybrid): A hardy hybrid that produces medium to large, pyriform, yellow-green fruits with light strawberry pulp and a rich flavor.

Evaluation

Three varieties of fig viz., Black Ischia, Puna and Dinkar were evaluated at ICAR-CAZRI, Jodhpur. The variety Dinkar was found best with fruit yield of 10-15 kg per plant with larger fruit size and high TSS (12-14°Brix). The variety Black Ischia was at par with respect to yield but fruit size and TSS content (10-12°Brix) was less. The exotic varieties Deanna, Excel and Conardia performed well at Bengaluru.

Jharber (*Ziziphus nummularia* Burm. f.)

Jharber is a perennial, deciduous, thorny shrub, 1–2 m in height, with drooping branches. It is naturally found in a variety of habitats in extremely arid environments, including crop fields, grazing lands, sandy-saline areas, rocky terrain, and degraded pastures (Rathore, 2009). Its anatomical adaptations, such as papillae, crypt stomata, a thick outer epidermal wall, a robust cuticle, and a deep taproot system, enable exceptional tolerance to drought, salinity, and high temperatures, making it well-suited for survival in extremely arid regions (Padaria*et al.*, 2016; Uchoi *et al.*, 2022). The shrub flowers from July to August, and its fruit ripens between November and December.

The fruit is a small, globose-ovoid drupe, dark red, with a limited amount of sub-acidic edible pulp. Dried fruits of jharber contain triterpenoids, alkaloids, and saponins, which contribute to their medicinal properties, including anticancer, stomachic, sedative, blood-purifying, anti-obesity, antipyretic, anodyne, refrigerant, pectoral, anti-anemia, anti-vomiting, and styptic effects. The leaves, locally called 'Pala,' are a valuable source of fodder for camels, cattle, goats, and sheep, as they are rich in crude fiber, crude protein, calcium, and phosphorus (Bohra and Ghosh, 1981). Furthermore, different parts of the plant have traditional medicinal uses: Leaves are applied as poultices for wound healing and are used to treat asthma, fever, gum bleeding, and liver issues. The bark is used to manage diarrhea. Roots are consumed as a decoction for fever treatment or powdered to heal ulcers and wounds. Fruit acts as a laxative and antiemetic. Seeds possess sedative properties (Singh and Meghwal, 2020). This multipurpose shrub plays a vital role in both ecological and medicinal contexts, particularly in arid regions.

Pilu (*Salvadora persica* L.)

Pilu is an indigenous drought hardy species found growing naturally mostly in Rajasthan and Gujarat and also to some extent in Punjab. Another species under the genus is *S. persica* which is also equally important. It is highly resistant against abiotic stresses such as drought and salinity. In Gujarat, it occurs near the coastal areas and along the tidal creeks in Maharashtra where it is a boon to wasteland development. It is abundantly found in Jalore, Barmer, and Jodhpur district in western Rajasthan. Shankar and Kumar (1987) have also reported its abundance in the peripherals of all major runs of Jaisalmer district. The maximum density (120 trees/ ha) of *S. oleoides*was recorded at Shantipura area followed by Bibasar area (112 trees/ ha) in Jalore district of Rajasthan. Its density varies from 5 to 78 trees/ ha depending upon the soil types and rainfall. The rainfall range of the species is between 180 to 700 mm per annum and it can tolerate maximum temperature up 50ºC and a minimum of 4ºC.

On the farm boundaries, the rows of the plants act as wind breaks preventing soil erosion. Its ability to grow under harsh climatic condition of desert areas provides a pleasant site during summer months under which large number of wild animals and birds get shelter and protection. It is small to medium sized evergreen tree with dense foliage. It coppices fairly well and regenerates freely by root suckers. Apart from edible fruits, other parts of the tree also have economic value. Leaves are very good feed for animals especially goats and camels while the twigs are used for cleaning the teeth. The other plant parts such as root bark and leaves etc. have value in folk medicine. It grows upto 5 m height, gregarious, evergreen with dense round crown and has deep as well as lateral root system to utilize the moisture according to availability. The species flowers during January to April and ripe fruits called "*peelu*" are available during May-June. The ripe fruits are sweet but immature fruits are highly acrid. The fruit contains small seeds which is about 10% of fruit weight. The fruit yield ranges between 30-80 kg per plant.

Manila Tamarind (*Pithecellobium dulce* (Roxb.) Benth.)

Manila Tamarind also known as Madras thorn, Monkey pod, or *Jungle jalebi*, belongs to the Fabaceae family. This versatile, fast-growing, medium-sized thorny tree is used as live fencing, animal fodder, hardwood timber, windbreaks, and as a potential source for lac culture. Its fruits have a sweet-acidic taste and are rich in dietary fiber, proteins, calcium, iron, phosphorus, unsaturated fatty acids, and antioxidants (Brewbaker, 1992). The fruit is utilized for treating toothaches, mouth ulcers, sore gums, dysentery, chronic diarrhea, stress, aging symptoms, and skin pigmentation.

PKM (MT)-1: This variety was developed as an open-pollinated seedling selection from Soolakkarai in Virudhunagar district, Tamil Nadu. It is a hardy plant that thrives in sandy, saline, and alkaline soils, and is particularly suited for rainfed areas. The fruits are spirally twisted with pale yellow pods and white arils, yielding about 79 kg per tree annually, with a potential maximum yield of 125 kg per tree (https://agritech.tnau.ac.in/horticulture/horti-TNAUvarietiesfcmtamarind.html)

Tendu/ Timroo (*Diospyros melanoxylon* Roxb.)

Tendu/Timroo belongs to the Ebenaceae family and is native to India and Sri Lanka. It thrives in limited endemic regions, including Gujarat, Madhya Pradesh, Rajasthan, Jharkhand, Bihar, Chhattisgarh, and Tamil Nadu. This long-lived, deciduous, dioecious, seedless parthenocarpic berry-producing tree is recognized for its leaves, which are extensively used for making bidis (traditional cigarettes), as well as in agricultural tools and furniture. It is also a bio-indicator for high sulfur dioxide concentrations (Behera and Nath, 2012).

Tendu fruits boast high phenolic content, flavonoids, anti-oxidants, scavenging properties, and β-carotene levels comparable to or exceeding those of guava, plum, star fruit, mango, kiwi, and apple. Its bark extract is traditionally used to treat dyspepsia, diarrhoea, and smallpox (Hmar *et al.*, 2017).Currently, there are no officially developed or named varieties of Tendu. However, efforts are focused on selecting superior genotypes from natural populations for propagation and cultivation. Tendu plays a vital role in rural livelihoods and forest economies.

Way ahead

Several underutilized and wild fruits naturally grow in arid and semi-arid regions. These fruits have been used by the local inhabitants since time immemorial. Very little attention has been given on the collection, conservation and evaluation of these fruits. Climate change, changing land-use patterns, deforestation and expansion of major fruits are the threats to the diversity of these crops. There is a need for comprehensive efforts for exploration, collection, conservation and utilization of these fruits. The research efforts have been made on some fruits, and several promising lines have been identified. The collection and conservation of germplasm of these fruits should be a priority as genetic erosion is occurring at a rapid pace due to loss of habitat. Besides, it will be necessary to identify areas with elite populations in the wild and/or in protected/managed areas, so that *in-situ* conservation of these species could be promoted. There is a need to select genotypes that are shorter in stature, regular in bearing, fewer seeds/ smaller stone, and better fruit quality. The morphology and qualitative variability present in these species can be exploited through hybridization.

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

This review article did not generate any supplementary data.

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Review Article

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Environmental modulation and genetic variation of quality traits in onion (*Allium cepa* L.): A review

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ABSTRACT

Onion (*Allium cepa* L.) stands among the most widely cultivated vegetable crops worldwide, valued for both its culinary uses and rich phytochemical composition and associated health benefits. Among the bioactive compounds, phenolics, flavonoids and anthocyanins play crucial roles in determining antioxidant capacity, nutritional quality and market preference. This review compiles recent findings on how environmental conditions and genotypes influence on onion quality traits. Evidence consistently demonstrates wide variability among cultivars, with red onions exhibiting the highest values of total phenolics, flavonoids, anthocyanins and antioxidants, followed by yellow and followed by white type cultivars. Antioxidant activity, assessed through diverse assays such as FRAP, DPPH showed variation across various parts of onion plant. Notably, onion skins, particularly from red varieties, contain substantially higher concentrations of flavonoids and anthocyanins than bulbs, showing their potential as valuable by-products. Environmental factors, including cultivation conditions, geographic location and harvest timing, further modulate phytochemical accumulation, highlighting the importance of genotype x environment interactions. Overall, the biochemical diversity observed across onion genotypes and ecotypes presents opportunities for breeding and selection strategies aimed at enhancing nutritional and functional quality, while also emphasizing the need for standardized analytical approaches.

Introduction

The onion (*Allium cepa* L.) has been used as a food, medicine, spice and condiment for centuries because of its numerous health benefits. It is consumed fresh in salads and also processed into products such as pickles, chutneys, sauces and dehydrated powders for flavouring (Teshika *et al.*, 2019). It is known as the "Queen of the kitchen" for its distinct flavour, onions offer a nutrient-rich profile, including protein, vitamins, minerals, fibers, sugars, micro and macro-nutrients (Gupta *et al.*, 2025a, Gupta and Lawande, 2010). It is the most important species of the Alliaceae family and cultivated as a hardy bulbous plant- grown annually for bulb harvest and biennially for seed production. The edible portion of onion is bulb which develops underground. Onion is the third most vegetable produced after tomato across 146 countries worldwide. In 2023, it was covered on an area of 58.42 lakh hectares producing 111.27 million tons (FAOSTAT, 2023). Recent statistics revealed that India as the leading producer of onions,

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with a production of 30.21 million tons across 17.40 lakh hectares. Other major onion-producing countries include China, Egypt, USA, Turkiye, Bangladesh, Indonesia, Pakistan and Mexico. The global average productivity of onion is 27.06 t/ha. In 2022–23, the Republic of Korea leading with 67.87 t/ha, followed by Guyana (64.36 t/ha) and the United States (61.28 t/ha), while India ranked 93rd by 17.36 t/ha. The principal onion-growing states in India include Maharashtra, Karnataka, Gujarat, Bihar, Madhya Pradesh, Rajasthan, Andhra Pradesh and Tamil Nadu. Among these, Maharashtra and Karnataka are the leading producers, contributing nearly half of the country's total production (Gupta *et al.*, 2025a).

According to Gupta *et al.* (2025b), onions are a great combination of numerous beneficial phytochemicals, including phenolic compounds, organosulphur compounds, flavonoids (quercetin, kaempferol and their glycosides), anthocyanins, pyruvic acids, antioxidants, thiosulfinates, saponins and fructooligosaccharides. These bioactive constituents of onions have been associated with a wide spectrum of health-promoting properties, including antioxidant, anticancer, antimicrobial, antimutagenic, antiproliferative, antiplatelet, antithrombotic and antibiotic activities (Suleria *et al.*, 2015). They lower the incidence of stomach ulcers by scavenging free oxygen radicals and preventing the growth of bacteria that cause ulcers. Additionally, it functions as an antibacterial and antiparasitic substance (Tabussam *et al.*, 2022).

The total phenolic content varies among cultivars with red and yellow onions typically possessing higher levels than white onions (Lee *et al.*, 2015). The onion's outer layers are known to contain a higher concentration of polyphenolic flavonoids and other phenolic chemicals than the inner and middle layers of the bulb. In general, peels exhibit the highest levels, ranging from about 80 to 1758 mg GAE/100 g DW across white, red and dark red varieties (Gorrepati *et al.*, 2024; Duan *et al.*, 2015), while bulbs contain lower concentrations, typically in the range of 6 to 22 mg GAE/g DW in both yellow and red onions (Cheng *et al.*, 2013). Traditional onion ecotypes fall within a comparable range, with reported values of about 6 to 11 mg GAE/g DW (Brahimi *et al.*, 2022). This variation reflects differences in onion colour, variety and tissue type, with outer layers and pigmented cultivars consistently showing higher phenolic contents. Climatic factors such as temperature, rainfall, humidity and wind speed further modulate onion quality. High maximum temperatures typically reduce total phenols (TPC) and total flavonoids (TFC), though moderate temperature may sometimes enhance flavonoid synthesis (Wang, 2006; Kumar *et al.*, 2017; Moreira *et al.*, 2020; Bibi *et al.*, 2022). Rainfall and relative humidity can have variable effects, sometimes negatively correlating with phenolic and flavonoid contents, but occasionally increasing antioxidant activities depending on the variety and environmental context (Bibi *et al.*, 2022; Boussaa *et al.*, 2020). Altitude also plays a role, with higher elevations often associated with reduced TPC and TFC, though some cultivars display increased antioxidant potential under these conditions (Liu *et al.*, 2016; Bernal *et al.*, 2013; Downey *et al.*, 2006). Despite the well-documented nutritional and functional value of onions, the considerable variation in their phytochemical profile arising from both genotypic diversity and environmental influences remains a critical challenge for breeders, producers, and food industries. While several studies have independently examined the role of onion genotype, cultivation practices and ecological conditions, there is a need for an integrated understanding of how these factors interact to shape quality traits. Addressing this gap is essential not only for improving breeding strategies and varietal selection but also for optimizing agronomic practices to enhance nutritional quality, antioxidant potential and industrial utility of onions and their by-products. This review therefore synthesizes current evidence on the combined influence of environmental factors and genotypic variation on onion quality traits, with the aim of providing awareness that can guide future research, cultivation and utilization strategies.

Environmental factors

The various environmental factors affecting levels of various quality parameters of onion have been listed in Table 1.

i. Temperature

This is a critical determinant of onion quality. High maxima (>25 °C) accelerate enzymatic degradation of TPC, TFC and antioxidant capacity, while low storage temperatures (4-10 °C) maintain phenolic content, antioxidant activity and pungency (Bibi *et al.*, 2022; Kumar *et al.*, 2017; Moreira *et al.*, 2020; Wang, 2006). Cold storage at 0-5°C markedly reduces metabolic degradation, preserving sugars, amino acids and peel color (Latt *et al.*, 2025; Demissew, 2018). In contrast, warm storage accelerates moisture loss, sprouting and deterioration, as shown in traditional ventilation systems compared with forced or natural ventilation (Hatem *et al.*, 2014). Optimal temperature control, including cold storage or controlled atmosphere at 2.5 °C (Ríos-González *et al.*, 2018) and short-term curing at 30°C in high humidity to improve skin integrity (Eshel *et al.*, 2014), can substantially extend shelf life and maintain marketable quality.

ii. Relative humidity (RH)

Relative humidity strongly influences onion quality by affecting moisture loss, microbial growth and biochemical stability. Moderate RH (65-75%) generally minimizes dehydration while avoiding conditions that promote rot (Bibi *et al.*, 2022; Sabaragamuwa *et al.*, 2011). Lower RH accelerates weight loss, whereas excessive RH (>90%) increases microbial spoilage risk. Controlled curing at 30-50 °C with 30-70% RH improves skin quality and reduces weight loss (Zewdie *et al.*, 2022). In long-term cold storage, 70% RH at 0 °C preserved firmness, sweetness and biochemical quality (Latt *et al.*, 2025). Natural ventilation with perforated pipes maintained moderate RH, limiting moisture loss and deterioration while reducing sprouting compared with traditional storage (Hatem *et al.*, 2014). Optimal RH control, particularly around 75%, therefore essential for balancing physical preservation, microbial safety and enhancing biochemical composition.

Fig. 1a. Onion plant

Fig. 1b. Onion bulbs

iii. Rainfall

Rainfall exhibits inconsistent relationships with onion phytochemicals. Liu *et al.* (2016) and Mditshwa *et al.* (2013) found mostly no significant correlation between rainfall and TPC & TFC, though occasional negative associations occur possibly due to excess moisture stress. Some studies noted positive correlations between rainfall and antioxidant activity, which may reflect stress-induced phenolic synthesis under moderate water availability (Moreira *et al.*, 2020). Overall, the timing and amount of rainfall appear to influence onion quality variably, often indirectly through effects on plant health and fungal pressure (Bibi *et al.*, 2022).

Table 1. Impact of environmental factors on level of onion of quality parameters

Environmental Factor	Phenols	Flavonoids	Antioxidants	Sugars	Pyruvic Acid
High Temperature	Low	Low	Low	Variable	Short-term
Low Temperature	High	High	High	High	Maintained
Nutrient deficiency	Low	Low	Low	Low	Low
Water Stress (Moderate)	High	High	High	Low	High
Low Light/Shading	Low	Low	Low	No Change	No Change
Long-Term Storage	Low	Low	Low	Low	Low
Salinity (Moderate)	High	High	High	Low	Low
High CO_2	Low	Low	Low	High	No Change
Soil pH	Low	Low	Low	Low	Low
Wind (mild stress)	High	High	High	No change	No change

iv. Soil pH

Soil pH influences nutrient availability, thereby affecting secondary metabolite accumulation in onions. Alkaline soils tend to correlate positively with antioxidant activity, enhancing free radical scavenging capacity (Bibi *et al.*, 2022; Khalsi Ahvazi *et al.*, 2016). Acidic soils, by contrast, have been linked to increased phenolic content, suggesting stress-induced biosynthesis under such conditions (Bibi *et al.*, 2022). These pH-dependent effects reflect varying nutrient interactions and stress responses that modulate onion phytochemicals, emphasizing the importance of soil management practices in quality optimization.

v. Soil salinity

Soil salinity, reflected in electrical conductivity (EC), imposes abiotic stress that alters onion biochemical pathways. Studies show EC can variably increase or decrease TPC, TFC, and antioxidant levels depending on the onion genotype and tissue type (Bibi *et al.*, 2022; Curcic *et al.*, 2012). Salinity stress often elevates antioxidant compounds as a protective response; however, excessive salt can degrade quality by impairing growth and metabolism (Khalsi Ahvazi *et al.*, 2016). Venâncio *et al.* (2022) reported that higher soil salinity have reduced sugars and total soluble solids in onions during storage and increased mass loss. Silicon fertilization (121.8-127.0 kg/ha) mitigated these effects by enhancing firmness and boosting pyruvic and ascorbic acid content. Thus, moderate control of soil salinity is critical for maintaining onion bulb nutritional and storability traits.

vi. Altitude

Altitude affects onion quality parameters mainly through environmental stressors such as UV radiation and temperature fluctuations. Higher elevations often correspond with reduced TPC and TFC, possibly due to lower temperatures and altered metabolic activity (Liu *et al.*, 2016; Bernal *et al.*, 2013). Interestingly, antioxidant capacity may increase in some varieties at higher altitudes, indicating adaptive responses to enhanced oxidative stress (Downey *et al.*, 2006). Shukla (2024) reported that onions cultivated at high altitude (3340 m) in Leh-Ladakh exhibited higher yield, crude protein, carbohydrates, total phenols, flavonoids, quercetin content and antioxidant activity compared to low-altitude (321 m). These findings suggest that altitude-mediated environmental variation can modulate onion phytochemical profiles in complex ways.

vii. Wind speed

Wind exposure can induce physical and oxidative stress impacting onion secondary metabolites. Bibi *et al.* (2022) observed that low inverse correlations between wind speed and TPC/TFC, while Maslennikov *et al.* (2020) reported occasional positive effects on antioxidant activity. Wind-induced stress likely triggers defense mechanisms, leading to variable modulation of quality parameters depending on intensity and duration of exposure. Such environmental dynamics highlight the multifactorial nature of onion quality regulation. Maude *et al.* (1984) found that drying topped onions at 30 °C with forced airflow within 48 h of harvest markedly reduced neck rot incidence compared to ambient drying at ~18°C, highlighting the role of elevated postharvest temperatures and rapid drying in maintaining onion health and storability.

Storage conditions

Effective control of temperature and humidity during postharvest storage is essential for preserving onion quality and extending shelf life. Storage conditions also have been reported to affect the quality of onion (Fig. 2). Cold storage (4-10 °C) maintains key parameters such as total phenolics, flavonoids, antioxidant capacity, sugars and pyruvic acid, minimizing metabolic degradation and sprouting (Sharma et al., 2025). Advanced non-thermal processing technologies-including irradiation and cold plasma-help retain onion phytochemicals more effectively than conventional heat treatments (Sharma et al., 2025), supporting nutritional and sensory quality. Both storage conditions and duration can influence the stability of bioactive compounds (Ren & Zhou, 2021), while temperature, humidity, and handling are key determinants of shelf life and nutritional value (Kiran et al., 2024). Controlled atmosphere storage offers further benefits, significantly improving preservation compared to traditional methods (RíosGonzález et al., 2018). Notably, high temperature and humidity exacerbate microbial spoilage, such as Fusarium-induced rotting, with losses of up to 50% (Suravi et al., 2024); however, practices like curing, improved ventilation, and elevated CO_2 can help reduce sprouting and decay.

The use of beneficial microbial inoculants appears to influence several physiological and biochemical aspects of onion bulbs. According to Islam *et al.* (2019), microbial inoculation seems to be associated with increases in total soluble solids and pyruvic acid, which might relate to enhanced bulb pungency and overall quality. Microorganisms could also contribute to nutrient uptake and stress resilience, possibly leading to changes in phenolic and antioxidant levels. The adoption of such biological inputs may therefore provide a potential avenue for modifying onion quality characteristics. Additionally, environmental stress and infection (Al-Khayri *et al.*, 2023; Suravi *et al.*, 2024) are known to provoke onion secondary metabolite accumulation-which may impact disease resistance-but postharvest losses can rise sharply under adverse conditions. Pellegrini *et al.* (2021) and Vojnović *et al.* (2024) indicated that microbial seed inoculation and application of biostimulants can improve crop yield, bulb quality, and other soil parameters; however, the effects on phenolics and antioxidants remain variable. Optimum planting density and variety selection, such as the use of the 'Nafis' variety under a 10 cm planting spacing, have been shown to enhance bulb yield and quality including biochemical constituents important for storability and nutritional value (Alemu *et al.*, 2022).

Fig. 2a. Onion storage boxes

Fig. 2b Onion storage structure

Genotypic variations

Onions display significant biochemical variation, especially in total phenolic content, total flavonoid contents and antioxidant activity, which influence their nutritional and functional value. Studies indicate that red and pink onion genotypes generally contain higher TPC and TFC, correlating with greater antioxidant activity compared to white varieties (Dalamu *et al.*, 2010; Singh *et al.*, 2009; Benítez *et al.*, 2011; Gupta *et al.*, 2025a). Quercetin and its derivatives are the primary flavonoids responsible for these effects, with concentrations varying among cultivars (Slimestad *et al.*, 2007; Lanzotti, 2006). Genetic and environmental factors contribute to this variability, suggesting the importance of comprehensive phytochemical profiling and bioactivity assessments to identify superior onion varieties for breeding programs aimed at enhancing health benefits (Paşazade and Hanci, 2025; Bibi *et al.*, 2022). The chemical structures of these phytochemicals are provided in Fig. 3.

i. Total phenolic content

Phenolic compounds, known for their antioxidant benefits, vary markedly with onion colour in Table 2. Red onions consistently show the highest total phenolic content (TPC), averaging 867.8mg gallic acid equivalents (GAE)/kg in red onion, compared to 702.0mg/kg in pink onions and just 165.0 mg/kg in white onions. High-performing red cultivars like Sel-397, Burgundy, and Sel-383 exceeded 1,000 mg/kg, while some pink varieties, Sel-20-411, Pusa Red and white types ranged from 60.1 to 512.8 mg/kg, reinforcing the trend of lower TPC in lighter bulbs (Dalamu *et al.*, 2010). Similarly, Elhassaneen (2006) reported red onions had 187.17 mg/100g fresh weight (FW) TPC versus 131.65 mg/100g FW in white onion. Onion genotypes displayed TPC levels ranging from 740.67 to 1,145.33 µg GAE/ml, with Hissar 2, Pusa Red, Arka Kalyan, L-28, Arka Pitamber, and JWO-1 among the top performers, though skin colour showed no consistent correlation (Kaur *et al.*, 2009). Studies investigating phenolic content across onion ecotypes reveal wide disparities. Using the Folin-Ciocalteu (F-C) method, TPC values among eleven ecotypes extended from 5.94-11.22 mg GAE/g dry weight (DW). Similarly, Italian cultivars showed TPC between 3.9 and 8.2 mg GAE/g, Czech cultivars recorded from 2.66 to 3.37 mg GAE/g DW (Mitrova, 2016) and Korean cultivars varied from 2.95 to 5.54 mg GAE/g DW (Sharma *et al.*, 2014).

Other research reported even higher phenolic concentrations, such as 25.96 mg GAE/g DW (Petropoulos *et al.*, 2015). Most studies indicated that white onions contain the lowest phenolic levels relative to red and yellow types (Lee *et al.*, 2015). In contrast, research in China reported that yellow cultivars had the highest TPC, followed by red and white (Zhang *et al.*, 2016). In 2004, TPC ranged from 42.22 mg/100 g in Pusa White Flat to 146.90 mg/100 g in Sel-383, whereas in 2005, it varied between 41.74 mg/100 g in Early Grano and 112.33 mg/100 g in Sel-383. Across both years, the average values spanned 42.95-129.62 mg/100 g, with Sel-383, Pusa Red, Sel-402 and N-53 grouped as high TPC genotypes and Pusa White Flat, Early Grano, and Pusa White Round classified as low. Red cultivars consistently exhibited significantly higher phenolic content than white ones. (Kaur *et al.*, 2009; Yang *et al.*, 2004). Indian genotypes confirmed this trend, with phenolic content highest in red onions (867.8 mg/kg FW), followed by pink (702.0 mg/kg) and lowest in white (165.0 mg/kg). In skins, dark red cultivars showed maximum levels (289.04 mg GAE/g DW), followed by pink (231.73 mg GAE/g DW) and white (19.74 mg GAE/g DW), confirming the association between bulb colour intensity and phenolic concentration (Gupta *et al.*, 2025b). Studies on onion skin powder also reflected significant variability. TPC ranged from 14.55 mg GAE/g DW in the white cultivar 'Bhima Shubhra' to 288.74 mg GAE/g DW in the red cultivar 'NHRDF Red' (Sagar *et al.*, 2020). Other investigations reported red onion skin TPC values between 63.62 and 208.42 mg GAE/g depending on extraction solvents, with ethanolic extracts yielding higher concentrations (Skerget *et al.*, 2009). Comparisons consistently show red onion skins containing substantially more phenolics than their edible parts or white skins (Nuutila *et al.*, 2003; Prakash *et al.*, 2007).

Further analyses of ten exotic onion cultivars identified 'Fireball' as having the highest TPC, whereas the yellow cultivar 'Starito' showed the lowest. Late varieties such as Kamal F_1 were rich in phenolics, while white and yellow cultivars like Diamant and Mundial had the lowest. Notably, TPC was also influenced by cultivation year, reflecting the combined effects of genetics, agronomy, climate and harvest maturity on phenolic composition and nutritional quality (Yang *et al.*, 2004; Lu *et al.*, 2011). Generally, TPC values span a wide range, from 1.17 to 2.10 g/kg, emphasizing the broad genetic and environmental influences shaping phenolic profiles in onions (Mlcek *et al.*, 2015). A meta-analysis confirmed that red and purple onions consistently have higher TPC than yellow or white onions, regardless of geographic origin. This pattern was observed in onions grown in Europe, Asia, and North America, with red onions often exhibiting TPC values up to three times higher than white onions (Benkeblia, 2005; Slimestad *et al.*, 2007). A comprehensive review by Griffiths *et al.* (2002) concluded that, while genetic factors (variety and colour) are the primary determinants of TPC, environmental and agronomic practices can modulate phenolic accumulation.

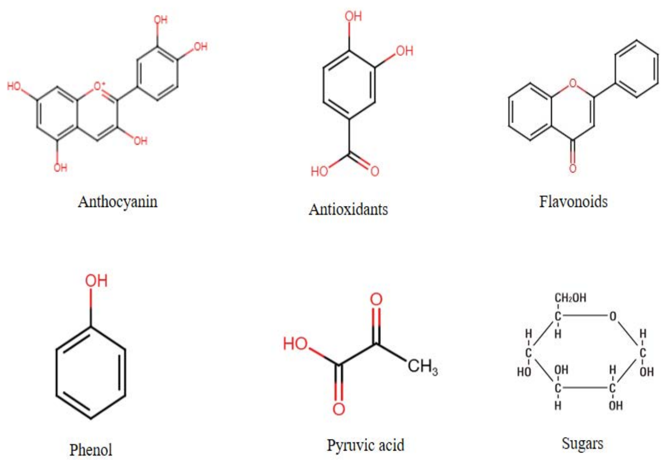

Fig. 3. Chemical structure of the major secondary metabolites found in onion

ii. Anthocyanins and flavonoids

Flavonols and anthocyanins are the primary subclasses of flavonoids present in onion. The flavonoid contents influenced by genotypes has been listed in Table 3. For Moroccan ecotypes, quercetin content ranged between 0.67 and 1.52 mg/g DW. Comparative studies have also reported values of 449.75 µg/g FW in other cultivars (Metrani *et al.*, 2020), while flavonol concentrations in red and yellow onions varied from 415–1917 mg/kg FW and 270-1187 mg/kg FW, respectively (Khandagale and Gawande, 2019). It is well documented that flavonoid concentration in onion bulbs tends to decrease from the outer to the inner layers (Cheng *et al.*, 2013). Several studies have also indicated that red-skinned onions generally exhibit higher flavonoid concentrations than yellow or white-skinned varieties (Cheng *et al.*, 2013; Zhang *et al.*, 2016). According to Pérez-Gregorio *et al.* (2010), red onion cultivars exhibited the greatest flavonol concentrations, with Vermelha da Povoa and Red Creole recording 280.24 ± 1.5 and 304.3 ± 81.2 mg quercetin/kg FW, respectively. Their studies concluded that red onions are distinguished not only by elevated flavonol levels but also by their anthocyanin content. In contrast, Zhang *et al.* (2016) observed a complete absence of flavonoids in Chinese white onion varieties. Consistently, subsequent analyses indicated that flavonoid concentrations in white onion ecotypes were significantly lower than those in red or yellow bulbs (Brahimi *et al.*, 2022).

Historical data also support considerable variability in flavonoid content among onion cultivars. Marotti and Piccaglia (2002) reported that golden and red onions contained relatively high flavonoid levels, averaging 765.1 and 610.5 mg/kg, respectively, whereas white onions had only trace amounts (1.8 mg/kg). These results are consistent with earlier reports, which reported flavonoid levels in the range of 37.8-55.78 mg/100 g FW (Ewald *et al.*, 1999). Overall, red cultivars consistently demonstrated higher average flavonoid contents than white cultivars (Bilyk *et al.*, 1984). Comparative studies revealed that red onions possessed higher flavonoid content (70.38 mg/100 g FW) relative to white onions (32.49 mg/100 g FW). A similar trend was observed for anthocyanins, with red onions recording 7.56 mg/100 g FW compared to 4.90 mg/100 g FW in white types (Elhassaneen, 2006; Kaur *et al.*, 2009).

Onion genotypes are categorized into six colour groups-white, yellowish brown, light brown, dark brown, brown and purplish brown-with the purplish brown, yellowish brown and dark brown types exhibiting the greatest flavonoid concentrations. Flavonoid levels varied widely among genotypes, ranging from 0.15 to 2.56 QE/g, with *MKS8823GO* recording the maximum (Tabussam *et al.*, 2022). A study on ten onion varieties and shallots demonstrated strong genotype effects on flavonoid content, with values ranging from 69.2 mg catechin equiv/100 g in Western Yellow to only 5.8 mg/100 g in Western White, representing an 11-fold difference (Nuutila *et al.*, 2003). The lowest flavonoid concentration was recorded in Pusa White Flat (31.67 µg QE/ml), while Arka Pitamber, a yellow cultivar, showed the highest (465.00 µg QE/ml). Genotypes were accordingly classified as low (<200 µg/ml), medium (200-300 µg/ml), and high (>300 µg/ml) and nine cultivars-including Hissar-2, Pusa Red, Arka Pitamber, and the white JWO-1-were grouped as high, surpassing several red types (Islam *et al.*, 2019). Furthermore, anthocyanin and flavonoid levels were strongly linked to bulb colour, with anthocyanin contents arranged as red > yellow > white and flavonoid levels similarly higher in red (111.10 mg/100 g FW) and yellow (36.64 mg/100 g FW) onions, while white onions showed negligible flavonols (Zhang *et al.*, 2016).

A comparative study of white (Branca da Póvoa, hybrid SK409) and red onions (Vermelha da Póvoa, its selected line and Red Creole) revealed clear differences in flavonoid and anthocyanin composition. The dominant flavonols identified included quercetin and isorhamnetin glycosides in red onions, particularly Vermelha da Póvoa (selected line) and Red Creole, displaying much higher levels (280.2-304.3 mg/kg FW) while white onions showing the lowest concentrations (89.3-101.0 mg quercetin/kg FW). Red onions also contained significant anthocyanins, namely cyanidin derivatives, with Red Creole reaching 28.6 mg/kg FW (Pérez-Gregorio *et al.*, 2010). Recent findings further confirm strong varietal differences in onion flavonoid content. In one study, AC-2, AC-3 and AC-10 exhibited the highest total flavonoids (219.00-220.90 mg QE/g), while AC-8 and AC-11 also stood out for their high dry matter content (up to 42.37%), underscoring the potential for selecting nutritionally rich and commercially valuable varieties (Paşazade & Hanci, 2025). Similarly, another evaluation reported 'NHRDF Red' with the highest flavonoid content (168.77 mg QE/g DW) and 'Bhima Shubhra' with the lowest (1.31 mg QE/g DW), with most cultivars showing significant differences (Sagar *et al.*, 2020).

Flavonoid content in onions is strongly influenced by tissue type, with the skin consistently showing much higher levels than the bulb. For example, red onion skin contained the highest flavonoid concentrations (20.22 mg QE/g DW) compared to yellow skin (10.69 mg QE/g DW) (Albishi *et al.*, 2013), and other studies reported even greater values, such as 165.20 mg QE/g in red onion skin (Singh *et al.*, 2009) and 163.14 mg QE/g in skin *vs* only 13.76 mg QE/g in the bulb (Skerget *et al.*, 2009). Similar findings were noted by Duan *et al.* (2015), who measured 49.69 mg QE/g in onion peel. In contrast, bulb flavonoid levels were generally much lower, ranging from 7.48 to 9.92 mg/100 g FW across six cultivars (Rodríguez *et al.*, 2008) and 1.85-2.13 mg QE/g FW in 18 Korean varieties (Sharma *et al.*, 2014).

iii. Antioxidant activity

Onions are rich in antioxidant compounds such as flavonoids, quercetin, kaempferol, and their derivatives (Liguori *et al.*, 2017). The comparative antioxidant activity as influenced by various genotype groups has been listed in Table 4. Assessment of antioxidant capacity using FRAP showed that red onions possess the highest antioxidant activity, with values ranging from 1.97 to 5.45 mmol Trolox/g and reducing power up to 345 mmol ascorbic acid equivalents/g; notable genotypes include I-80, I-33, Sel-383, and Sel-397, while white genotypes exhibited the lowest antioxidant and phenolic content (Dalamu *et al.*, 2010). Similar trends were reported in antioxidant assays, with FRAP values ranging from 1.60 to 4.63 µmol Trolox/g FW and CUPRAC values from 2.23 to 5.14 µmol Trolox/g FW. Among the genotypes, Pusa White Flat (white) recorded the lowest activity, whereas L-28 (dark red) showed the highest (Islam *et al.*, 2019). Comparable findings were observed in the USA, where FRAP ranged from 2.48 µmol Trolox/g in sweet onions to 5.76 µmol Trolox/g in red cultivars (Lu *et al.*, 2011). Another FRAP and CUPRAC analyses confirmed red and yellow onion cultivars (e.g., Sel-383, N-53, Pusa Red) consistently exhibited superior antioxidant activities compared to white varieties, with rank orders largely stable across years and methods (Kaur *et al.*, 2009). In a research of 15 short-day onion varieties, antioxidant activity (AOA) measured by the Folin-Ciocalteu assay ranged from 440–785µg/mL and by DPPH from 19.1-79.8 µg/mL, with white onions generally showing lower AOA and red onions higher values, albeit with exceptions (Lee *et al.*, 2015). While some studies found bulbs to contain higher flavonoid content and antioxidant capacity than leaf blades, others highlight strong genotype-dependent differences (Arena *et al.*, 2024). Across ecotypes, antioxidant capacity generally follows the trend white < yellow < red, although exceptions exist, such as Moroccan yellow ecotypes displaying antioxidant levels comparable to red ones. Moroccan onions overall showed strong antioxidant activity (0.0989-1.15 mg ascorbic acid equiv/g DW), exceeding that of Czech varieties (Brahimi *et al.*, 2022). Similarly, Chinese onions demonstrated a clear color-dependent pattern, with red cultivars consistently exhibiting the highest antioxidant activity compared to yellow and white types (Zhang *et al.*, 2016). The FRAP from 0.31-27.22 µmol Trolox/g, with red onions often showing peaks such as 82.04mg/100g FW for DPPH, 175.2 mg/100g FW for ABTS and 143.37mg/100g FW for FRAP, illustrated the significant influence of genotype, pigment and agronomic practices on antioxidant potential (Gupta *et al.*, 2025a).

Red onions demonstrated the highest antioxidant activities, recording 82.04 mg/100 g FW (DPPH), 175.2 mg/100 g FW (ABTS), and 143.37 mg/100 g FW (FRAP). In contrast, white onions, despite lacking flavonoids and anthocyanins, still exhibited moderate values of 33.38, 66.48, and 54.36 mg/100 g FW, respectively (Zhang *et al.*, 2016). Similarly, antioxidant assays on onion skin powder from fifteen Indian cultivars revealed wide variability, with DPPH scavenging ranging from 5.71% in the white cultivar 'Bhima Shubhra' to 94.17% in the red cultivar 'NHRDF Red', confirming significant differences ($P < 0.05$) in antioxidant potential across genotypes (Sagar *et al.*, 2020). Studies have shown that red onion skins exhibit the highest antioxidant activity (84.1%), followed by violet (73.9%) and white (23.4%) (Prakash *et al.*, 2007). Similarly, Nuutila *et al.* (2003) reported higher DPPH activity in red skins (74.7%) compared to yellow (40.8%). Additional studies found similar trends: Singh *et al.* (2009) measured DPPH activity at 75.3 ± 4.5% for red onion peel, Skerget *et al.*

(2009) at 47.17 ± 1.85%, and Duan *et al.* (2015) observed a remarkable 93.45 ± 0.42%. ABTS assays further confirmed wide variation, with values ranging from 6.97% in 'Bhima Shubhra' to 96.04% in 'NHRDF Red', and consistently higher inhibition in darker cultivars (Manohar *et al.*, 2017; Burri *et al.*, 2017).

Conclusions

Onions hold both nutritional and functional importance, with their health advantages largely linked to their high levels of phenolic compounds, antioxidants and flavonoids. The significant variations in total phenols, total flavonoids and antioxidant activity among different onion genotypes and colour categories, especially the elevated concentrations in red and yellow onions have been reported in various studies which highlights the opportunity for selecting and breeding improved varieties that provide enhanced health benefits. Elements such as environmental conditions, agricultural practices, postharvest techniques and storage conditions also influence these quality traits, underscoring the necessity for integrated management approaches to maximize the preservation of phytochemicals. There is a need for thorough phytochemical profiling and bioactivity assessments of Indian onion varieties, which are presently inadequately researched. By tackling this gap through targeted breeding and refined cultivation practices, we can significantly improve the nutritional value of onions and further their contribution to public health.

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Contributions

Amar Jeet Gupta and Volaguthala Sairam-*Literature Review*; Amar Jeet Gupta, Volaguthala Sairam and Priyanka Kotapati-*First Draft Preparation*; Amar Jeet Gupta and Supriya Kaldate-*Review and Editing*; Amar Jeet Gupta and Vijay Mahajan-*Conceptualization, Supervision and Final Review*.

Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

This review article did not generate any supplementary data.

Informed Consent

All the authors agree with the content of this review article.

Table 2. Comparative analysis of total phenolic content (TPC) in onion

Category	Range of TPC	High TPC varieties	Reasons	References
Red, Pink and White Onions	Mean values of Red onion :867.8 mg/kg; Pink onion: 702.0 mg/kg; and White onion: 165.0 mg/kg	Sel-397, Burgundy, Sel-383; Sel-20-411 and Pusa Red	Red onions are characterized by a predominance of quercetin derivatives, with quercetin-3, 4-diglycoside being the major compound.	Dalamu *et al*., 2010
Red, Pink, White, Yellow and Purple Onions	Yellow: 741.84 mg/100 g FW; Red: 622.27 mg/100 g FW; White: 389.69 mg/100 g FW; Skin: DR: 289.04, Pink: 231.73, White: 19.74 mg / 100 g FW	The onion genotypes of Yellow, Red (bulb and skins); Dark Red (skin) had both anthocyanin and flavonol contents more compared to white onion	Phenolic content correlates with colour intensity; skins have notably higher TPC; Yellow > red > pink > white.	Gupta *et al*., 2025a
Red and White Onions (India, USA)	Total phenolics was highest in red genotypes (867.8 mg GAE/kg), followed by pink (702.0 mg GAE/kg), and lowest in white onions (165.0 mg GAE/kg)	Sel-383, Pusa Red, Sel-402 and N-53	Red colour is associated with higher levels of flavonoids, particularly quercetin glycosides which contributed the colour intensity and the higher antioxidant potential.	Kaur *et al*., 2009
Red, White Onions (Turkey/ Iran)	Red: 6.4-13.8 mg GAE/g DW; White: 2.2-4.7 mg GAE/g DW	Turkish Red Onions	Red onions are rich in flavonoids which contribute to both the red pigmentation and the higher antioxidant/phenolic levels.	Guner *et al*., 2021

Red, White Onions (Iran)	Red onions contain 1.5-2x times and more phenolics than white varieties	Red Onions	Due to the presence of anthocyanins and higher levels of other polyphenolic compounds in red onion varieties.	Mardani *et al*., 2023
Ecotypes and Cultivars (Czech)	Czech: 2.66-3.37 g GAE/Kg DW	Elenka (brown-skinned, Italian cultivar)	Due to their genetic background and reflecting inherent genetic variation rather than environmental effects	Mitrova *et al*., 2016
Korean cultivars	All Cultivars: 2.39 ± 0.05 mg GAE/g DW to 6.63 ± 0.66 mg GAE/g DW	Korean cultivars: 2.39 ± 0.05 mg GAE/g DW	Genetic variation of onion cultivars is the major factor influencing phenolic and flavonoid levels.	Sharma *et al*., 2014
Multiple cultivars and year-wise	Highest in Fireball; lowest in Starito; late varieties richer than early	Fireball, Kamal F_1 (late maturing)	The type of Cultivar, colour, and year (environment) shown impact on TPC; late-maturing and red varieties had higher phenolics contents.	Yang *et al*., 2004; Lu *et al*., 2011
Various genotypes	TPC: 740.67 to 1145.33 µg GAE/ml	Among the tested varieties, Hissar 2, Pusa Red, Arka Kalyan, L-28, Arka Pitamber & JWO-1 have ranked among the top for TPC	The genotypic differences played a major role in the accumulation of bioactive compounds.	Islam *et al*., 2019
Onion skin powder	14.55-289.04 mg GAE/g DW	Red type: NHRDF Red	Significant variation in TPC of onion skin powder depending on cultivar; red skin richest in phenolics.	Sagar *et al*., 2020

Table 3. Comparative analysis of flavonoid Content in onion

Category	Range of flavonoids content	High flavonoid sample	Reasons	References
Red, yellow, white onions	Total flavonoid content was 111.10 ± 5.98 mg/100 g in red onions, 36.64 ± 3.59 mg/100 g in yellow onions & absent in white onions	Red onions	The presence of quercetin and its glycosides was more in red and yellow cultivars due to their high pigment concentration and genetic ability to synthesize flavonoids.	Zhang *et al*., 2016
Red & Yellow onions	Red: 415-1917 mg/kg FW Yellow: 270-1187 mg/kg FW	Red onions	Variations in bulb colour arise from mutations in structural and regulatory genes such as *dihydroflavonol 4-reductase*, *chalcone isomerase* and *anthocyanidin synthase*.	Khandagale and Gawande, 2019
White vs. Red onions	Among the tested cultivars, Vermelha da Povoa and Red Creole red onions contained the greatest quercetin concentrations, with 280.2 ± 41.5 and 304.3 ± 81.2 mg/kg FW, respectively	Red onions	Due to their richness in flavonols (e.g., quercetin derivatives like quercetin 7,4-diglucoside and quercetin 3,4-diglucoside) and the presence of anthocyanins (e.g., cyanidin derivatives).	Pérez-Gregorio *et al*., 2010
Red and Yellow onion ecotypes (Morrocan)	The flavonoid content ranged from 0.67 to 1.52 mg equivalent of quercetin/g DW respectively	Red onions	Due to inherent genetic differences that determine their biochemical expression and antioxidant profiles.	Brahimi *et al*., 2022
Various onion cultivars (India)	Ranged from 7.26–49.29 mg/100 g FW	Pusa Red, N-53, Sel-402, H-44 (>40 mg/100 g FW)	Major onion flavonoids include quercetin and kaempferol, along with derivatives such as quercetin-3,4′-O-diglucoside, quercetin-4′-O-monoglucoside, and isorhamnetin glucosides.	Ewald *et al*., 1999; Marotti and Piccaglia, 2002
Onion genotypes by colour groups	Total flavonoids range from 0.15-2.56 QE/g FW	Purplish brown, yellowish brown, dark brown genotypes (e.g., MKS8823GO)	The interaction between genotype and environment causes phenotypic plasticity, resulting in fluctuations in flavonoid content even within the same cultivar.	Tabussam *et al*., 2022

Ten onion varieties and shallots	Flavonoids: 5.8–69.2 mg catechin equiv/100 g FW.	Western Yellow (69.2 ± 3.7), New York Bold (55.2 ± 5.8) were on the top	Varieties with darker skin pigmentation, such as red onions, possess higher flavonoid contents due to their enhanced phenolic compound profiles, which contribute to greater antioxidant capacity.	Nuutila *et al.*, 2003
Onion bulb varieties AC series	Total flavonoid content: AC-2 (219.00 mg QE/g), AC-3 (219.952 mg QE/g), AC-10 (220.904 mg QE/g).	AC-2, AC-3 and AC-10	Among onion varieties and between bulbs & leaves, indicated that the genetic background of each ecotype strongly influences flavonoid biosynthesis.	Paşazade and Hanci, 2025
Varietal flavonoid differences in Indian cultivars	Total flavonoids ranged from 1.31 ± 0.32 (Bhima Shubhra) to 168.77 ± 0.87 mg QE/g DW (NHRDF Red)	NHRDF Red	The elevated flavonoid content in onion cultivars like NHRDF Red and Hissar-2 is primarily explained by their genetic makeup, pigment intensity and the protective function of onion skins as flavonoid reservoirs.	Sagar *et al.*, 2020
Onion skin *vs.* bulb flavonoid content	Red skin: 20.22–165.20 mg/g DW Peel: 49.69 mg/g DW; Bulbs (6 cultivars): 7.48–9.92 mg/100g FW; Korean cultivars: 1.85–2.13 mg/g FW	Red onion skin	Onion skin-especially from red cultivars-is a concentrated reservoir of flavonoids and a valuable source of natural antioxidants while bulb has lower metabolic activity and thus lower flavonoid levels.	Albishi *et al.*, 2013; Singh *et al.*, 2009; Skerget *et al.*, 2009; Sharma *et al.*, 2014

Table 4. Comparative analysis of antioxidant activity/ content in onion genotypes

Variety/ colour category	Range of total antioxidant activity	High antioxidant sample	Assessed via	Reasons	References
Red and White onions	Highest antioxidant levels; FRAP: 1.97–5.45 mmol Trolox/g; Reducing power up to 345 mmol ascorbic acid equiv./g	I-80, I-33, Sel-383, Sel-397	FRAP, CUPRAC, Reducing power	The specific onion cultivars reflect the combined effects of pigment-associated biochemical pathways and inherent genotypic potential.	Dalamu *et al.*, 2010
White, Yellow, Red Onions	FRAP: 1.60–4.63 µmol Trolox/g; CUPRAC: 2.23–5.14 µmol Trolox/g	Dark red genotype L-28	FRAP, CUPRAC	This attributed to their phenolic composition and genetic variation among coloured cultivars.	Lu *et al.*, 2011; Islam *et al.*, 2019
Short-day onions (white, yellow, red)	AOA (Folin-Ciocalteu): 440–785 µg/mL; DPPH: 19.1–79.8 µg/mL	Onions with higher anthocyanin and quercetin	Folin-Ciocalteu, DPPH	The onions richer in anthocyanins and quercetin consistently exhibited higher AOA levels.	Lee *et al.*, 2015
Bulbs vs. leaf blades of various genotypes	Bulbs higher antioxidant capacity and flavonoid content	Red onion bulbs	FRAP, DPPH, ORAC	High antioxidant contents in certain cultivars, particularly red and traditional landraces, reflect their pigment-rich biochemical, genetic makeup and organ-specific metabolic allocation.	Arena *et al.*, 2024
Moroccan onion ecotypes (white, yellow and red)	Antioxidant potential: 0.0989 to 1.15 mg ascorbic acid equiv./g DW	Red and some yellow ecotypes	Assay not specified	The higher flavonoid and antioxidant contents in some Moroccan onion varieties are directly attributed to their intrinsic genetic differences among ecotypes in their capacity to biosynthesize and accumulate secondary metabolites.	Brahimi *et al.*, 2022
Red vs Yellow Onions (Red Cross F_1, Vatikiotiko, Sivan F_1, Creamgold)	DPPH radical scavenging capacity lower in red varieties compared to red-yellow and yellow	Sivan F_1 (red-yellow), Creamgold (yellow)	DPPH	The low antioxidant content in "Vatikiotiko" was due to its genetic and biochemical characteristics, distinguishing it from the flavonoid-rich red commercial varieties.	Petropoulos *et al.*, 2015
Onion skins of different colours	Red skins highest AOA 84.1%, violet 73.9%, white 23.40%; DPPH in red peel 75.3 ± 4.5%, up to 93.45 ± 0.42%	Red onion skins	DPPH, AOA	Darker skins have significantly greater antioxidant activity.	Duan *et al.*, 2015; Nuutila *et al.*, 2003; Skerget *et al.*, 2009

FRAP values in onion cultivars	The range of 0.12 ± 0.03 to 37.12 ± 0.49 µmol gallic acid/g; 'NHRDF Red' highest, 'Bhima Shubhra' lowest; 'Donna' 43.6 ± 4.4; 'Barito' 28.2 ± 1.8 µmol gallic acid/g	NHRDF Red, Donna	FRAP	The cultivars with darker pigmented outer skins contained higher levels of quercetin, which is strongly linked to both anthocyanin presence and overall antioxidant activity.	Burri *et al*., 2017
Red vs White Cultivars (Korean onions)	Red cultivars FRAP: 33.18 ± 0.43 µmol TE/g dw; White cultivars FRAP: 12.58 ± 1.14 µmol TE/g dw; Range 11.59 ± 0.99 to 27.22 ± 1.34 µmol TE/g dw across 18 cultivars	Red cultivars	FRAP	Higher antioxidant activity in certain genotypes was associated with increased accumulation of quercetin and its glycosides, such as quercetin-3,4′-O-diglucoside and quercetin-4′-O-monoglucoside.	Sharma *et al*., 2015
10 Onion Cultivars (Total Antioxidant Capacity, TAC)	Significant variation in TAC; Fireball highest TAC; yellow Starito lowest; among late onions, Kamal F_1 & Rolex highest; Hamlet & Mundial low	Fireball, Kamal F_1, Rolex	TAC	The cultivars pigmentation (linked to flavonoid and anthocyanin content) plays a significant role in determining antioxidant potential	Mlcek *et al*., 2015

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Review Article

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Optimizing yield and quality in guava through crop regulation: comprehensive review

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ABSTRACT

Guava (*Psidium guajava* L.) is a prominent tropical and subtropical fruit crop valued for its high nutritional content, economic returns, and adaptability to diverse agro-climatic conditions. However, its productivity and fruit quality are often challenged by irregular flowering, excessive fruit set, and off-season bearing, which lead to small fruit size, poor market value, and high management costs. Crop regulation in guava is a critical agronomic strategy aimed at synchronizing flowering and fruiting, improving fruit quality, and enhancing overall profitability. This review consolidates existing knowledge on the various crop regulation techniques employed in guava cultivation, including mechanical methods (pruning and deblossoming), chemical treatments (application of growth regulators such as NAA, ethrel, and urea), and cultural practices (water stress, root exposure, and nutritional management). Each method is discussed with respect to its physiological basis, effectiveness under different environmental conditions, and impact on flowering intensity, fruit set, yield, and quality attributes. The role of innovative approaches such as the use of bio-regulators and precision horticulture is also explored to address emerging challenges in climate-resilient guava production. Comparative evaluation of crop regulation strategies across different seasons—particularly in tropical regions where guava tends to bear multiple crops—provides insights into season-specific recommendations. Emphasis is also placed on integrating crop regulation with canopy management and varietal selection for maximizing resource-use efficiency. The review identifies key research gaps, including the need for region-specific standardization of practices, development of environmentally safe chemical alternatives, and deeper understanding of the molecular and hormonal mechanisms governing floral induction and abscission. This article aims to serve as a comprehensive reference for researchers, extension workers, and growers seeking sustainable solutions to enhance guava productivity and fruit quality through effective crop regulation practices.

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Introduction

Guava (*Psidum guajava* L.) is one of the most favourable fruit crops in India and is considered to be a well-executed, nutritionally valuable and profitable crop. Recently, guava has secured higher demand within the global trade because of its nutritional value and processed products (Kumar *et al.*, 2017). The fruit is an excellent source of ascorbic acid, pectin, minerals like phosphorus, iron and calcium etc. as well as vitamins like vitamin A, thiamine, riboflavin, pantothenic acid and niacin (Sharma, 2010). It is a hardy, prolific bearer and produces a fairly remunerative fruit crop (Mishra *et al.*, 2025). It is mainly cultivated on a large commercial scale. Guava fruit bears three bahar seasons, *viz.*, Ambe bahar, Mrig bahar, and Hasth bahar. Among the three bahar seasons, the heaviest flowering is observed in the Ambe bahar, but the fruit quality of this season is rough, watery, insipid in taste, poor in quality, less nutritive and is heavily attacked by many insects, pests and diseases. The fruit quality of winter season crops is excellent, nutritive, and escaped from the attack of fruit flies. Therefore, the crop regulation practice is to force the tree for rest and produce profuse blossoms and fruits throughout any one of the two or three flushes. It is necessary to reduce the fruit set during the rainy season and subsequently increase the fruit set during the winter season through the use of various chemicals like NAA, ethereal, urea etc. to regulate the guava crop (Kumar *et al.*, 2014).

Crop regulation in guava is a horticultural practice aimed at optimizing the productivity and quality of guava fruit while ensuring a more predictable and even yield throughout the year (Dongre and Choudhary, 2023). This is particularly important for commercial growers who need to manage large orchards for maximum efficiency and profit. The purpose of crop regulation is to force the tree to rest and produce profuse blossoms and fruits (Kumar *et al*., 2021). It can be achieved through with holing irrigation water, root exposure, root and shoot pruning, de-blossoming, spray of chemical and other plant growth regulators. Several crops that bloom more than once a year do not produce a good yield and quality of fruit throughout the year.

Why crop regulation?

The rainy season crop of guava is poor in terms of consumer acceptance quality and crop is affected by many biotic and abiotic stresses as compared to winter season crop (Zaid *et al.*, 2024). The environmental factors which are more supporting in obtaining winter season quality fruit production include diurnal variation during winter and also reduction in temperature facilities, higher total soluble solids content in guava fruits. The winter season crops which ripen from second fortnight of October to first fortnight of January are superior in quality, free from diseases and pests and fetch higher income. This requires regulation of flowering to obtain most profitable crop by withholding irrigation, root exposure, pruning and thinning of flowers. The flowering is more in guava during summer season because of heavy new flushes that lead to more fruit production in rainy season. In this season, duration of fruit harvesting is reduced to 30 days due to high temperature and rainfall and it causes glut in the market which lead to poor price and less demand in the market. Winter season crop is superior in quality which fetches higher prices than rainy season crop. In rainy season there is a serious attack of fruit flies which deteriorates its quality and fruits become unfit for human consumption. So far getting the quality fruits in guava only winter season crop should be taken and rainy season crop should be avoided. Water availability is also a big issue in Maharashtra, Rajasthan and Gujarat during summer season for guava grower. Farmers always avoid taking ambe bahar crop and regulate this crop to mrig bahar concurrent with the onset of monsoon and crop is harvested during winter.

Principle of crop regulation

The basic principle of crop regulation is to manipulate the natural flowering behaviour of the guava plant in desired season which contributes to increased fruit yield, quality and profitability. This concept is based on the fact that guava flowers are borne only on new, succulent, vigorously emerging vegetative growths. These new growth flushes can be either on new emergences of lateral bud on older stems or extensions of already established spurs of various size and vigour.

Objectives of crop regulation

The main objective of crop regulation is to force the tree for rest and produce profuse blossom and fruits during any one of the two or three flushes. The advantage is to regulate a uniform good quality of fruits with rise in the production as well as augmented profit to the growers. The prime benefit is to reduce cost of cultivation because uninterrupted continuous blossom would produce light crops over the whole year and requires a high cost for the monitoring and marketing.

Methods of crop regulation in guava

Withholding irrigation method

In guava, the induction of water stress by withholding irrigation after harvesting of the winter crop results in the shedding of flowers and the trees go to rest. The operations of withholding water exhibit feeding roots and also prune the fibrous roots to force blossom in the desired season. June flowering is inspired to get a winter crop; for that, the basin of the tree is dug up, manured, and irrigated in June. After 20-25 days of fertigation, the tree offers profuse flowering in July and fruiting in the winter season. Water stress may be induced by practices like root exposure and root pruning. It has been suggested that withholding of water and removing the earth from around the upper roots by 10th June and again covering it with soil and manure mixture (Howes *et al.*, 1955). Two irrigations were also suggested before a normally heavy one when the rains did not start. Likewise, it has also been suggested that the root pruning practice is done along with withholding irrigation in heavier soils during December or January (Singh, 1963). In guava the operations of withholding water, expose of feeder roots and pruning of fibrous roots to force blossom in the desired season are practiced in Maharashtra and Deccan plateau growing belt of guava in India. Some researchers recommended withholding of water for those areas of the western India where soils were lighter in texture.

*B*ending of shoots

The bending method is very much dependent on the training of guava branches. On the basis of the calculation of expected flowering, the branches of guava plants are bent down about 45-60 days before the expected date of flowering to produce fruits in the off season. Initially, bending of branches of guava plants ought to be done at the age of two years of the plant. Before bending the leaves, small shoots, flowers, and fruits from the branch are removed or cut off, keeping 10-12 inches of terminal twigs intact. During autumn (September-November), the new shootlets take 20-25 days to emerge. Bent branches ought to be untied once the new shootlets are about 1 cm in length. Flowering occurs in the new shootlets at 4-5 pairs of leaf stage after 45-50 days of summer and 60-65 days of autumn bending. Manures and fertilizers should be applied 15 days before the bending of branches and again at the peak stage of fruit growth followed by irrigation (Singh, 2013).

In case of bending of branches of guava wood tension of branch is increased and phloem formation decreased. As a result, photosynthetic assimilates pass slowly from the shoots of bent branch to the other parts, maintaining increased C: N ratio and induce more flowering and fruit set. Bending forces dormant reproductive buds into active growth. Shoot bending is one of the ways to produce better quality fruits in the off-season of guava (Sarker *et al.*, 2005). The upright branch produces fewer flowers and fruits than the bent branch (Ito *et al.*, 1999). Bending induces profuse flowering and fruiting, as well as fetches greater returns and regulate flowering by bending of shoots (Mitra *et al.*, 2008). Bending consistently increased the lipid, tryptophan, proline, polyphenol oxidase, catalase, and peroxidase levels in leaves, bark, and fruits, but decreased phenolics (Eassa *et al.*, 2012). Shoot bending increased the fruit set per plant during off-season was also reported by Sarker and Ghosh (2006). Shoot bending increased the fruit yield per plant and quality fruit during off-season (Sarkar *et al.*, 2005). Samant *et al.* (2016) has also shown the positive effect of shoot bending in guava.

Thinning

Thinning is part of an integrated approach to crop regulation in guava that balances the tree's energy expenditure between growth and fruit production. By implementing a thoughtful thinning regime, growers can significantly improve fruit quality and tree health, thereby enhancing the overall productivity of orchards (Figure 1). This practice involves selectively removing a portion of the fruit or flowers from a tree. Thinning can be done manually or chemically and offers several benefits, including reducing the risk of branch breakage due to heavy fruit loads, ensuring better nutrient

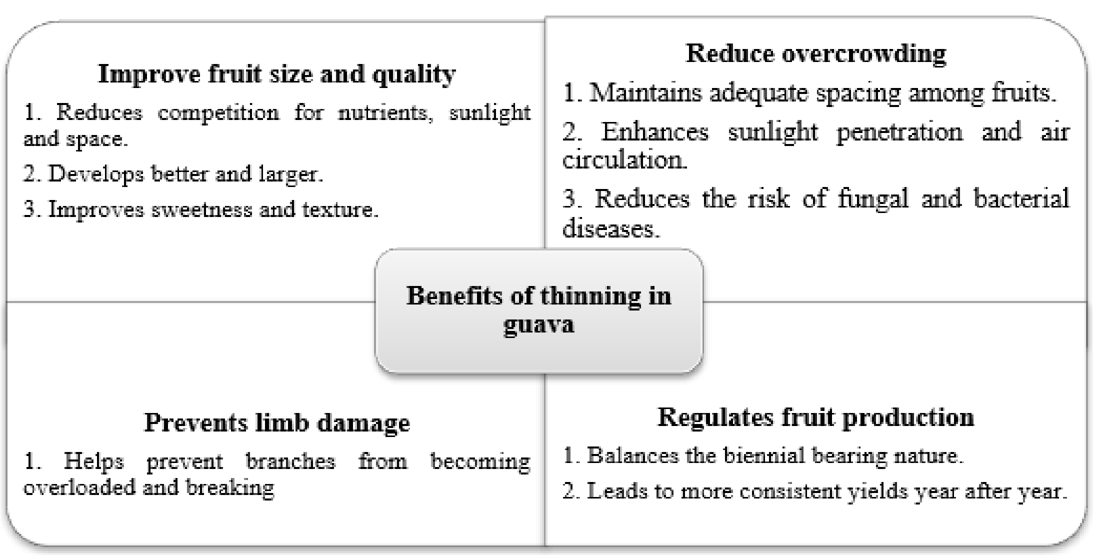

Fig. 2. Various benefits of thinning management practices in guava

allocation to remaining fruits, and potentially reducing the incidence of certain diseases by improving air circulation within the canopy. Mamun *et al*. (2012) conducted an experiment to check out effect six different management practices viz., (i) control (no shoot bending + no fruit thinning); (ii) shoot bending; (iii) 25% fruit thinning; (iv) 50% fruit thinning; (v) 75% fruit thinning and (vi) 100% fruit thinning and found out that 50% fruit thinning treatment showed the highest fruit yield (20.46 kg/plant) and 75% fruit thinning treatment performed lowest fruit yield (10.06 kg/ plant) during on-season. Additionally, they found that highest fruit retention in both seasons (on-season 89.28 % and off-season 90.47 %) was observed in 50 % fruit thinning treatment. Similarly, Rahman *et al*. (2017) also revealed that thinning practice in guava crop is helpful in increasing fruit weight.

Methods of thinning in guava

Manual thinning: This is the most common method and involves physically removing flowers or young fruits by hand. It allows for selective removal based on size, location, and health.

Best practices for manual thinning

Timing: The best time for thinning guava fruits is when they are small, usually pea to marble size. Early thinning is more effective as it prevents the tree from wasting resources.

Technique: Gently twist and pull the fruit or use small shears to cut them off. Be careful not to damage the branch or the remaining fruits.

Selection Criteria: Remove fruits that are misshapen, damaged, or diseased first. Then, thin the fruits based on spacing, leaving the healthiest and best-positioned fruits.

Flower thinning: Removing a portion of the flowers can reduce the number of fruits that set, which is particularly useful if a high fruit set is expected.

Fruit thinning: Typically done at the early stage of fruit development, usually a few weeks after fruit set. The goal is to space out fruits adequately, often leaving them about 4-6 inches apart on each branch.

Chemical thinning: This method can be less labour-intensive but requires careful handling and precise application to avoid damaging the tree or affecting unintended parts of the crop.

Growth regulators: Substances like gibberellic acid (GA) and naphthalene acetic acid (NAA) can be used because they affect the hormonal balance in the plant, which can reduce the initial fruit set.

Monitoring and management: It is crucial to monitor the tree's response after thinning by noticing signs of new growth and general tree health. Tree may need less water and nutrients than before thinning due to the reduced fruit load and water and nutrient supply should be adjusted.

Pruning and exposure techniques

Pruning is essential in fruit culture for long-term guava production. It helps in shaping the tree, removing dead or diseased branches, and promoting better air circulation and sunlight penetration, which are essential for fruit development. The orchard's life and harvesting period are extended by proper pruning. It is typically done after the harvest to prepare the tree for the next cropping season. Pruning is a critical technique used in the crop regulation of guava trees, helping to enhance both fruit quality and yield by influencing the growth and productivity of the tree. Effective pruning practices can also aid in controlling the harvest period and ensuring that the trees remain healthy and productive over time. Annual pruning is used as a cheap and effective culture technique for regulating the cropping pattern and increasing fruit yield and quality in guava" (Bhagawati *et al*., 2015). It has been reported that the maximum number of fruits in a winter crop is found from guava trees when three-fourths of the shoot length is pruned during May (Singh, 2013). The practice is popularly known as elicit treatment and is achieved by root exposure and root pruning or exposure to hot sun before the onset of monsoon. Root pruning, however has a harmful effect on the longevity of trees". It has been studied that the effect of pruning on vegetative growth, flowering, and fruiting in Sardar guava favoured the production of more flowers in the July-August flush thereby more fruits in the winter season. In addition, 50% shoot pruning of guava cv. L-45 (Sardar) in May produced the highest fruit yield of any winter crop (Sharma, 2006).

Objectives of Pruning in Guava

- To regulate fruit production
- To improve fruit quality
- To maintain tree health
- To manage tree size and shape

*T*ypes of pruning in guava

Formative pruning: It is done in the early years of a guava tree's life to shape the structure of the tree. This type of pruning establishes a strong framework of branches that can support fruit production in later years. It usually involves selecting 3-4 well-spaced branches as the main scaffold limbs.

Maintenance pruning: This is carried out annually to remove unwanted growth, maintain shape, and encourage the development of new fruiting wood. It includes thinning out branches to improve light penetration and air flow within the canopy.

Rejuvenative pruning: This is more severe pruning used to revitalize older trees that have become less productive. It involves cutting back a significant portion of the tree to stimulate new growth and can help in managing diseases and pests.

Technique:

- Remove all diseased, broken, or dead branches.

Cut back overly vigorous, vertical branches (water sprouts) that typically do not bear fruit.

- Thin out the centre of the tree to enhance sunlight penetration and air circulation.
- Maintain the desired shape and height for easier harvesting.

Precautions: Sharp pruning shears/scissors or secateurs should be used to prune the plant (Pilania *et al*., 2010), so that branches are not damaged. These tools should be sterilized with alcohol to prevent spread of disease. No branch should touch the ground. Pruning should not be performed during intense high temperatures (May, June, July), as it may cause wilting, and also not on rainy days, which may lead to fungal attack. Fungicide must be sprayed in case of misty weather. Meena *et al*. (2017) found that just after pruning, a spray of copper oxychloride stopped disease attack.

Deblossoming techniques

Some of the plant growth regulators (NAA, NAD, 2, 4-D, carbaryl and ethrel) or certain chemical compounds have been found very effective in thinning of flowers, increasing the winter crop as well as manipulating the cropping season under different agro-climatic conditions. Post-bloom application of NAA @ 80- 100 ppm has been useful in reducing fruit set. This treatment can reduce more than 80% of the rainy season crop and also increase flowering of the winter crop. The spray of 2, 4-D @ 30 ppm was also found to be effective for de-blossoming in summer flowers. Manual deblossoming of rainy season flowers at small scale, kitchen garden and early age of the plant is very effective as compared to large commercial plantation. Flower thinning by using naphthalene acetic acid (NAA), naphthalene acetamide (NAD), 2,4-dichlorophenoxy acetic acid (2,4-D), potassium iodide (KI), ethephon, 4,6-dinitro-ocresol (DNOC) and urea has been tried with varying degrees of success. This variation may be due to cultivars, tree condition, soil type, and environment. Most of the workers are of the opinion that chemical thinning is economical, as it increases the winter yield and also helps in improvement of fruit quality. In guava, deblossoming with NAA @ 600 ppm prevents flowering and cropping during the rainy season in order to augment cropping in the winter season. It has been found that 15 per cent urea at 50 per cent bloom stage showed the most effective in deblossoming during the rainy season guava crop (Choudhary *et al*., 1997). Similar results have been reported by Tiwari and Lal (2007). Khan *et al*. (2013) studied 3–4-year-old guava cv. Gola plants and found that 50% de-blossoming without defoliation resulted in uniform and better sized fruit with high organoleptic properties, reducing sugars, ascorbic acid, and TSS. However, more than 50% de-blossoming causes low yield. One of the previous studies conducted by Thakre *et al*. (2016) revealed that one-leaf-pair pruning achieved the maximum cost–benefit ratio as compared to flower bud thinning by hand, retaining one leaf pair at the top, removal of all leaves and flowers by hand, and one leaf-pair shoot pruning in guava cv. Pant Prabhat.

Nutrient Management

Balanced and timely application of nutrients, especially nitrogen, phosphorus, potassium, and essential microelements, is crucial for the healthy growth of guava trees and optimal fruit production. Soil tests can help determine the necessary fertilizer requirements. Nutrient management in guava cultivation is crucial for ensuring the health and productivity of the trees. Proper fertilization helps regulate growth, enhances fruit quality, and increases yields. Understanding the specific nutrient needs of guava trees at different stages of their growth cycle is key to effective nutrient management.

Controlled Irrigation

Water management is vital in guava cultivation (Figure 2). Controlled irrigation can help manage flowering and fruiting cycles. For instance, a period of water stress followed by adequate irrigation can stimulate flowering. This method is often used to schedule harvests according to market demand. Controlled irrigation is a crucial aspect of guava cultivation, significantly impacting both fruit yield and quality. Guava trees are relatively drought tolerant, but for optimal fruit production, they require specific watering strategies. The goal of controlled irrigation is to regulate water supply in a manner that optimizes the tree's growth phases, from flowering to fruit set and maturation. Here's how controlled irrigation can be effectively used for crop regulation in guava.

Fig. 3. Benefits of controlled irrigation in guava

Strategies for controlled irrigation

Water stress and regulated deficit irrigation (RDI)

It involves applying less water than the crop evapotranspiration demands during certain phases of the growth cycle (usually post-harvest and pre-flowering stages) to save water and control vegetative growth, focusing the tree's energy on fruit development. Temporary water stress before the onset of flowering can stimulate the flowering process. This is useful for synchronizing and inducing flowering, particularly for off-season production.

Supplemental irrigation

During dry periods, supplemental irrigation ensures that guava trees do not suffer from moisture stress, especially during critical phases like fruit setting and ripening. This can be particularly crucial in regions with seasonal rainfall where dry spells may occur during these critical growth phases.

Drip irrigation

Drip irrigation delivers water directly to the base of the tree, minimizing evaporation and runoff. It's highly efficient for conserving water and allows for the addition of fertilizers directly into the irrigation system (fertigation). The irrigation schedule can be adjusted based on the season, tree age, soil type, and local climate. For instance, younger trees require frequent, smaller amounts of water, while mature trees benefit from less frequent but deeper irrigation to encourage root growth. Using sensors or tensiometers helps in monitoring the moisture levels in the soil, thus allowing precise control over irrigation based on actual soil moisture status. Regular checking of soil moisture by feeling the soil can also guide irrigation needs, although it is less precise than using sensors. In areas with high evaporation rates, more frequent irrigation may be necessary. Sandy soils require more frequent irrigation than clayey soils, which hold water longer. Larger, older trees have deeper root systems and can access water from deeper soil layers, potentially reducing the frequency of irrigation required. Controlled irrigation, when done correctly, not only optimizes the productive output of guava orchards but also enhances the sustainability of water resources. It is a vital tool in the management of crop production, particularly in water-scarce areas, and can significantly affect the profitability of guava cultivation.

Use of growth regulato*rs*

Growth regulators are chemical substances that influence the growth and development of plants. In guava cultivation, these regulators are used to manage and enhance various aspects of plant growth, from flowering and fruit set to fruit size and ripening. Besides, all available high production technologies such as use high yielding varieties, high density orcharding, the use of PGR's has been proved as a powerful tool to meet demand of guava fruits to the increasing population of the country by influencing fruit production directly or indirectly (Bhardwaj and Mishra, 2005).

Common growth regulators used in guava

Gibberellic Acid (GA_3): GA_3 promotes cell elongation and division, which help in increasing fruit size and improving fruit quality. It can also delay fruit maturation, allowing for an extended harvest period.

Naphthaleneacetic acid (NAA): A synthetic auxin used to promote fruit set and reduce fruit drop. It can also be used to enhance the uniformity of fruit ripening.

Ethephon (Ethrel): It encourages the ripening of fruit by releasing ethylene, which is a natural plant hormone involved in the ripening process. Ethephon treatment can help synchronize fruit ripening, making harvest more manageable and timely.

Paclobutrazol (PBZ): It inhibits gibberellin synthesis, thus controlling excessive vegetative growth and promoting more reproductive growth, leading to improved fruit yields. It can also help induce uniform flowering and manage tree size, which is beneficial for mechanical harvesting.

Applications of growth regulators in guava

Inducing flowering

Gibberellic acid and Paclobutrazol: These can be used to manipulate the flowering stages of guava trees. For example, applications of paclobutrazol during the post-harvest period can induce more uniform and synchronous flowering, which is crucial for off-season production.

Enhancing fruit set and size

Naphthaleneacetic acid: Spraying NAA shortly after flower bloom helps improve fruit set and reduces premature fruit drop. It can also assist in achieving a more uniform fruit size.

Gibberellic acid: Application during the early stages of fruit development can enhance fruit size by promoting cell division and elongation.

Regulating fruit development and ripening

Ethephon: If it is applied during the later stages of fruit maturity, ethephon can accelerate fruit ripening, which is particularly useful for synchronizing harvest and improving the colour and quality of the fruits for market (Kumar *et al.*, 2016).

Defoliation

Defoliation, the deliberate removal of leaves from a plant, can be a strategic tool in guava crop regulation. In guava cultivation, defoliation is primarily used to manage and synchronize flowering, which can help in stabilizing the production cycle and enhancing fruit quality and yield.

In some cases, artificial defoliation (removal of leaves) is practiced to induce stress and promote uniform flowering. This technique, however, must be used cautiously as it can lead to reduced vigour if not managed properly. The timing of defoliation is critical and varies based on the desired outcomes and climatic conditions. It is usually done after the harvest of the main crop, before the onset of the next flowering period. In tropical climates, where guava can have multiple flowering periods, defoliation might be timed to encourage off-season flowering.

Purpose of defoliation in guava

Inducing uniform flowering: Defoliation can trigger a stress response in guava trees that leads to uniform and synchronized flowering. This is particularly useful for producing off-season crops.

Improving fruit quality: By reducing the leaf mass, more resources (like nutrients and carbohydrates) are redirected towards fruit development, potentially improving fruit size and quality.

Pest and disease management: Removing older leaves may help reduce the incidence of certain leaf-borne diseases and pests (Kumar *et al.*, 2025).

Conclusion

Crop regulation in guava is a vital horticultural practice that plays a key role in managing flowering behavior, improving fruit quality, and ensuring synchronized harvesting for better market returns. The integration of mechanical, chemical, and cultural methods offers a flexible and effective approach to control excessive fruiting, manage crop load, and optimize yield. Among these, techniques like strategic pruning, application of growth regulators, and regulated water and nutrient management have shown promising results across various agro-climatic zones. However, the success of these practices largely depends on factors such as cultivar, season, and local environmental conditions. With the increasing demand for quality produce and the challenges posed by climate change, there is a growing need to refine existing crop regulation strategies through region-specific research and promote the use of eco-friendly and sustainable methods. Future advancements in molecular biology and plant physiology can further enhance our understanding of guava's flowering mechanisms, paving the way for more precise and innovative regulation practices. Ultimately, adopting an integrated and scientific approach to crop regulation will be essential for improving productivity, profitability, and sustainability in guava cultivation.

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

This review article did not generate any supplementary data.

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Research Article

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Morphological characterization of *Ziziphus* species fruits in the Mid-Zambezi Valley in northern Zimbabwe

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ABSTRACT

Emergence of industrial-scale *Ziziphus* fruits processing in the Mid-Zambezi Valley necessitates selection of superior genotypes for cultivation to meet anticipated increased demand. The study evaluated morphological variation among *Ziziphus* fruits to determine their agronomic value and genetic diversity. Dry fruit samples were collected from bulked fruits and separated into three perceived varieties, which were further separated into 12 collections. Data depicted large coefficients of variation ≈50% for fruit and seed mass. Fruit parameters ranges were: mass (0.56–2.57 g), length (1.14–2.33 cm), width (1.05–2.16 cm), density (0.24–0.38 g/cm^3), percent pulp (63.03–89.28). Seed parameters were: mass (0.15–0.56 g), length (0.57–1.27 cm), width (0.43–0.66 cm). Fruit mass was positively correlated to yield components. Cluster analysis grouped the collections into two clusters with two sub-clusters each. I concluded that there could be two *Ziziphus* species in the area. The WF-variety is recommended for cultivation and further improvement because of its superior yield and taste variation. The HSDB variety is recommended for its high percent pulp subject to confirmation that hollowness is not a physiological disorder. Research is recommended to determine the *Ziziphus* spp. genotypes; genotypes nutritional composition; effect of ecology on fruit morphology; and evaluate agronomic performance.

Introduction

The genus *Ziziphus* (Rhamnaceae family) has about 100 species distributed in tropical and subtropical regions between latitude 34°S and 51°N and from zero to 2800 m a.s.l. (Razi *et al*., 2013). Major species in the Rhamnaceae family are *spina-christi*, *mucronata*, *nummularia*, *lotus*, *selata*, *spinosa*, *oenoplia*, *vulgaris*, *jujuba* and *mauritiana* (Khan *et al*., 2023). *Ziziphus mauritiana* L. (Indian ber or jujube, Chinese apple, Musawu in Zimbabwe) is native to South Asia and eastern Africa (Bebawi *et al*., 2016) and it is the species that is reported to occur in the Mid-Zambezi Valley where the tree has naturalised. Dhileepan (2017) report on invasive *Z. mauritiana* populations in southern

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Africa, specifying Zimbabwe and Zambia. However, the species can be positively exploited to produce economic benefits of national importance. *Ziziphus* spp. fruit quality is best under sunny, dry and hot conditions that enhance accumulation of important biochemicals (phenols and flavonoids) and antioxidant activity, which ultimately increases the fruits' medicinal and nutritional value (Riaz *et al.*, 2021). The Mid-Zambezi Valley provides optimum conditions for production of high quality fruits because fruit growth and ripening occurs during the dry season, making the region a high potential area for *Ziziphus* fruits production.

Information on exceptional nutritional, medicinal and cosmeceutical value of *Ziziphus* fruits, and the forms in which they are utilised is widely documented (Butt *et al.*, 2021; Ma *et al.*, 2021; Jailani *et al.*, 2020; Nyanga *et al.*, 2013 and Rathore, 2009). Despite acknowledgement of the significant contribution of *Ziziphus* fruits in the livelihoods of local people in the Mid-Zambezi Valley, the genus has not been adequately researched compared to China and India (Razi *et al.*, 2013). However, emergence of industrial-scale processing of *Ziziphus* fruits through establishment of the Zambezi Valley Masawu Value Addition Plant in 2025 might prompt selection of varieties for cultivation to meet the anticipated fruit demand.

Morphological parameters provide indices for characterization, taxonomic classification, and agronomic value of plants, and information on genetic diversity (Riaz *et al.*, 2021). Therefore, the first step in the cultivar selection process is to characterize the morphological diversity of existing *Ziziphus* fruits gene pool in the Mid-Zambezi Valley, in order to develop a reliable identification key, which helps selection of better genotypes for cultivation. Although the species reported to occur in the Mid-Zambezi Valley is *Z. mauritiana*, there are no published reports on characterisation of genetic and morphological traits of the *Ziziphus* spp., therefore, it is possible that other species exist in the region.

Ziziphus spp. produce stone fruits whose morphological traits include colour, size, shape, flesh (mesocarp) weight, and stone weight. Remarkable variations of fruit morphological traits have been reported in *Z. jujuba* cultivars (Ivanišová *et al.*, 2017). The colour of dried Chinese *Z. jujuba* is an important quality index with darker colours having low market value and quality (Fang *et al.*, 2010). Markovski and Velkoska-Markovska (2015) found that *Ziziphus* fruits seed weight, fruit weight, fruit flesh/seed ratio, and fruit yield showed high heritability estimates and genetic advance. Accordingly, they reported that these traits can be improved through selection.

The objective of the study was to evaluate morphological variation among *Ziziphus* fruits in the Mid-Zambezi Valley in order to determine their agronomic and industrial value, and genetic diversity. The study combined conversational interviews with local *Ziziphus* fruits harvesters and traders (local suppliers); measurements of fruit mass, length, width, percent edible portion (pulp), and density; and seed mass, length, and width; and qualitative assessment of fruit shape, colour, firmness and skin texture. Fruit and seed size and mass are yield components, whilst fruit colour, shape, firmness, and percent pulp are quality attributes.

Material and Methods

Description of the study area

The study was conducted in Muzarabani (16.12°S, 31.15°E, 334 m a.s.l.) in northern Zimbabwe. Soils in the area range from fine-grained loamy sands to sandy clays. Mean annual rainfall is < 650 mm and the area is frost-free with a mean maximum temperature of 28–30°C (Manatsa *et al.*, 2020). The vegetation is dry savanna (Hoare *et al.*, 2002) comprising *Colophospermum mopane* Kirk ex Benth., and *Combretum*, *Sterculia* and *Vachellia* spp. *Ziziphus mauritiana* is dominant along waterways.

Data collection

Conversational interviews

Data on indigenous knowledge about local *Ziziphus* fruit varieties was collected from 112 local fruit suppliers through conversational interviews (West and Conrad, 2018) from September to December 2024. Participants were interviewed individually or in groups. In some cases multiple interviews were conducted with same participants for checking consistency of responses. The main question that I asked participants was: "How many varieties of Musawu are found in your area?" Follow-up questions captured morphological differences among varieties, fruit taste, and the production context that affects fruit size and mass.

Sampling of fruits for measurements

Seven sampling visits were conducted and at each visit fruits were placed in separate containers with the aid of local suppliers based on perceived varieties. Three varieties were identified: (i) wrinkled firm with colours ranging from reddish brown to dark brown, sub-divided into sweet sub-variety and less sweet sub-variety; (ii) hollow soft dark brown; and (iii) small golden-yellow to light brown sweet. At the end of the sampling period, the fruits varietal categories were bulked in separate 50-kg bags. From the varieties, fruits were graded into 12 sub-categories (collections) of different morphologies (Table 1). From the 12 collections, fruit samples measuring about 2000 cm^3 were collected through the quartering technique and placed in plastic sampling bags ready for physical measurements.

Undisturbed fruits quantitative measurements

Quantitative measurements were conducted at the Bindura University Biology Laboratory. Before measurement, all fruit samples were air-dried in the open sun for 5 days to remove moisture that could have been absorbed during handling. The twelve 2000 cm^3 samples were separated into four quarters each using the quartering technique. Three quarters were placed in three 650 cm^3 beakers and filled to the brim using fruits from the fourth quarter forming three replicates per sample. The number of fruits in each replicate 650 cm^3 beaker were counted. Fruit parameters measured were mass, width and length. Fruit mass was measured using a digital analytical balance (Model Adam Nimbus, NBL-254i, USA) with a sensitivity of ±0.0001g). From each replicate, three fruits were randomly selected for measuring width and length using Vernier's caliper (Model 6050926 Shangai Shenhan Measuring Tools Co. Ltd.) with an accuracy of 0.02 mm.

Undisturbed fruits qualitative measurements

Fruit colours were determined using a Munsell Colour Sheet. Fruit skin texture was assessed visually and by hand feel noting features like smoothness or wrinkling. Firmness or softness of fruits was assessed through pressing the fruits between fingers and fruit shape, fruit apex shape and fruit base shape were assessed visually.

Disturbed fruits measurements

After undisturbed fruit measurements, fruits were boiled for 30 minutes in 1.25 litres of water and the pulp [pulp (mesocarp) and skin (exocarp)] was separated from the seed [seed covering (stone) (endocarp) and seed] by pressing using a stainless steel potato masher. The samples were left to cool down before seeds were picked by hand, cleaned

Table 1. Description of varieties of *Ziziphus* spp. fruits identified by local suppliers and sub-categories (collections)

Variety description	Collection	Sub-category description	Remarks
Wrinkled firm	1	Large wrinkled firm sweet	Fruits exhibited similar morphology, grading was based on fruit size except for sample number 1, which was selected for its sweetness
	2	Large wrinkled firm	
	3	Medium wrinkled firm	
	4	Small wrinkled firm	
Hollow soft dark brown	5	Large soft dark brown	Fruits exhibited similar morphology, grading was based on fruit size
	6	Medium soft dark brown	
	7	Small soft dark brown	
	8	Very small soft dark brown	
Small golden-yellow sweet	9	Wrinkled golden-yellow very sweet	Fruits exhibited varying degrees of wrinkling and sweetness with the golden-yellow being very sweet
	10	Soft light brown sweet	
	11	Small wrinkled light brown sweet	
	12	Small soft light brown	

with distilled water and further cleaned to remove pulp with the aid of a kitchen knife for the wrinkled firm variety, which exhibited the 'clingstone' characteristic, where pulp adheres to the seed strongly (Figure 1). After cleaning seeds were sun-dried to a constant weight for five days and the seed length, seed width and seed mass were measured.

Fig. 1. Seeds from *Ziziphus* spp. wrinkled firm variety fruit depicting 'clingstone' behaviour

Data analysis

Qualitative data analysis

Data from conversational interviews was analysed using selective coding, that is, focussing on core terms that described varieties and management of the fruit trees.

Calculation of derived parameters

Fruit and seed shape indices were calculated by dividing the lengths by their respective widths. Individual fruit mass was calculated by dividing the mass of fruits in each sub-sample by the number of fruits in that sub-sample. Fruit bulk density was calculated by dividing the mass of fruits in sub-sample by the volume of the beaker (650 cm^3). Percent pulp on a dry mass basis was calculated as:

Percent pulp = [((Mass of dry fruits – Mass of dry seeds)/Mass of dry fruits) × 100] [Eq. 1]

Statistical analysis

Variability of quantitative parameters was evaluated using descriptive statistics. Fruit mass, density, length, width and shape index; and seed mass, length, width, and arcsine-transformed percent pulp values, and shape index data for the 12 collections were subjected to ANOVA. Pearson correlation analysis was performed to establish the relation between fruit mass and, fruit and seed quantitative parameters. Fisher's LSD test was used to separate significantly different means at P = 0.05. Hierarchical cluster analysis was conducted using Ward's method and the Squared Euclidean distance. Cluster analysis was performed using z-scores for fruit mass, fruit length, fruit width, fruit shape index seed mass, seed length, seed width and seed shape index. All quantitative data analyses were performed using IBM SPSS for Windows Version 20.0.

Results and Discussion

Description of Ziziphus species varieties and agronomic practices

The local people identified three *Ziziphus* spp. varieties based on fruit morphology: wrinkled firm; hollow soft dark brown; and small golden-yellow sweet varieties (Table 1, Figure 2). The large wrinkled firm variety was perceived to have more pulp than other varieties and preferred for dry fruit consumption. Fruit wrinkling and firmness were regarded good quality indicators because they were linked to fruit filling, i.e. having more pulp. The hollow soft dark brown variety was the least preferred because it was regarded as having cavities in the fruit pulp. The small golden-yellow sweet variety was distinguished by its small size and colour. Whilst occurrence of small fruits in the other varieties was reported to be caused by water stress or tree ageing, fruits from this variety were reported to be 'genetically' small.

Some varieties were reported to cause discomfort in the form of sharp, pain in the teeth in response to acidity (dentin hypersensitivity). The wrinkled firm variety, varied in sweetness or sourness, the hollow-soft dark brown variety was generally reported to be sour whilst the small golden-yellow sweet variety was reported to be always sweet to very sweet.

All light brown to golden-yellow fruits were reported to be sweet regardless of variety. Fang *et al.* (2010) state that the colour of dried Chinese *Z. jujuba* is an important quality index; the darker the colour, the less the quality and market value. Due to the underdevelopment of *Ziziphus* fruits value chain in the Mid-Zambezi Valley, the importance of colour did not feature in this study but it could enhance acceptability of the small golden-yellow sweet collections to some users. For evaluated collections fruit colour differed among varieties as reported by local suppliers (Figure 2); wrinkled firm and hollow soft dark brown varieties varied from dark brown to reddish brown; whilst the small golden-yellow sweet variety was golden-yellow to light brown. Fruit skin texture varied from winkled in the wrinkled firm variety and some collections in the small golden-yellow sweet variety, to smooth in some collections in the small golden-yellow sweet variety and slightly smooth in the hollow soft dark brown variety (Figure 2). Fruit shapes in the wrinkled firm variety varied from oval, obovate, oblong, and round whilst those in the other two varieties were generally round. Fruit apex shapes were oblate and rounded in all varieties and fruit base shapes were mostly flattened in all varieties but there were some fruits with oval bases in the wrinkled firm variety and the hollow soft dark brown variety.

Fig. 2. *Ziziphus* fruit collections from three perceived varieties identified with the help of local suppliers in the Mid-Zambezi Valley

The wrinkled firm variety and wrinkled collections in the small golden-yellow sweet variety were firm whilst the hollow soft dark brown variety and non-wrinkled collections in the small golden-yellow sweet variety were soft. The hollow soft dark brown variety cracked when pressed between fingers creating a popping sound most of the times. These variations suggest that there could be at least three varieties as reported by local suppliers. Conversational interviews revealed that the only management practice that was implemented on *Ziziphus* trees was pruning to increase fruit size.

Quantitative characteristics of *Ziziphus* species fruits

The twelve collections depicted large variation for the major yield parameters, fruit mass and seed mass, coefficients of variation (CV) 56.6% and 49.2% respectively and moderately large variations for fruit length, fruit width, and seed length CV ≥ 25% (Table 2). The variations were also confirmed by cluster analysis, which showed existence of two divergent genotypes with sub-clusters (Figure 3). Clustering of the two clusters at a long genetic distance, ± 25, signifies large genetic divergence probably at species level. High fruit weight in *Ziziphus* plants is a supreme characteristic in breeding programmes Norouzi *et al.* (2017), but it can be affected by ecological conditions and cultivars (Riaz *et al.*, 2021). Therefore, differences in mass of fruits from similar geographical areas may be due to genotypic effects (Karadeniz, 2002). This implies that the large variations in fruit mass observed in this study may be due to genotypic variations among the collections supporting local suppliers' perceptions. Results from this study agree with previous studies on *Ziziphus* spp., which showed high genetic CVs in fruit mass (Norouzi *et al.*, 2017; Islam *et al.*, 2010).

Fruit density had a moderate CV of 15.1%. The densest collections from the wrinkled firm variety were 1.6 times denser than the least soft light brown sweet collection (Table 2). Coefficient of variation for percent pulp showed low variability (10.4%) being lowest in the small wrinkled light brown sweet collection (63.03%) and highest in the large soft dark brown collection (89.28%).

Fruit mass was positively related ($P<0.001$) to: fruit length, $r = 0.852$; fruit width, $r= 0.823$; seed mass, $r =0.941$; seed length, $r = 0.836$; and seed width, $r = 0.810$. Similarly seed mass was positively correlated with seed length, $r = 0.800$ and width, $r = 0.733$). High positive correlations of these traits with fruit mass implies that they may be suitable criteria for selecting *Ziziphus* genotypes for cultivation and breeding. Grygorieva *et al.* (2014) also obtained high correlations between the fruit mass and the fruit width ($r = 0.971$) and fruit mass and fruit length ($r = 0.771$).

Hurtado *et al.* (2012) highlighted the significance of investigating phenotypic diversity in determining uniqueness and distinctness of genotypes. Ward's method resulted in two clusters at a short genetic squared Euclidean distance of 6 (Figure 3) showing that within each cluster there are genetically related varieties with shared ancestry and adaptation to similar ecological conditions. Clustering of three wrinkled firm and two hollow soft dark brown collections into one cluster at a relatively short distance of 6 (Figure 3) suggests that part of the observed hollowness may be a physiological disorder. It is important to note that, although hollowness ("fruit shrink") is a genetic trait, in *Ziziphus* fruits it is generally considered a physiological disorder caused by poor ovule fertilization, high temperatures, drought, nutrient imbalance, or pests and diseases Kumar *et al.* (2015). Ranked using fruit (mass, length, width, density, percent pulp) and seed (mass, length, width) the large soft dark brown, large wrinkled firm sweet, and medium soft dark brown collections were the top three (Table 2).

Conclusion

Twelve collections of *Ziziphus* spp. fruits in three perceived varieties were evaluated quantitatively and qualitatively. The collections exhibited large variation in yield and quality parameters suggesting that there were genotypic variations. Cluster analysis separated the collections into two clusters at a relatively short Squared Euclidean distance of 6 that combine ±25, implying huge genotypic divergence suggesting that there could be two species in the area. Wrinkled firm and large soft dark brown collections depicted superior characteristics for yield components. The golden-yellow sweet variety exhibited inferior yield attributes but its unique colour may be desired in industrial production. Overall, this study provides a basis for selection of cultivars for cultivation but genetic studies will be required for fruit improvement.

Table 2. Measured quantitative characteristics of Ziziphus species fruits collected from the Mid-Zambezi Valley in northern Zimbabwe

Variety description	Collection identity	Description of fruits in sub-category (collection)	Mean fruit dimensions/ parameters (SD)[1]				Mean seed dimensions/ (SD)			
			Length (cm)	Width (cm)	Shape index	Mass (g)	Mass (g)	Length (cm)	Width (cm)	Shape index
Wrinkled firm	1	Large wrinkled firm sweet	2.07 (0.11)^{a}	1.81 (0.13)^{ac}	1.14 (0.05)^{ac}	2.33 (0.03)^{a}	0.52 (0.05)^{a}	1.27 (0.15)^{a}	0.61 (0.06)^{ac}	2.09 (0.28)^{aci}
	2	Large wrinkled firm	1.96 (0.18)^{a}	1.68 (0.20)^{ad}	1.18 (0.14)^{abd}	2.05 (0.09)^{b}	0.47 (0.02)^{a}	1.15 (0.15)^{bd}	0.62 (0.06)^{ac}	1.86 (0.29)^{abif}
	3	Medium wrinkled firm	1.72 (0.12)^{b}	1.38 (0.18)^{bf}	1.27 (0.20)^{d}	1.34 (0.02)^{c}	0.34 (0.03)^{b}	1.19 (0.11)^{ab}	0.56 (0.04)^{ab}	2.11 (0.14)^{cde}
	4	Small wrinkled firm	1.49 (0.15)^{c}	1.33 (0.10)^{bg}	1.12 (0.07)^{abe}	1.11 (0.10)^{d}	0.33 (0.03)^{b}	0.99 (0.05)^{c}	0.51 (0.07)^{bd}	1.92 (0.29)^{adf}
Hollow soft dark brown	5	Large soft dark brown	2.33 (0.11)^{d}	2.16 (0.10)^{e}	1.08 (0.03)^{abe}	2.57 (0.16)^{e}	0.56 (0.07)^{c}	1.06 (0.05)^{de}	0.66 (0.07)^{ce}	1.62 (0.166)^{bg}
	6	Medium soft dark brown	2.09 (0.51)^{a}	1.92 (0.40)^{c}	1.08 (0.07)^{abe}	1.68 (0.12)^{f}	0.41 (0.01)^{d}	1.03 (0.10)^{ce}	0.61 (0.05)^{ae}	1.69 (0.13)^{bfj}
	7	Small soft dark brown	1.65 (0.19)^{bc}	1.51 (0.23)^{dfg}	1.10 (0.12)^{abe}	1.21 (0.04)^{d}	0.15 (0.04)^{e}	0.98 (0.12)^{c}	0.52 (0.06)^{d}	1.91 (0.30)^{ef}
	8	Very small soft dark brown	1.51 (0.33)^{c}	1.40 (0.31)^{fg}	1.08 (0.09)^{abe}	0.78 (0.02)^{g}	0.22 (0.01)^{f}	0.80 (0.11)^{f}	0.50 (0.04)^{df}	1.64 (0.30)^{bk}
Small golden-yellow sweet	9	Wrinkled golden-yellow very sweet	1.15 (0.09)^{e}	1.08 (0.06)^{h}	1.07 (0.03)^{ce}	0.56 (0.00)^{h}	0.16 (0.01)^{ef3}	0.67 (0.07)^{gh}	0.46 (0.04)^{fh}	1.47 (0.09)^{gjkl}
	10	Soft light brown sweet	1.14 (0.08)^{e}	1.05 (0.06)^{h}	1.09 (0.10)^{abe}	0.56 (0.02)^{hi}	0.15 (0.01)^{ef}	0.57 (0.07)^{hi}	0.43 (0.06)^{gh}	1.35 (0.16)^{hl}
	11	Small wrinkled light brown sweet	1.22 (0.10)^{e}	1.10 (0.10)^{h}	1.11 (0.07)^{abe}	0.70 (0.04)^{gij}	0.20 (0.03)^{ef}	0.75 (0.10)^{fg}	0.47 (0.08)^{dh}	1.60 (0.21)^{gjk}
	12	Small soft light brown	1.24 (0.09)^{e}	1.12 (0.07)^{gh}	1.10 (0.11)^{abe}	0.63 (0.02)^{hj}	0.17 (0.02)^{ef}	0.68 (0.07)^{gi}	0.43 (0.07)^{h}	1.62 (0.24)^{gjk}
Coefficient of variation (%)			26.8	27.0	9.9	56.6	49.2	25.3	13.3	17.7

[1]Values in the same column with a common letter in the superscript are not significantly different ($P > 0.05$)

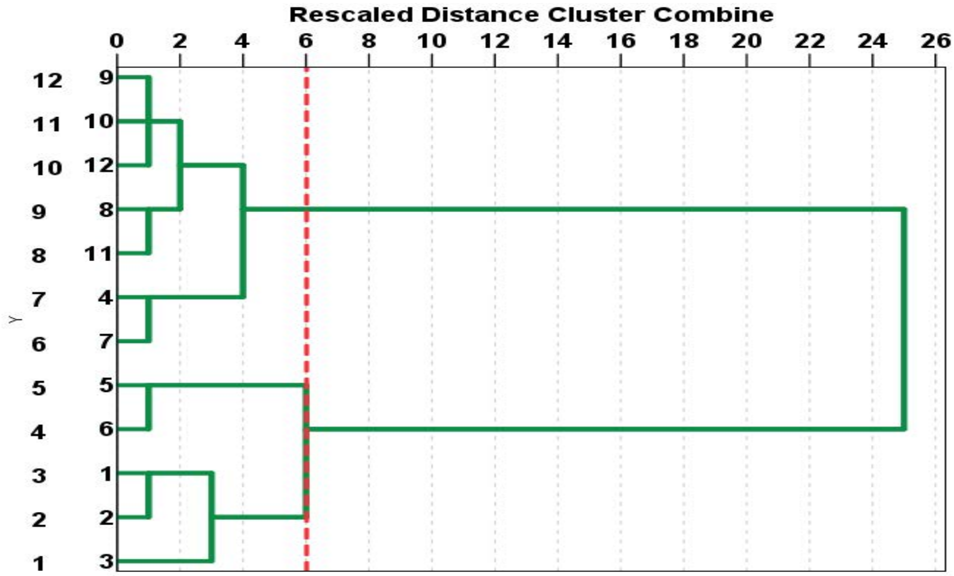

Fig. 3. Cluster analysis of 12 *Ziziphus* spp. collections based on fruit mass, length, width, shape index; and seed mass, length, width and shape index using squared Euclidean distances (1-Large wrinkled firm sweet, 2-Large wrinkled firm, 3-Medium wrinkled firm, 4-Small wrinkled firm, 5-Large soft dark brown, 6-Medium soft dark brown, 7-Small soft dark brown, 8-Very small soft dark brown, 9-Wrinkled golden-yellow very sweet, 10-Soft light brown sweet, 11-Small wrinkled light brown sweet, 12-Small soft light brown)

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Investigating the influence of pollen sources on fruit traits of date palm (*Phoenix dactylifera*) cv. Barhee in hot arid condition

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ABSTRACT

Date palm is a dioecious species thus the commercial cultivation of date palm depends on the efficient pollination process to achieve higher fruit set and quality. This research experiment was conducted at ICAR-Central Institute for Arid Horticulture, Bikaner during 2021 and 2022 to investigate the effects of different male date palm (M1, M2, M3 and Ghanami) on various fruit traits, yield and total soluble solids of date palm variety Barhee. Among the four pollen sources, M1 resulted in the highest number of berries per strand, lowest fruit drop percentage, maximum fruit bunch weight, fruit length, fruit width and yield. The TSS percentage was higher when pollens from M1 were used compared to others. The study suggests that the selection of pollen source plays a crucial role in determining the yield and quality of date palm variety Barhee. These findings can be useful for the cultivation and breeding of date palm trees, especially for improving fruit yield and quality.

Introduction

Date palm (*Phoenix dactylifera* L.) is a perpetual, diploid, monocotyledonous plant that exhibits dioecious characteristics (Zhao *et al.*, 2012). It possesses a total of 36 chromosomes, organized into 18 pairs (2n = 36). It is unisexual species with male and female inflorescences are located on distinct individual trees (Robinson *et al.*, 2012). The palm tree bears its inflorescences, commonly referred to as racemes, within the leaf axils near the trunk. These racemes are enclosed by a rigid casing known as a spathe, which unfolds upon the maturation of the inflorescence (Zaid and Arias-Jimenez, 2002). Male spathes emerge and open from December to March, releasing pollen, while female spathes open from January to late March (often around 7:00 AM). There is lack of synchronization in anthesis, which resulted in non-availability of pollen grain for pollination if the not stored (Iqbal *et al.*, 2004).

Pollen grains from male flowers, which are transferred to female palms, the process is known as pollination (Bekheet and Hanafy, 2011). Date palm pollination occurs both naturally—through insects and wind—and artificially, using methods such as placing pollen strands, dusting pollen, or suspending pollen. Date palm being dioecious in nature, the mechanical or hand pollination is essential for proper fruit set, as natural pollination through wind or insects is negligible (Saroj *et al.*, 2021). Artificial pollination using compatible pollen sources significantly enhances fruit set, ripening and quality in commercial date palm cultivation (Omar and El-Abd, 2014). The phenomenon of metaxenia, where pollen directly influences the physical and chemical properties of

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fruits, affects fruit ripening time, color, size, weight and seed characteristics (Al-Khalifah, 2006). Similarly, different male parent sources have been shown to directly affect date fruit quality. However, achieving high economic yields depends on a greater percentage of successful fruit setting, which is influenced by the effectiveness of pollination, pollen quality, pollination efficiency, timing, male-female compatibility and environmental factors such as temperature, irrigation, soil conditions and fertilization (Iqbal *et al*., 2012; Sharma *et al*., 2021).

Numerous studies have been conducted to evaluate the impact of various pollen sources on fruit characteristics and yield in order to determine the most suitable pollenizers for achieving optimal crop production and to assess the compatibility between different cultivars (Al-Khalifah, 2006; Al-Muhtaseb and Ghnaim, 2006; Shafique *et al*., 2011; Iqbal *et al*., 2012; Rezazadeh *et al*., 2013; Hafez *et al*., 2014 and Salomon-Torres *et al*., 2017). Considering the critical role of pollen in date palm cultivation, this study aims to assess how different pollen sources influence key fruit traits of cv. Barhee under hot arid conditions. The study seeks to determine the extent to which pollen from various male genotypes influences fruit set, fruit size, fruit quality parameters, and overall productivity. By understanding these pollen–parent effects, the research aims to identify the most suitable pollen sources capable of enhancing yield, improving fruit characteristics, and optimizing date palm production in arid environments.

Material and Methods

The endeavour of current study was to conclude the effects of four pollinizer sources (M1, M2, M3 and Ghanami) on the yield and physicochemical fruit characteristics of one date palm cultivar viz., Barhee at the ICAR-Central Institute for Arid Horticulture, Bikaner during 2021 and 2022 (Latitude 28o06'N and Longitude 73o20'E). Fifteen-year-old plants of cv. Barhee planted at a spacing of 8 m × 8 m were used as female parents. The experiment was conducted using a Randomized Block Design (RBD) with five replications. Five spathes of similar size from each palm, which had emerged and opened on the same date, were selected for data collection in each replication.

Male inflorescences were harvested immediately after the spathes opened naturally. They were carefully transported to a designated drying area, where the spathes were removed. Each inflorescence was individually suspended in a well-ventilated space for one week. Pollen was collected daily by gently shaking the inflorescences over a clean newspaper surface. The collected pollen was then stored at 4°C in airtight containers until use for pollination.

Each female plant was pollinated only once, using pollen from a single male parent. Female spathes were monitored for natural cracking and then manually opened. Pollination was performed between the second and fourth days after spathe opening to optimize receptivity. Manual pollination was achieved by dipping a small piece of sterile cotton into the stored pollen and gently inserting it into each female flower, ensuring direct contact with the stigma for effective pollen transfer. After pollination, the spathes were immediately covered with breathable brown paper bags to prevent contamination from wind- or insect-mediated natural pollination. The bags were removed once fruit set was confirmed (typically 10–14 days after pollination).

Among the different morphological traits, the number of berries per strand was determined by counting the total number of berries from five individual strands from each replication. Subsequently, the average number of berries per strand was calculated. Similarly, the percentage of fruit drop was determined by counting the number of scars per strand at three-week intervals for each tree and the average fruit drop percentage was calculated. The weight of the entire fruit bunch was measured after harvest using an electric weighing machine and expressed in kilograms (kg). To determine the total yield at harvest, each spathe was individually weighed using a weighing balance and expressed in kilograms (kg). Additionally, for each replication, 10 fruits were randomly selected from each strand and weighed to calculate the average fruit weight, which was expressed in grams (g). The pulp thickness of 10 representative fruits per replication was measured using a Vernier caliper and the average pulp thickness was calculated in millimetres (mm). Moreover, the seeds of the same selected fruits were weighed using an electronic balance and the average seed weight was calculated in grams (g). The length and width of the selected fruit seeds were measured using a vernier calliper and the average seed length and width were calculated in millimeters (mm). Finally, to measure the TSS, a digital refractometer (RX 5000, Atago, Japan) was used and the TSS was expressed in degree Brix (°Brix).

The collected data were subjected to statistical analysis using the method of analysis of variance (ANOVA) for a randomized block design (RBD), as described by Gomez and Gomez (1984).

Results and Discussion

Table 1 shows that the 'Barhee' cultivar, when pollinated with M1, exhibited significantly ($P \leq 0.05$) higher values for the number of strands per bunch (64.60), number of berries per strand (18.40) and bunch weight (4.74 kg). In contrast, pollination with M3 resulted in the lowest values for these traits, with strands per bunch (44.40), berries per strand (13.20) and bunch weight (2.70 kg). However, bunch per plant, stalk length, bunch length and strand length showed non-significant differences. According to Table 2, all pollen sources significantly affected fruit characteristics. Pollination with M1 the highest fruit weight (8.65 g), fruit length (27.46 mm) and fruit width (20.51 mm). Conversely, the lowest fruit weight (6.71 g) and fruit width (16.72 mm) were observed with M3, while the shortest fruit length (24.99 mm) was recorded with M2. Stone weight, stone length and stone width showed non-significant differences.

This phenomenon can be attributed to the metaxenia effect, where the growth of the ovarian tissues is influenced by the hormones released by the growing endosperm and embryo tissues, which are dependent on the pollen source. These hormones diffuse into the ovarian tissue and have a distinct impact on the growth of the fruit. These findings are consistent with Rezazadeh *et al*. (2013), who reported that different pollen sources had significant effects on marketable yield, with the best male pollens increasing the yield up to 41%. Similarly, (Iqbal *et al*., 2012) reported significant effects of different male pollen sources on different pomological traits and the economical yield index.

However, the statistical analysis showed non-significant effects for stone weight, stone length and stone width. Kumawat *et al*. (2022) also reported a non-significant difference in seed weight when pollen from various sources was used. Similarly, in the current experiment, comparable results were obtained. This may be attributed to the fact that the pollen sources employed in their study differed from those used in the present investigation. Consequently, the interactive effect of pollen from different cultivars may vary depending on the cultivars used as receivers. The data in Table 3 showed that the different pollen sources shows non-significant effects on per cent fruit drop and pulp thickness. The 'Barhee' exhibited the maximum (41.68°B) TSS when pollinated with M1, followed by M2 (41.40°B) and Ghanami (40.70°B) pollen source. Contrary to our research Salomon-Torres *et al*. (2017) found no significant variation in TSS in response to different pollen sources. The quality of the pollen, its germination rate and the growth of pollen tubes may also contribute to the differences in TSS content.

The variability in yield can be attributed to variations in the quality of the pollen source, its viability and the compatibility between male and female plants. The highest total yield (57.47 kg) was obtained in Barhee pollinated with the M1 (Table 3). The lowest total yield (48.33 kg) was obtained when pollinated with the M3 pollen. The quality of the pollen, its germination rate and the growth of pollen tubes may also contribute to the differences in yield.

Table 1. Effect of different pollen sources on bunch characteristic of variety Barhee

Barhee	Bunch/ plant	Stalk length (cm)	Bunch length (cm)	No. of strands/ bunch	Strand length (cm)	No. of berry/ strands	Bunch weight (kg)
M1	10.68	78.14	31.20	64.60	48.80	18.40	4.74
M2	10.30	74.14	29.00	60.20	48.00	15.60	3.40
M3	10.24	71.06	28.40	44.40	43.20	13.20	2.70
Ghanami	10.40	75.94	31.00	63.20	47.40	17.00	3.52
CD at 5%	NS	NS	NS	6.62	NS	2.24	0.98
SEm±	0.17	2.20	1.11	2.13	2.13	0.72	0.32
CV (%)	3.67	6.56	8.26	8.18	10.61	10.01	19.63

NS: Non-significant

Table 2. Effect of different pollen sources on fruiting characteristic of variety Barhee

Barhee	Fruit weight (g)	Fruit length (mm)	Fruit width (mm)	Stone weight (g)	Stone length (mm)	Stone width (mm)
M1	8.65	27.46	20.51	0.84	16.17	8.80
M2	7.54	24.99	17.16	0.66	16.12	7.43
M3	6.71	27.27	16.72	0.78	15.71	7.76
Ghanami	7.46	26.39	18.02	0.76	15.94	7.19
CD at 5%	0.60	1.51	1.54	NS	NS	NS
SEm±	0.19	0.48	0.50	0.06	0.53	0.44
CV (%)	5.71	4.08	6.11	16.63	7.39	12.70

NS: Non-significant

Table 3. Effect of different pollen sources on fruiting characteristic of variety Barhee

Barhee	Per cent fruit drop	TSS (°Brix)	Pulp thickness (mm)	Yield per plant (kg)
M1	35.10	41.68	6.14	57.47
M2	53.00	41.40	5.41	53.61
M3	53.70	36.28	5.24	48.33
Ghanami	39.36	40.70	5.51	55.09
CD at 5%	NS	1.21	NS	2.06
SEm±	7.27	0.39	0.26	0.66
CV (%)	35.91	2.18	10.22	2.76

NS: Non-significant

Conclusion

Based on the results it can be concluded that the choice of pollen source has a significant effect on the yield and quality of date fruit produced by Barhee cultivar. These results suggest that date palm growers should prioritize using pollen from reliable sources for pollinating their trees. The present study concluded that the pollen grains obtained from M1 exhibit superior results regarding fruit growth and quality characteristics. This can help to maximize yield and produce higher quality fruit, ultimately leading to increased profits for the growers. Overall, this study provides valuable information for date palm growers and researchers seeking to improve the productivity and quality of date palm. Further research could investigate the potential benefits of using pollen from promising male date palm genotypes to enhance both yield and fruit quality.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Characterisation of Indian jujube (*Ziziphus mauritiana* Lamk.) germplasm under semi-arid conditions

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ABSTRACT

A comprehensive characterization of 28 germplasm of Indian jujube (*Ziziphus mauritiana* Lamk.) was conducted for morphological traits of fruit and stone. Significant variability was observed in fruit shape apex and fruit colour at maturity. Twelve germplasm had round fruit apex and eleven germplasm exhibited pointed fruit apex, rest five showed flat apex of fruit. Fruit skin colour like yellow, light yellow, yellowish green, greenish yellow, light green with yellow shade, greenish, green, pale green, light green and mixture of greenish to yellowish was recorded. Most of germplasm (16) exhibited ridged and wart fruit surface and remaining had plain fruit surface. Germplasm Dandan, Safeda Selection, Rohtak Safeda, Seo, Hsaianaul, Katha Bombay, Thornless, Sanori and Kaithali had soft pulp texture whereas; Bawal Selection 1 and Umran had hard pulp texture. Remaining germplasm were grouped in medium soft pulp texture. Stone shapes further classified into oblong, oval, spindle, club, and falcate categories along with stone shape apex. Further the selected germplasm grouped as per DUS guidelines. Based on fruit shape, the maximum germplasm (10) fell in group of ovate fruit shape, followed by oval (eight germplasm) and had falcate (one germplasm). Similarly for pulp texture, most of germplasm (17) were grouped in medium pulp texture fruit. The two germplasm were grouped under hard pulp texture and rest of nine germplasm had soft pulp texture. Stone shape of fourteen germplasm fell in oval shape group, followed by club shape (five germplasm) and falcate, spindle, oblong group contain three germplasm in each. Wide variability was observed in various morphological traits and suggests differences in the evolutionary origins of these cultivars within the species.

Introduction

The Indian jujube (*Ziziphus mauritiana* Lamk.), commonly referred to as ber, pertains to the Rhamnaceae family and predominantly inhabits tropical regions spanning southern Asia, Africa, Australia and including Taiwan and China (Pasternak *et al.*, 2009). Ber is renowned for its exceptional climatic adaptability, it is used for multipurpose under arid to semi-arid areas, playing a pivotal role in mitigating soil erosion and desertification (Pareek, 2001). The *Jhar beri i.e. Z. mauritiana* exhibits resilience to drought, salinity,

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and desiccation (Grice, 1997). The ber tree contributes significantly to the sustenance of desert inhabitants by providing nutritious fruits for consumption, serving as an excellent agroforestry species, offering valuable fodder, and exhibiting medicinal properties. It is lauded as a "gift of mother nature" symbolizing the productive capacity of seemingly infertile ecosystems. Beyond its agricultural utility, the ber tree finds application in fencing, hedges, and windbreaks. The leaves are a staple in the diets of camels, cattle, sheep, and goats. Notably, the Indian jujube serves as a host for the lac insect *Kerria lacca*, and its leaves are utilized to feed tasar silkworms.

Ber fruits renowned for its nutritional and medicinal properties, its fruit surpasses the most preferred fruit apple in terms of vitamin C content, phosphorus, calcium, protein and carotene (Krishna *et al*., 2014) and exceeds oranges in phosphorus, iron, vitamin C and carbohydrate content (Krishna and Parashar, 2013). The fruits are acknowledged for their sedative, flavonoid, anti-cancer, tonic, wound-healing, and anti-asthmatic properties (Ashraf *et al*., 2015). Consequently, the Indian jujube is colloquially known as desert apple, Indian plum, or poor man's apple, earning the title "King of arid zone fruits" (Shoba and Bharati, 2007). Its remarkable characteristics designate it as a "Famine Reserve Fruit." Extracts from the fruits, leaves, and seeds exhibit antioxidant activity (Okala *et al*., 2014; Dahiru and Obidoa, 2007). Sadeghi (2015) observed antibacterial activity and nanoparticles of gold during synthesis from *Z. mauritiana* extracts.

Despite its historical significance, the ber fruit has witnessed diminished importance, gradually supplanted by costlier fruits such as apples, grapes, and strawberries. This underutilization is attributed to inadequate awareness, limited technological internention, and insufficient attention from the global scientific community. Recognizing the urgency, there is a compelling need to focus on ber improvement by augmenting, characterizing, evaluating germplasm, and incorporating it into breeding programs for enhanced productivity and superior fruit quality. The characterization and evaluation of *Z. mauritiana* germplasm predominantly rely on morphophysiological traits, with researchers utilizing morphological descriptors encompassing growth and fruiting habit to classify and distinguish various germplasm (Vashishtha, 2001 and Saran *et al*., 2006). The variability in the germplasm is employed to develop high yielding variety as most of the varieties are released as a seedling selection (Meghwal and Singh, 2024). The judicious selection of cultivars assumes paramount importance for success. Consequently, there is an imperative for the improvement of *Z. mauritiana* for fruit quality across diverse agro-ecological environments. This study aims to estimate the morphological characteristics of collected germplasm, identify unique traits for ber quality improvement.

Material and Methods

A total of 28 ber germplasm (Table 1) were evaluated at CCS Haryana Agricultural University, RRS, Bawal for two years (2020-21 and 2022-23). The experiment site located at latitude 28.1ºN, longitude 76.5ºE with the mean sea level height of 266 m in South - West part of Haryana. The semi-arid climate of this region is typical and distinguished by scorching, dry summers and chill winters. The experiment was laid out in randomized block design replicated thrice. Nine characters of germplasm were recorded as per the stage mentioned in the DUS guidelines (Anonymous, 2013). Observations on the mature fruit and stone parameters were recorded when fruit was ready for harvesting. Further, germplasm was grouped into different categories to assess the distinctiveness. Characteristics were observed by the jury members and these parameters were matched with the descriptors to know the variability among different germplasm. The characteristics used to group the germplasm/ varieties are fruit maturity group, mature fruit: shape, pulp texture and stone shape as described in DUS guideline.

Table 1. List of evaluated 28 ber germplasm

Dandan	Tasbtso	Jhajjar Special	Kathaphal
Gola Gurgaon	Hsaianaul	Thornless	Umran
Govindgarh Selection 3	Sandhura Narnaul	Vilati	Kaithali
Safeda Selection	Katha Bombay	Bawal Selection 1	Thar Sevika
Rohtak Safeda	Katha Gurgaon	Bawal Selection 2	Thar Bhubhraj
Bhadurgarhia	Narua	Illaichi	Narendra Ber Selection 1
Seo	Narkali	Sanori	Narendra Ber Selection 2

Results and Discussion

The Table 2 and Figure 1a, b, c) present a comprehensive analysis of various germplasm of Indian jujube, based on several morphological characteristics related to fruit and stone traits. Fruit of these ber germplasm varied in fruit shape apex, fruit shape, fruit colour, fruit surface, pulp texture, pulp cavity at stylar end and stem end, stone shape and shape of stone apex. As per DUS guideline, round fruit apex was noticed in Dandan, Gola Gurgaon, Safeda Selection, Rohtak Safeda, Bhadurgarhia, Hsaianaul, Katha Gurgaon, Narkali, Bawal Selection 1, Kathaphal, Umran, Narendra Ber Selection 2 while, it was pointed in Govindgarh Selection 3, Tasbtso, Sandhura Narnaul, Narua, Jhajjar Special, Thornless, Vilati, Sanori, Kaithali, Thar Sevika, Thar Bhubharaj germplasm. Germplasm Seo, Katha Bombay, Bawal Selection 2, Illaichi, Narendra Ber Selection 1 had flat fruit apex. Further it is clear from data that the shape of mature fruit varied significantly among ber germplasm. The oblong fruit shape was recorded in Bawal Selection 1, Bawal Selection 2, Umran, Narendra Ber Selection 2 while, oval fruit shape was found in Dandan, Gola Gurgaon, Bhadurgarhia, Seo, Hsaianaul, Narkali, Kathaphal, Narendra Ber Selection 1. Germplasm Govindgarh Selection 3, Tasbtso, Sandhura Narnaul, Jhajjar Special, Thornless, Vilati, Sanori, Kaithali, Thar Sevika, Thar Bhubharaj had ovate fruit shape. Further, Oblate and Falcate fruit shape was noticed in Rohatk Safeda, Illaichi and Narua, respectively. Safeda Selection, Katha Bombay, Katha Gurgaon exhibited round fruit shape.

The data presented in Table 2 and Figure 1 (a,b,c) showed variation in ripe fruit skin colour among the ber germplasm. Fruit skin colour like yellow, light yellow, yellowish green, greenish yellow, light green with yellow shade, greenish, green, pale green, light green and mixture of yellowish to greenish was recorded. This variation is mainly due to the prevailing agro-climatic condition during growing region, genetic inheritance of germplasm or may be due to fruits remained on the plant for a longer time to attain maturity/ ripening or due to more uptakes of nutrients, water and translocation of more photosynthates from source to sink (Patel *et al*., 1977). Differences in the fruit colour and fruit-bearing characteristics among various germplasm may be intrinsic traits of the germplasm itself (Krishna *et al*., 2016). Fruit surface was plain in most of the local germplasm except for Safeda Selection, Rohtak Safeda, Tasbtso, Sandhura Narnaul, Narua, Jhajjar Special, Umran, Kaithali, Bawal Selection 1, Bawal Selection 2, Narendra Ber Selection 1, Narendra Ber Selection 2, Thar Sevika, Thar Bhubharaj, had ridged and wart fruit surface on maturity. Similar results were also reported by Singh *et al*. (2019), Krishna *et al*. (2016), and Kumar *et al*. (2024) among different ber germplasm.

The germplasm namely Dandan, Safeda Selection, Rohtak Safeda, Seo, Hsaianaul, Katha Bombay, Thornless, Sanori and Kaithali had soft pulp texture whereas; Bawal Selection 1 and Umran had hard pulp texture. Remaining germplasm (Gola Gurgaon, Govindgarh Selection 3, Bhadurgarhia, Tasbtso, Sandhura Narnaul, Katha Gurgaon, Narua, Narkali, Jhajjar Special, Vilati, Bawal Selection 2, Illaichi, Narendra Ber Selection 1, Narendra Ber Selection 2, Kathaphal, Thar Sevika and Thar Bhubharaj) were grouped in medium soft pulp texture. The most of ber germplasm had pulp cavity at stylar end while, it was absent in Dandan, Gola Gurgaon, Safeda Selection, Hsaianaul, Katha Bombay, Narkali, Bawal Selection 1, Sanori, Kathaphal germplasm. Similarly, pulp cavity at stem end was present in Dandan, Gola Gurgaon, Govindgarh Selection 3, Safeda Selection, Rohtak Safeda, Bhadurgarhia, Tasbtso, Hsaianaul, Sandhura Narnaul, Narua, Narkali, Jhajjar Special, Thornless, Vilati, Bawal Selection 1, Bawal Selection 2, Sanori, Kathaphal, Umran, Kaithali, Narendra Ber Selection 1, Narendra Ber Selection 2, Thar Sevika, Thar Bhubharaj germplasm and it was absent in few germplasm i.e., Seo, Katha Bombay, Katha Gurgaon and Illaichi. These variations in various traits of fruit among the germplasm might be due to the genetic features of particular germplasm (Kumar *et al*., 2024).

Likewise fruit apex, the stone apex was recorded as acute in Dandan, Govindgarh Selection 3, Tasbtso, Sandhura Narnaul, Narkali, Jhajjar Special, Thornless, Vilati, Sanori, Umran, Kaithali, Thar Sevika, Thar Bhubharaj, Narendra Ber Selection 2 while, apex of stone was obtuse in Gola Gurgaon, Safeda Selection, Rohtak Safeda, Bhadurgarhia, Seo, Hsaianaul, Katha Bombay, Katha Gurgaon, Narua, Bawal Selection 1, Bawal Selection 2, Illaichi, Kathaphal, Narendra Ber Selection 1. Further, the oblong stone was noticed in Dandan, Narua, Kaithali while, most of germplasm exhibited oval stone shape i.e., Gola Gurgaon, Safeda Selection, Rohtak Safeda, Bhadurgarhia, Seo, Hsaianaul, Katha Bombay, Katha Gurgaon, Narkali, Bawal Selection 1, Bawal Selection 2, Illaichi, Sanori, Kathaphal. The club stone shape was found in Govindgarh Selection 3, Jhajjar Special, Thornless, Vilati, Umran. Further, falcate stone shape was noticed in Tasbtso, Sandhura Narnaul, Thar Sevika and spindle type stone was found in Narendra Ber Selection 1, Narendra Ber Selection 2, Thar Bhubharaj. The findings of this research are also confirmed by the earlier researchers (Singh *et al*., 2019; Krishna *et al*., 2016 and Kumar *et al*., 2024).

The data presented in Table 3 represents grouping of ber germplasm based on selected characteristics as per DUS guidelines. The diverse morphological characteristics among the cultivars highlight the rich genetic diversity within *Z. mauritiana*. This information is crucial for breeders and researchers in selecting appropriate cultivars for specific agro-ecological environments and for the improvement of ber quality. Further, the distinct characteristics observed in certain cultivars can guide breeding programs aimed at enhancing specific traits of interest.

Table 2. Variability in fruit and stone traits of ber germplasm

Germplam	Fruit shape apex	Mature fruit shape	Mature fruit colour	Fruit surface	Pulp texture	Pulp cavity stylar end	Pulp cavity stem end	Stone shape apex	Stone shape
Dandan	Round	Oval	Pale green	Plain	Soft	Absent	Present	Acute	Oblong
Gola Gurgaon	Round	Oval	Yellowish green	Plain	Medium soft	Absent	Present	Obtuse	Oval
Govindgarh Selection 3	Pointed	Ovate	Greenish yellow	Plain	Medium soft	Present	Present	Acute	Club
Safeda Selection	Round	Round	Light yellow	Ridged and wart	Soft	Absent	Present	Obtuse	Oval
Rohtak Safeda	Round	Oblate	Yellowish	Ridged and wart	Soft	Present	Present	Obtuse	Oval
Bhadurgarhia	Round	Oval	Yellowish green	Plain	Medium soft	Present	Present	Obtuse	Oval
Seo	Flat	Oval	Yellowish green	Plain	Soft	Present	Absent	Obtuse	Oval
Tasbtso	Pointed	Ovate	Light green with yellow shade	Ridged and wart	Medium soft	Present	Present	Acute	Falcate
Hsaianaul	Round	Oval	Yellowish	Plain	Soft	Absent	Present	Obtuse	Oval
Sandhura Nar-naul	Pointed	Ovate	Greenish	Ridged and wart	Medium soft	Present	Present	Acute	Falcate
Katha Bombay	Flat	Round	Yellowish green	Plain	Soft	Absent	Absent	Obtuse	Oval
Katha Gurgaon	Round	Round	Greenish yellow	Plain	Medium soft	Present	Absent	Obtuse	Oval
Narua	Pointed	Falcate	Greenish yellow	Ridged and wart	Medium soft	Present	Present	Obtuse	Oblong
Narkali	Round	Oval	Yellowish green	Plain	Medium soft	Absent	Present	Acute	Oval
Jhajjar Special	Pointed	Ovate	Greenish yellow	Ridged and wart	Medium soft	Present	Present	Acute	Club
Thornless	Pointed	Ovate	Yellowish green	Plain	Soft	Present	Present	Acute	Club
Vilati	Pointed	Ovate	Green	Plain	Medium soft	Present	Present	Acute	Club
Bawal Selection 1	Round	Oblong	Green	Ridged and wart	Hard	Absent	Present	Obtuse	Oval
Bawal Selection 2	Flat	Oblong	Green	Ridged and wart	Medium soft	Present	Present	Obtuse	Oval
Illaichi	Flat	Oblate	Yellowish green	Ridged and wart	Medium soft	Present	Absent	Obtuse	Oval
Sanori	Pointed	Ovate	Light green with yellow shade	Ridged and wart	Soft	Absent	Present	Acute	Oval

Kathaphal	Round	Oval	Reddish green	Plain	Medium soft	Absent	Present	Obtuse	Oval
Umran	Round	Oblong	Pale green	Ridged and wart	Hard	Present	Present	Acute	Club
Kaithali	Pointed	Ovate	Yellowish green	Ridged and wart	Soft	Present	Present	Acute	Oblong
Thar Sevika	Pointed	Ovate	Green light	Ridged and wart	Medium soft	Present	Present	Acute	Falcate
Thar Bhubhraj	Pointed	Ovate	Greenish	Ridged and wart	Medium soft	Present	Present	Acute	Spindle
Narendra Ber Selection 1	Flat	Oval	Light green	Ridged and wart	Medium soft	Absent	Present	Obtuse	Spindle
Narendra Ber Selection 2	Round	Oblong	Yellowish green	Ridged and wart	Medium soft	Present	Present	Acute	Spindle

Table 3. Grouping of ber germplasm based on selected characteristics

Characters	Expression and Notes	No. of germplasm	Germplasm
Mature fruit: Shape	Oblong (1)	4	Bawal Selection 1, Bawal Selection 2, Umran, Narendra Ber Selection 2
	Oval (2)	8	Dandan, Gola Gurgaon, Bhadurgarhia, Seo, Hsaianaul, Narkali, Kathaphal, Narendra Ber Selection 1
	Ovate (3)	10	Govindgarh Selection 3, Tasbtso, Sandhura Narnaul, Jhajjar Special, Thornless, Vilati, Sanori, Kaithali, Thar Sevika, Thar Bhubharaj
	Oblate (4)	2	Rohatk Safeda, Illaichi
	Round (5)	3	Safeda Selection, Katha Bombay, Katha Gurgaon
	Falcate (6)	1	Narua
Pulp texture	Soft (3)	9	Dandan, Safeda Selection, Rohtak Safeda, Seo, Hsaianaul, Katha Bombay, Thornless, Sanori, Kaithali
	Medium (5)	17	Gola Gurgaon, Govindgarh Selection 3, Bhadurgarhia, Tasbtso, Sandhura Narnaul, Katha Gurgaon, Narua, Narkali, Jhajjar Special, Vilati, Bawal Selection 2, Kathaphal, Illaichi, Thar Sevika, Thar Bhubharaj, Narendra Ber Selection 1, Narendra Ber Selection 2
	Hard (7)	2	Bawal Selection 1, Umran
Stone shape	Oblong (1)	3	Dandan, Narua, Kaithali
	Oval (2)	14	Gola Gurgaon, Safeda Selection, Rohtak Safeda, Bhadurgarhia, Seo, Hsaianaul, Katha Bombay, Katha Gurgaon, Narkali, Bawal Selection 1, Bawal Selection 2, Illaichi, Sanori, Kathaphal
	Spindle (3)	3	Thar Bhubharaj, Narendra Ber Selection 1, Narendra Ber Selection 2
	Club (4)	5	Govindgarh Selection 3, Jhajjar Special, Thornless, Vilati, Umran
	Falcate (5)	3	Tasbtso, Sandhura Narnaul, Thar Sevika

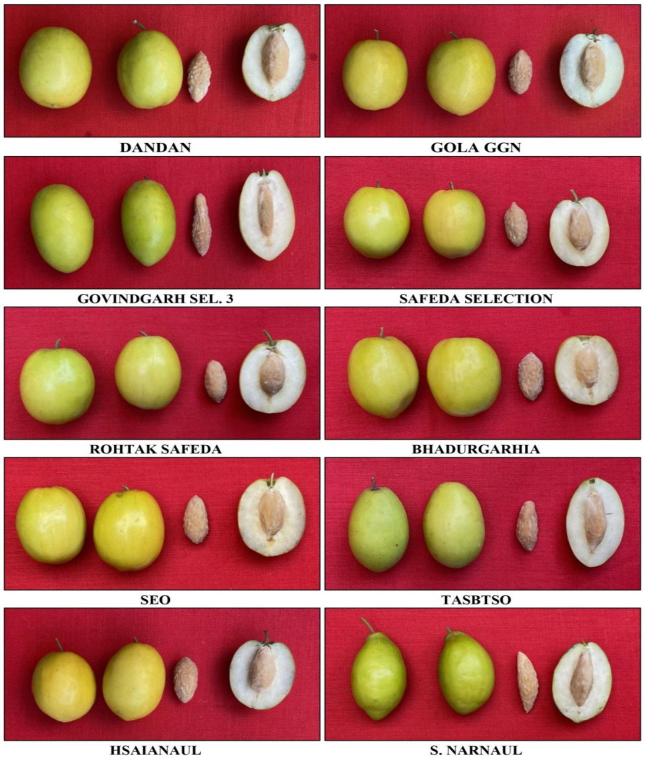

Fig. 1a. Divergence in the morphological characteristics of the ber germplasm

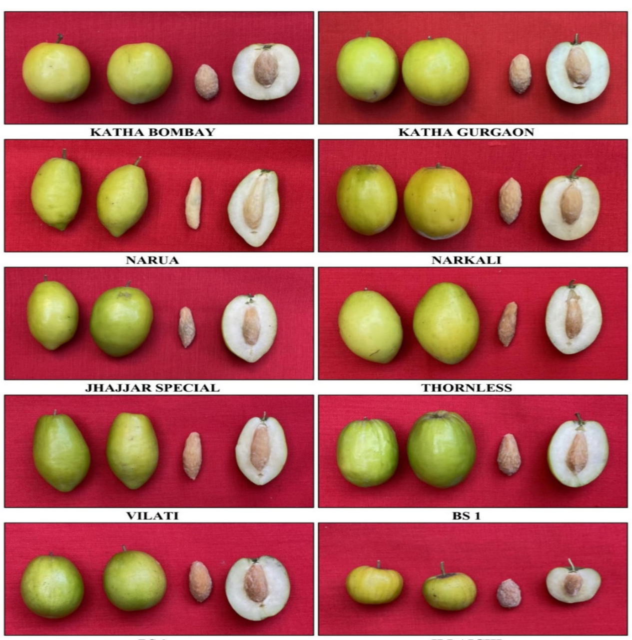

Fig. 1b. Divergence in the morphological characteristics of the ber germplasm

Fig. 1c. Divergence in the morphological characteristics of the ber germplasm

Conclusion

The morphological characterization of Indian jujube (*Ziziphus mauritiana* Lamk.) germplasm revealed significant variation in fruit and stone traits, including fruit shape, colour, surface, pulp texture, and cavity presence, as well as stone shape and apex type. These differences, influenced by genetic and environmental factors, highlight the rich genetic diversity within the species. Such variability is essential for cultivar identification, selection, and breeding programs aimed at trait improvement and suitability to specific agro-climatic conditions, in accordance with DUS guidelines.

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Studies on standardization of organic production technology for Aloe (*Aloe barbadensis*) cultivation in semi-arid region

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ABSTRACT

This present study was conducted to standardize the nutrient requirement of plant through different organic sources for optimum growth and yield and quality of Aloe (*Aloe barbadensis* Mill.) plant during 2018-19 and 2019-20 at CCS HAU, Hisar for cultivation under arid and semi-arid conditions of Haryana. Results achieved during 2018-19, revealed that maximum plant height (59.70 cm), suckers per plant (4.50); numbers of leaves per plant (10.35) and leaf length (47.40 cm) were recorded in T_5 (Vermicompost 7.5 t ha^{-1}) which was significantly higher than treatments T_1 (Control) and T_6 (Neem cake 1.5 t ha^{-1}). However, leaf yield and gel yield were found highest in T_5 (36667 & 20449 kg ha^{-1}, respectively) that was statistically superior with rest of treatments except T_3 and T_7. Likewise, the results achieved during 2019-20, revealed that maximum plant height (59.1 cm), suckers per plant (4.0), numbers of leaves per plant (10.80) and leaf length (57.6 cm) were registered with T_5 which was significantly higher than treatments T_1 and T_6. However, leaf yield was found significantly higher with T_5 (83117 kg/ha) that was statistically at par with T_3 and T_4. Gel yield was found significantly higher with T_5 (43377 kg/ha) that was statistically at par with T_3. Therefore, application of vermicompost 7.5 t ha^{-1} is recommended in aloe for commercial cultivation under arid and semi-arid region of Haryana.

Introduction

The demand of organic medicinal products is increasing over the year throughout the world after the COVID 19. The increasing demand of the medicinal plant-based products converts the traditional cropping to the high value medicinal cropping by marginal and low land holding farmers. It is requirement of the time to develop the suitable organic farming model or package of practice for emerging medicinal crop specially without application of chemicals and to motivate the farmers for adoption of such crops in a sustainable manner (Arya *et al*., 2021a).

Aloe (*Aloe barbadensis* Mill.) is also called as “Ghrith Kumari” in Hindi. It is an evergreen xerophytic perennial, CAM plant. (Liu *et al*., 2011; Silva *et al*., 2014). It originated from southern Africa, (Zheng *et al*., 2005). It found as well adapted in almost all part of India (Kiran and Tirkey, 2018). In India, this crop is adopted in different states of the country such as Rajasthan, Gujarat, Andhra Pradesh, Maharashtra Tamil Nadu and Himachal Pradesh. *Aloe vera* contains so many active constituents like minerals, vitamins, sugars, enzymes, saponins, lignin, amino acids and salicylic acids (Atherton, 1998). This crop is specially known for its use in beauty, heath and skin care products (Liu *et al*., 2011). This crop is not much adopted so the data on area and production is not available but the production of *Aloe vera* is about 294 q/ ha with gross return Rs 140536/ ha and net return Rs. 64708/- ha (Thakur *et al*., 2023).

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It is an important medicinal plant which has an enormous demand in food, medicinal, and cosmetic industries (Alagukannan and Ganesh, 2016). As aloe has therapeutic, cosmetic and nutraceutical properties. The dried latex of aloe known as aloin, it is laxative in nature. The gel obtained from aloe is widely used in cosmetic industry as a skin care product (Rajeswari *et al*., 2012). It is utilized to sooth the rashes, insect bites, burn pains and other skin irritations (Reddy *et al*., 2011; Arya *et al*., 2021b).

It is a well-known fact that chemical constituents of medicinal plants do not have any kind of side effect or adverse effect on health and environment (Heywood, 2002). The aloe crop is adaptable to the wide range of climatic conditions, the aloe germplam or accession have variability in genetic constituents as well as medicinal properties (Deore and Samantaray, 2015; Rana and Kanwar, 2017; Arya *et al*., 2021c). Keeping these aspects in view, the proposed study was undertaken to standardize organic production technology for cultivation of aloe specially under arid and semi-arid conditions of Haryana.

Material and Methods

In present investigation, eight different treatments were applied to aloe (*Aloe barbadensis* Mill.) genotype HAV-05-8 during 2018-19 and 2019-20 in the experimental area of the Medicinal and aromatic plants, Department of Genetics & Plant Breeding, CCS HAU, Hisar which is located 29° 10' N latitude and 75° 46' E longitude with the elevation from mean sea level 215.2m. The soil type of the experimental location was found sandy loam (Typic Ustochrepts), it contains medium range of organic carbon (0.046%), available N (191 kg/ha) and P (14 kg/ha), whereas high range of available potassium (340 kg/ha). Weekly weather parameters data recorded from Research Farm of CCS Haryana Agricultural University, Hisar during year 2018-19 and 2019-20 given in Fig. 1 & 2. Field experiment was conducted with eight different sources and levels of nutrient {T_1- Control, T_2- FYM 10 t ha^{-1}, T_3- FYM 15 t ha^{-1}, T_4- Vermicompost 5 t ha^{-1}, T_5- Vermicompost 7.5 t ha^{-1}, T_6- Neem cake 1.5 t ha^{-1}, T_7- Neem cake 2.5 t ha^{-1} and T_8- NPK (50:50:50 kg ha^{-1}) through inorganic fertilizers}to standardize the requirement of organic manures for proper growth, economical yield and quality of aloe. The experiment was laid out in RBD design with 4 replications at research farm, MAP Section, CCS HAU Hisar with plot size 4.8 × 2.7 m^2 and plant spacing was 60 cm x 45 cm. All the recommended package of practices was followed to raise a good healthy crop. The planting of crop was done by transplanting the suckers during June 2017. As this crop takes time to establish due to its slow growing nature, therefore, harvesting of leaves was started from next season. The plant observations for plant height (cm), number of leaves / plant, leaf length (cm), leaf width (cm), fresh leaf yield (q/ha) and gel (Mucilage) content (%) were recorded during both the years from each replication of randomly selected plants. The data was analyzed statistically as per standard procedure to compare the level of significance of data.

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Results and Discussion

Field experiment was conducted to standardize organic production technology for cultivation of *Aloe barbadensis* for better performance of plant and higher economic yield contributing traits and economical yield of aloe. The results of present experiment are presented and discussed under following sub-headings:

Growth contributing characters

Results achieved during 2018-19, revealed that maximum plant height (59.7 cm), suckers per plant (4.5), were observed in T_5 which was significantly higher than treatments T_1 and T_6 (Table 1-4). Results achieved during 2019-20, presented in Tables 1-4 revealed that maximum plant height (59.1 cm), suckers per plant (4.0), were obtained in T_5 which was significantly higher than treatments T_1 and T_6. However, the results achieved during 2018-19, revealed that maximum leaf width was observed in T_5 (6.92cm) followed by T_3 (6.85cm) and T_4 (6.84cm) but there was no significant difference. Results achieved during 2019-20, revealed that maximum leaf width was observed in T_5 (7.80cm), T_3 (7.80cm) and T_4 (7.80cm) but statistically there was no difference.

The results based on average basis of both the years also presented in (Table 1) revealed that maximum plant height (59.40 cm); suckers per plant (4.25) were observed with T_5 which was significantly higher than treatments T_1 and T_6. Application of 7.5 t ha^{-1} vermicompost recorded significantly higher plant height and number of suckers. The organic manures not only supply the nutrients to the plants but also enhance the fertility status, water holding capacity, availability of nutrients for better growth of the plants. According to Alagukannan *et al*., 2008, the plants which received more levels of vermicompost produce active substances more than those receiving lower levels of vermicompost. Higher levels of vermicompost lead to the increase in alkaloid production in the leaves, it enhances the active substances. Organic manures increased the availability of major and minor nutrients and also improves biological properties of the soil, which ultimately enhance the growth and yield of the plant. Shams *et al*., (2012) found the similar results of increasing fresh weight of Matricaria chamomile due to the combination of organic and chemical fertilizer. Kumar *et al*., (2006) observed the increase in growth and flower yield of marigold with the application of vermicompost as N source.

Yield contributing characters

The means values of both the years also presented in (Tables 2 & 3) revealed that maximum leaf length (52.50 cm); leaf width (7.36); numbers of leaves per plant (10.58) were observed in T_5 which was significantly higher than T_1 and T_6 treatments. Alam *et al*., 2007 found the similar results in red amaranth (A. tricolor) i.e. plant vigour, leaf number, length and breath, stem length and breath, weight of the plant, percentage of dry matter of plant and yield with the application of vermicompost in combination with inorganic fertilizers. In brinjal and tomato also observed maximum leaf number by application of vermicompost (Garg and Bhardwaj, 2000; Rajkumar *et al*., 2006). Kumar *et al*., (2007) observed that application of N thorough organic sources increased yield, nutrients and chlorophyll content of marigold. The organic manure in the soil is gradually discharged through mineralization to maintain the supply of nutrients to the plant for prolonged period resulted in increase in plant weight, leaf weight and leaf thickness. The increase in uptake or availability of nutrients enhance the biological weight or over all yield of the plant.

Leaf yield and gel yield

Results achieved during 2018-19, revealed that, leaf yield and gel yield were found highest in T_5 (36667 & 20449 kg ha^{-1}, respectively) that was statistically superior with rest of treatments except T_3 and T_7 (Table 3-4, Fig. 1). Results achieved during 2019-20**,** observed that, leaf yield was found significantly higher with T_5 (83117 kg/ha) that was statistically at par with T_3 & T_4. In similar way, gel yield was found significantly higher with T_5 (43377 kg/ha) that was statistically at par with T_3. Plant height, number of suckers, leaf weight and leaf length have strong and positive correlation with the gel yield. The increase in growth parameters resulted in increased production of gel (Fig. 2).

However, the results based on average of both the years presented in Tables 3-4, showed that leaf yield was found significantly higher with T_5 (59892 kg/ha) that was statistically at par with T_3 & T_4. Gel yield was found significantly higher with T_5 (31913 kg/ha) that was statistically at par with T_3. Using manure was most effective in increasing leaf weight per plant was supported by findings of Saha *et al*. (2005). Data on growth and production of *Aloe vera* with the application of different levels of vermicompost and nitrogen fertilizer as analyzed by Nejatzadeh (2019). He revealed the similar results with the application of vermicompost and nitrogen fertilizer in *Aloe vera* cultivation. Vermicompost plays an important role in the production and enhancement of sucker and plant yield mentioned. Integrated nutrient management increase the growth and yield of cumin (Kumar *et al*., 2025). However, Rao *et al*., (2024) observed best growth, yield and quality of carrot with the application of poultry manure @ 4t/ha + $ZnSO_4$ @ 0.75 %.

Table 1. Plant growth and number of suckers per plant under different organic practices

Treatments	Plant height (cm)			No. of suckers/ plant		
	2018-19	2019-20	Mean	2018-19	2019-20	Mean
T_1- Control	49.30	52.80	51.05	3.00	3.15	3.08
T_2- FYM 10 t ha^{-1}	56.60	54.70	55.65	4.25	3.35	3.80
T_3- FYM 15 t ha^{-1}	59.00	57.40	58.20	4.25	3.90	4.08
T_4- Vermicompost 5 t ha^{-1}	58.00	56.50	57.25	4.25	3.60	3.93
T_5- Vermicompost 7.5 t ha^{-1}	59.70	59.10	59.40	4.50	4.00	4.25
T_6- Neem cake 1.5 t ha^{-1}	54.20	54.50	54.35	3.25	3.50	3.38
T_7- Neem cake 2.5 t ha^{-1}	57.20	56.30	56.75	4.25	3.55	3.90
T_8- NPK (50:50:50 kg ha^{-1})	56.00	55.10	55.55	4.25	3.45	3.85
SEm±	1.59	0.88		0.33	0.13	
CD (5%)	4.72	2.60		0.98	0.38	

Table 2. Effect of organic manures on performance of leaf length and width

Treatments	Leaf length (cm)			Leaf width (cm)		
	2018-19	2019-20	Mean	2018-19	2019-20	Mean
T_1- Control	40.40	47.50	43.95	6.65	7.30	6.98
T_2- FYM 10 t ha^{-1}	41.90	54.60	48.25	6.70	7.50	7.10
T_3- FYM 15 t ha^{-1}	46.00	57.00	51.50	6.85	7.80	7.33
T_4- Vermicompost 5 t ha^{-1}	43.90	56.00	49.95	6.84	7.80	7.32
T_5- Vermicompost 7.5 t ha^{-1}	47.40	57.60	52.50	6.92	7.80	7.36
T_6- Neem cake 1.5 t ha^{-1}	41.60	52.30	46.95	6.69	7.30	7.00
T_7- Neem cake 2.5 t ha^{-1}	43.20	55.20	49.20	6.82	7.60	7.21
T_8- NPK (50:50:50 kg ha^{-1})	42.50	54.10	48.30	6.73	7.50	7.12
SEm±	0.90	1.40		0.21	0.10	
CD (5%)	2.92	4.16		NS	NS	

Table 3. Effect of organic organic manures on number of leaves per plant and leaf yield

Treatments	Number of leaves/ plant			Leaf yield (kg/ha)		
	2018-19	2019-20	Mean	2018-19	2019-20	Mean
T_1- Control	9.60	9.00	9.30	22815	65780	44298
T_2- FYM 10 t ha^{-1}	9.75	10.00	9.88	33659	74040	53850
T_3- FYM 15 t ha^{-1}	10.30	10.70	10.50	35093	80382	57738
T_4- Vermicompost 5 t ha^{-1}	10.25	10.50	10.38	34015	77676	55846
T_5- Vermicompost 7.5 t ha^{-1}	10.35	10.80	10.58	36667	83117	59892
T_6- Neem cake 1.5 t ha^{-1}	9.70	9.90	9.80	24818	70986	47902
T_7- Neem cake 2.5 t ha^{-1}	9.95	10.20	10.08	35000	74470	54735
T_8- NPK (50:50:50 kg ha^{-1})	9.90	10.10	10.00	34280	73153	53717
SEm±	0.16	0.26		792	2352	
CD (5%)	0.47	0.76		2346	6966	

Table 4. Effect of organic manures on gel yield (kg/ha) and percent gel content

Treatments	Gel yield (kg/ha)			Percent gel content		
	2018-19	2019-20	Mean	2018-19	2019-20	Mean
T_1- Control	12210	31558	21884	53.52	47.98	50.75
T_2- FYM 10 t ha^{-1}	17213	33812	25512	51.14	45.67	48.40
T_3- FYM 15 t ha^{-1}	18881	39624	29252	53.80	49.29	51.55
T_4- Vermicompost 5 t ha^{-1}	18584	34991	26787	54.63	45.05	49.84
T_5- Vermicompost 7.5 t ha^{-1}	20449	43377	31913	55.77	52.19	53.98
T_6- Neem cake 1.5 t ha^{-1}	14573	33471	24022	58.72	47.15	52.94
T_7- Neem cake 2.5 t ha^{-1}	18889	34397	26643	53.97	46.19	50.08
T_8- NPK (50:50:50 kg ha^{-1})	17586	33109	25347	51.30	45.26	48.28
SEm±	548	2124		-	-	
CD (5%)	1623	6290		-	-	

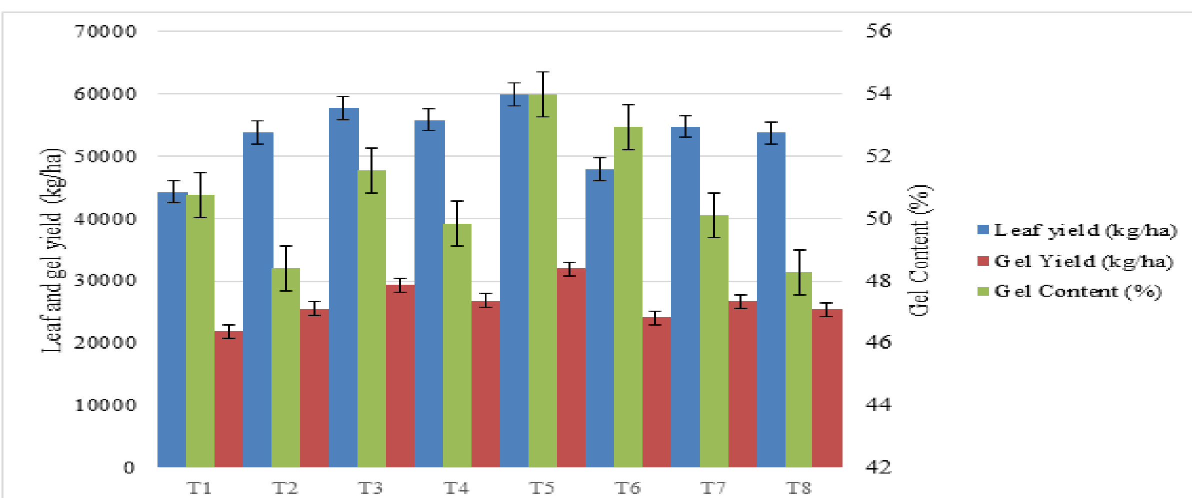
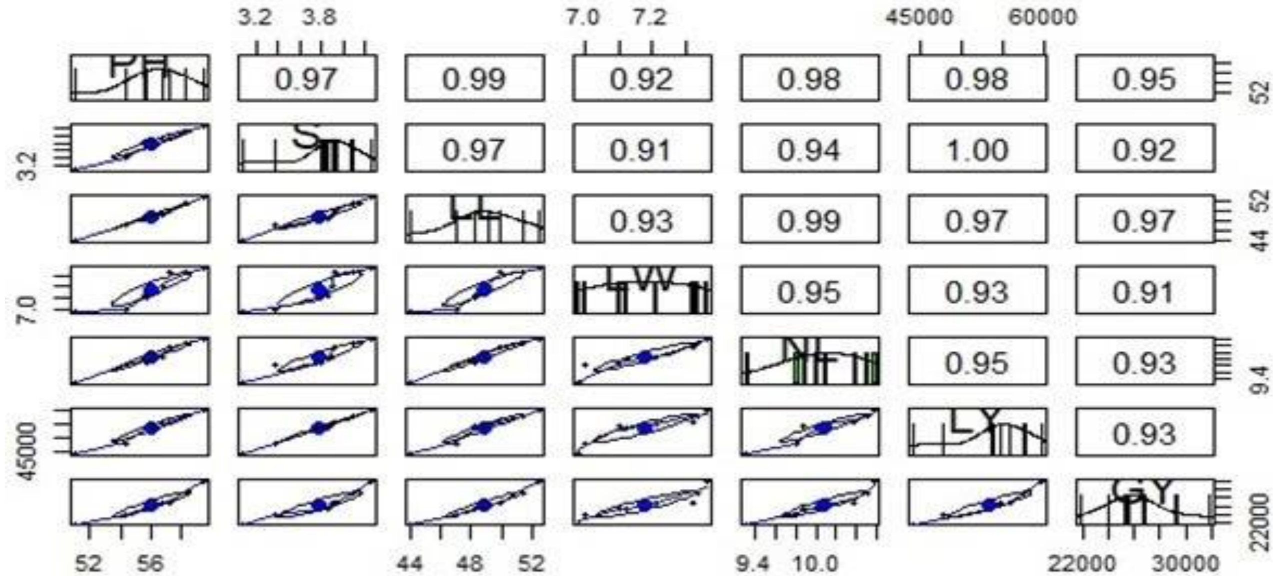


Fig. 1. Bar graphs of leaf yield, gel yield and gel content



Note: PH- Plant height, S- Number of suckers, LL- leaf length, LW -Leaf weight, GY- Gel yield

Fig. 2. Pearson correlation of different growth parameters for gel yield

Conclusions

It was concluded from the study that the application of vermicompost @ 7.5 t ha^{-1} had significantly enhanced the plant height, suckers per plant, numbers of leaves per plant and leave length of *Aloe vera*. Leaf yield was also found significantly higher with vermicompost @ 7.5 t ha^{-1} (59892 kg/ha) which was statistically at par with T_3 & T_4. Likewise, gel yield was also found significantly higher with T_5 (31913 kg/ha) that was statistically at par with T_3. Therefore, application of vermicompost 7.5 t ha^{-1} is recommended for commercial cultivation of aloe under arid and semi-arid region of Haryana.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Assessing drought resilience through morphological adaptations and survivability of citrus rootstocks

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ABSTRACT

Understanding rootstock-specific morphological responses is key to selecting resilient genotypes for water-limited orchards. A controlled pot experiment was conducted during the year 2024–25 at Banda University of Agriculture and Technology, Banda, using seven citrus rootstocks (Rangpur lime, Cleopatra mandarin, Rough lemon, Sour orange, NRCC RS-3, RS-4, RS-6) subjected to four water stress levels (control, 0.4, 0.6, and 0.8 bar) for 240 days. Plant mortality increased with stress, reaching 55.16% at 0.8 bar, with Cleopatra mandarin showing the highest mortality at 88.89%. Compared to the control, plant height, stem diameter, leaf number, leaf area, and root length declined by 26.1%, 26.3%, 46.8%, 15%, and 32%, respectively, at 0.8 bar. Rough lemon and Rangpur lime performed better, maintaining heights of 56.24 cm and 54.02 cm, leaf areas of 25.57 cm² and 23.64 cm², and root lengths of 28.02 cm and 25.94 cm. Significant interactions were noted in canopy traits, with Rough lemon having the highest leaf number (127.58) and minimal loss (45.9%), while Cleopatra mandarin showed the greatest canopy reduction (52.5% leaf loss). Although root length interactions were non-significant, Rough lemon had the least reduction (27.8%) under stress, indicating strong root plasticity. Rough lemon, Sour orange, and Rangpur lime exhibited superior drought resilience through greater canopy retention and root plasticity. These rootstocks are promising candidates for improving drought tolerance and sustaining productivity in water-limited citrus orchards.

Introduction

Citrus is one of the most important fruit crops worldwide, cultivated in over 140 countries and contributing significantly to global fruit production, trade, and rural livelihoods. However, citrus production is highly vulnerable to abiotic stresses, particularly drought, which has a devastating impact on plant growth, development, and fruit yield and quality (Wu *et al.*, 2013; Modica *et al.*, 2025). Severe water stress during the developmental stage can lead to fruit drop and produce lower-quality fruits due to increased evapotranspiration losses. Climate change is intensifying drought frequency and severity, further challenging citrus productivity in water-limited regions (Hayat *et al.*, 2022).

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Additionally, drought creates an imbalance between root water uptake and water loss through transpiration, resulting in dehydration and further reducing photosynthetic rates (Garcia-Sanchez *et al.*, 2007; Arbona *et al.*, 2005). These factors significantly impact citrus production, particularly in developing countries. Rootstock selection is a key strategy to mitigate drought effects because rootstocks differ in root architecture, hydraulic conductance, and hormonal signalling that regulate water uptake and stomatal control (Santana-Vieira *et al.*, 2016; Balfagón *et al.*, 2022). Studies have shown that drought-tolerant rootstocks maintain higher relative water content and membrane stability efficiently, thereby supporting better scion growth and yield under water stress (Morade *et al.*, 2025). As a result, plant breeders aim to develop rootstocks that exhibit high water-use efficiency to mitigate the effects of climate change on crop production (Berdeja *et al.*, 2015). These rootstocks are designed to enhance survivability and promote sustainable growth, providing resistance for citrus crops against both biotic and abiotic stresses (Garcia-Sanchez *et al.*, 2007; Rodriguez-Gamir *et al.*, 2010). This study evaluates the response of multiple citrus rootstocks under controlled water-deficit conditions to identify genotypes with superior drought tolerance and to improve rootstock recommendations for sustainable citrus production.

Material and Methods

The present investigation was conducted during the years 2024–2025 at the Hi-Tech Nursery of Banda Agriculture and Technology in Banda, Uttar Pradesh. This study involved seven rootstocks and four levels of water stress, replicated three times using a factorial completely randomised design (CRD). The seven rootstocks used were Rangpur lime (*Citrus limonia* Osbeck), Cleopatra mandarin (*Citrus reshni* Tanaka), Rough lemon (*Citrus jambhiri* Lush.), Sour orange (*Citrus aurantium* L.), NRCC RS-3 (Rough lemon × Troyer citrange), NRCC RS-4 (Rough lemon × Trifoliate orange), and NRCC RS-6 (Rough lemon × Trifoliate orange). The water stress levels were classified as control (at field capacity level), 0.4 bar, 0.6 bar, and 0.8 bar soil moisture tensions. A tensiometer was used to ensure that the moisture levels were consistently monitored and maintained throughout the study.

Seeds of the rootstocks were collected from ICAR-CCRI in Nagpur, ICAR-IARI in New Delhi, ARS in Sri Ganganagar, Rajasthan, and the Department of Fruit Science, Banda University of Agriculture and Technology, Banda, U.P. and then sown in nursery beds at the Hi-Tech nursery. One-month-old seedlings were transplanted into polybags. At 11 months of age, these seedlings were further transplanted into plastic pots (each with a soil capacity of 10 kg) and placed in a net house for establishment.

After 240 days of irrigation with different water stress treatments, various measurements were taken, including plant mortality (%), plant height (cm), stem diameter (mm), number of leaves, number of shoots, leaf area (cm^2), and root length (cm). Plant mortality percentage was calculated as the proportion of dead plants. Plant height was measured from the soil surface to the apex of the plant using a meter scale, while stem diameter was assessed with Vernier callipers at 5.0 cm above the soil surface on representative plants. Leaf area was recorded using a leaf area meter, and root length was measured with a meter scale at the end of the experiment.

The collected data were analysed using a two-factor analysis within a completely randomised design (CRD) with three replications, and a critical difference (CD) was calculated at a 5% probability level. Statistical analysis was conducted using OP Stat software, provided by CCS Haryana Agricultural University, Hisar, Haryana (Sheoran *et al.*, 1998).

Results and Discussion

***Plant mortality (%)*:** Plant mortality significantly increased with rising levels of water stress across all citrus rootstocks (Table 1). No mortality was observed under control conditions, while the maximum mortality rate of 55.16% was recorded under 0.8 bar of stress. Cleopatra mandarin exhibited the highest average mortality at 39.17%, followed by NRCC RS-4 at 35.97%, while Rough lemon had the lowest mortality rate at 15.14%. A notable interaction between rootstock and water stress revealed that Cleopatra mandarin under 0.8 bar of stress had the highest mortality rate, reaching 88.89%. Cleopatra mandarin shows high sensitivity to water deficits, indicating poor drought adaptability (Syvertsen & Garcia-Sanchez, 2014). In contrast, Rough lemon demonstrates greater drought tolerance, likely due to its vigorous root system and efficient water absorption (Castle *et al.*, 2010). Recent studies suggest that drought-tolerant rootstocks enhance survival through improved ABA signaling, antioxidant defense, and root growth plasticity (Morade *et al.*, 2025).

***Plant height (cm)*:** Plant height declined progressively with increasing water stress (Table 1), with a mean reduction of 26.1% at 0.8 bar compared to the control. Rough lemon (56.24 cm) and Rangpur lime (54.02 cm) maintained significantly greater mean heights, while Cleopatra mandarin recorded the lowest (41.91 cm). Interaction between rootstocks and water stress showed the significant effects indicated maximum height in Rough lemon under control (62.98 cm), 0.4 bar (59.30 cm), 0.6 bar (53.77 cm) and 0.8 bar (48.89 cm), which was closely followed by Rangpur lime and Sour orange. Whereas the minimum height was obtained in the Cleopatra mandarin under all four water stress levels, *i.e.*, 50.07 cm, 45.37 cm, 39.78 cm, and 32.44 cm under control, 0.4 bar, 0.6 bar and 0.8 bar, respectively. Balal *et al.* (2011)

reported that plant height is largely genetically controlled, but its expression is strongly modulated by environmental conditions. Water stress limits shoot elongation primarily by reducing cell expansion and photosynthesis (Romero *et al.*, 2018; Taiz *et al.*, 2015). Consistent with these findings, Wu *et al.* (2008) observed a 25% reduction in citrus seedling height under water deficit. The superior performance of Rough lemon and Rangpur lime under stress indicates their value as drought-tolerant rootstocks, likely due to better hydraulic conductivity and osmotic adjustment that sustain shoot growth (Sohail *et al.*, 2024).

***Stem diameter (mm)*:** Under conditions of water stress, the stem diameter experienced a substantial reduction of 26.3% at 0.8 bar when compared to the control group (Table 1), highlighting the critical impact of limited moisture on plant growth. Among the rootstocks tested, Rough lemon showed the largest average stem diameter at 7.92 mm, while Cleopatra mandarin had the smallest at 5.31 mm. However, the interaction among the rootstocks was not significant, indicating a consistent reduction pattern across all types. Decreases in stem diameter due to water deficit are typically linked to reduced cambial activity and a shift in the allocation of resources toward thickening the shoots (Hsiao & Xu, 2000). The ability of Rough lemon and NRCC RS-3 to maintain a larger stem girth under stress suggests that they have better hydraulic conductivity, which contributes to improved resilience to drought. Additionally, it is known that cambial activity and resource allocation decline during drought conditions (Chaves *et al.*, 2003), and more tolerant rootstocks likely support secondary growth by maintaining vascular function and xylem integrity (Costa *et al.*, 2025).

***Number of leaves and shoots*:** The results indicated that the number of leaves and shoots was significantly influenced by both the type of rootstock and the level of water stress applied, as well as the interaction between these two factors (Table 2). It was observed that the mean leaf count decreased progressively with increasing water stress, starting from an average of 108.04 leaves in the control group to just 57.48 leaves at the highest stress level of 0.8 bar. Rough lemon (97.98) and Cleopatra mandarin (88.21) maintained the highest mean leaf numbers, while Sour orange recorded the lowest (69.30). Similarly, mean shoot number decreased from 13.12 under control to 8.81 at 0.8 bar, with Rough lemon producing the maximum shoots (12.21) and NRCC RS-4 the fewest (10.12).

The significant interaction of rootstocks and water stress revealed that Rough lemon maintained higher leaf counts (127.58, 108.69, 86.74, and 68.92 under control, 0.4 bar, 0.6 bar and 0.8 bar, respectively) and shoot numbers (14.25, 12.99, 11.25 and 10.33 under control, 0.4 bar, 0.6 bar and 0.8 bar, respectively) under severe stress. While Cleopatra mandarin showed the steepest decline in the number of leaves (dropping from 120.75 leaves under control to 57.33 at 0.8 bar with 52.5% reduction) and shoots (dropping from 13.71 shoots under control to 8.00 at 0.8 bar with 41.6% reduction), indicating its greater susceptibility to water stress. These findings demonstrate that tolerant rootstocks like Rough lemon and Rangpur lime sustain 50–55% of their canopy and more than 70% of their shoot number even at 0.8 bar moisture stress, thereby preserving greater photosynthetic potential and vegetative growth under drought conditions, whereas sensitive rootstocks lose more than 50% of leaf and more than 40% of shoot production, severely limiting canopy development.

The interaction of rootstocks and water stress highlights genotype-specific differences, suggesting that tolerant rootstocks, *viz.,* Rough lemon, Sour orange and Rangpur lime, maintain canopy development more effectively under progressive stress, a key trait for maintaining source strength and long-term productivity in water-limited orchards. Water stress significantly reduces leaf and shoot production due to inhibited bud break and reduced assimilate allocation under limited water (Chaves *et al.*, 2003; Taiz *et al.*, 2015). However, rootstocks like Rough lemon maintained higher leaf and shoot numbers across stress levels, demonstrating better photosynthetic capacity, root–shoot signaling, and carbohydrate availability, which promote vegetative growth during drought (Morade *et al.*, 2025; Sohail *et al.*, 2024).

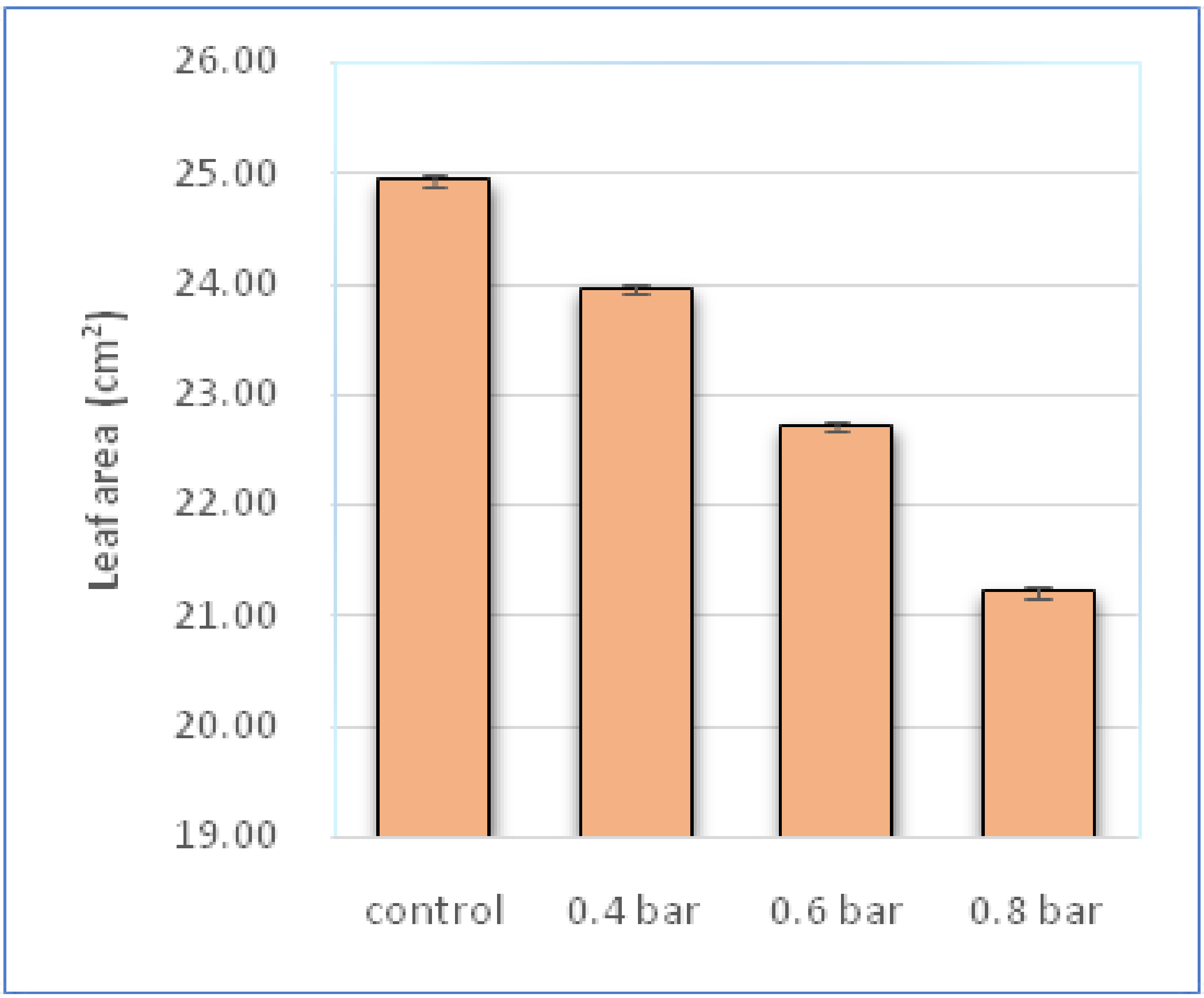
***Root length (cm)*:** Root length was significantly influenced by both the rootstock and the level of water stress, although the interaction between these factors was not statistically significant. Under control conditions, the average root length measured 29.55 cm, but as water stress increased to 0.8 bar, the average root length decreased to 19.98 cm (Fig. 2a). This decline represents a 32% reduction. Rough lemon maintained the highest mean root length (28.02 cm), followed by Rangpur lime (25.94 cm), whereas Cleopatra mandarin recorded the lowest (20.77 cm) (Fig. 2b). Although the interaction effect of rootstocks with water stress levels on root length was statistically non-significant, a clear trend of reduction with increasing water stress was observed (Fig. 2c). Rough Lemon maintained the highest root length across allstress levels, with 32.33 cm under control and 23.33 cm at 0.8 bar, showing a 27.8% reduction. Sour Orange (declined from 29.97 cm under control to 19.91 cm at 0.8 bar) and NRCC RS-3 (declined from 30.47 cm under control to 20.33 cm at 0.8 bar) followed similar patterns with reductions of 33.6% and 33.3%, respectively. The minimum root length was recorded in Cleopatra Mandarin at 0.8 bar (16.77 cm), corresponding to a 32.9% decline from the control (25.00 cm). The decline in root elongation is due to reduced cell division, inhibited meristematic activity, and lower carbohydrate allocation under water deficit (Chaves *et al.*, 2003; Taiz *et al.*, 2015). Rough lemon and Rangpur lime show greater root length under stress, indicating superior root plasticity and better drought avoidance (Morade *et al.*, 2025; Costa *et al.*, 2025). Despite reduced root growth across all genotypes, their relative ranking remained stable under stress.

Table 1. Impact of varying water stress levels on the plant mortality (%), plant height (cm) and stem diameter (mm) of citrus rootstocks

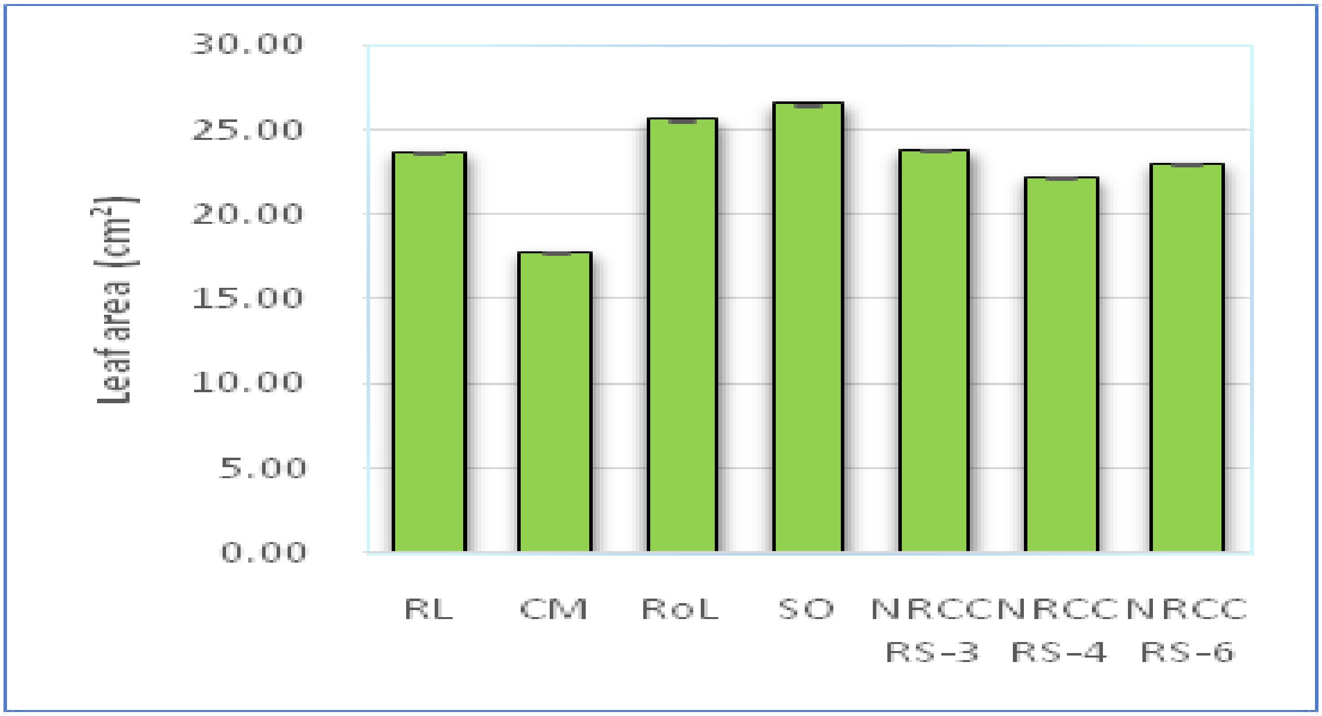
Rootstocks (R)	Water stress levels (W)														
	Plant mortality (%)					Plant height (cm)					Stem diameter (mm)				
	Control	0.4 bar	0.6 bar	0.8 bar	Mean (R)	Control	0.4 bar	0.6 bar	0.8 bar	Mean (R)	Control	0.4 bar	0.6 bar	0.8 bar	Mean (R)
Rangpur Lime	0.00	13.33	25.00	36.11	18.61	60.97	57.24	51.98	45.88	54.02	7.58	7.10	6.65	5.71	6.76
Cleopatra Mandarin	0.00	23.33	44.44	88.89	39.17	50.07	45.37	39.78	32.44	41.91	6.10	5.74	5.21	4.19	5.31
Rough Lemon	0.00	6.67	15.00	38.89	15.14	62.98	59.30	53.77	48.89	56.24	8.72	8.38	7.67	6.90	7.92
Sour Orange	0.00	26.11	44.44	50.00	30.14	60.05	56.62	49.83	45.91	53.10	7.22	6.73	6.05	5.17	6.29
NRCC RS-3	0.00	15.00	28.89	55.56	24.86	59.55	55.95	50.18	46.60	53.07	8.23	7.77	7.09	6.25	7.34
NRCC RS-4	0.00	32.78	50.00	61.11	35.97	58.00	53.11	47.00	39.97	49.52	7.03	6.45	5.91	5.03	6.11
NRCC RS-6	0.00	26.11	36.11	55.56	29.44	59.00	54.87	49.15	43.57	51.65	7.34	6.81	6.13	5.25	6.38
Mean (W)	0.00	20.48	34.84	55.16		58.66	54.64	48.81	43.32		7.46	7.00	6.39	5.50	
Factors	CD at 5%					CD at 5%					CD at 5%				
R	8.76					0.50					0.181				
W	6.62					0.38					0.137				
R×W	17.51					0.99					NS				

Table 2. Impact of varying water stress levels on the number of leaves and number of shoots of citrus rootstock

Rootstocks (R)	Water stress levels (W)									
	Number of leaves					Number of shoots				
	Control	0.4bar	0.6 bar	0.8 bar	Mean (R)	Control	0.4 bar	0.6 bar	0.8 bar	Mean (R)
Rangpur Lime	91.50	80.64	69.05	52.95	73.54	13.40	12.11	10.52	9.37	11.35
Cleopatra Mandarin	120.75	97.92	76.84	57.33	88.21	13.71	10.67	9.63	8.00	10.50
Rough Lemon	127.58	108.69	86.74	68.92	97.98	14.25	12.99	11.25	10.33	12.21
Sour Orange	88.47	76.11	63.94	48.67	69.30	12.95	11.50	10.05	8.93	10.86
NRCC RS-3	118.08	98.53	81.60	60.12	89.58	12.85	11.33	9.96	8.56	10.68
NRCC RS-4	99.87	89.75	73.62	55.97	79.81	12.10	10.91	9.33	8.12	10.12
NRCC RS-6	110.00	96.72	79.58	58.41	86.18	12.60	11.10	9.57	8.33	10.40
Mean (W)	108.04	92.62	75.91	57.48		13.12	11.52	10.04	8.81	
Factors	CD at 5%					CD at 5%				
R	2.79					0.231				
W	2.11					0.175				
R×W	5.57					0.462				



(a)



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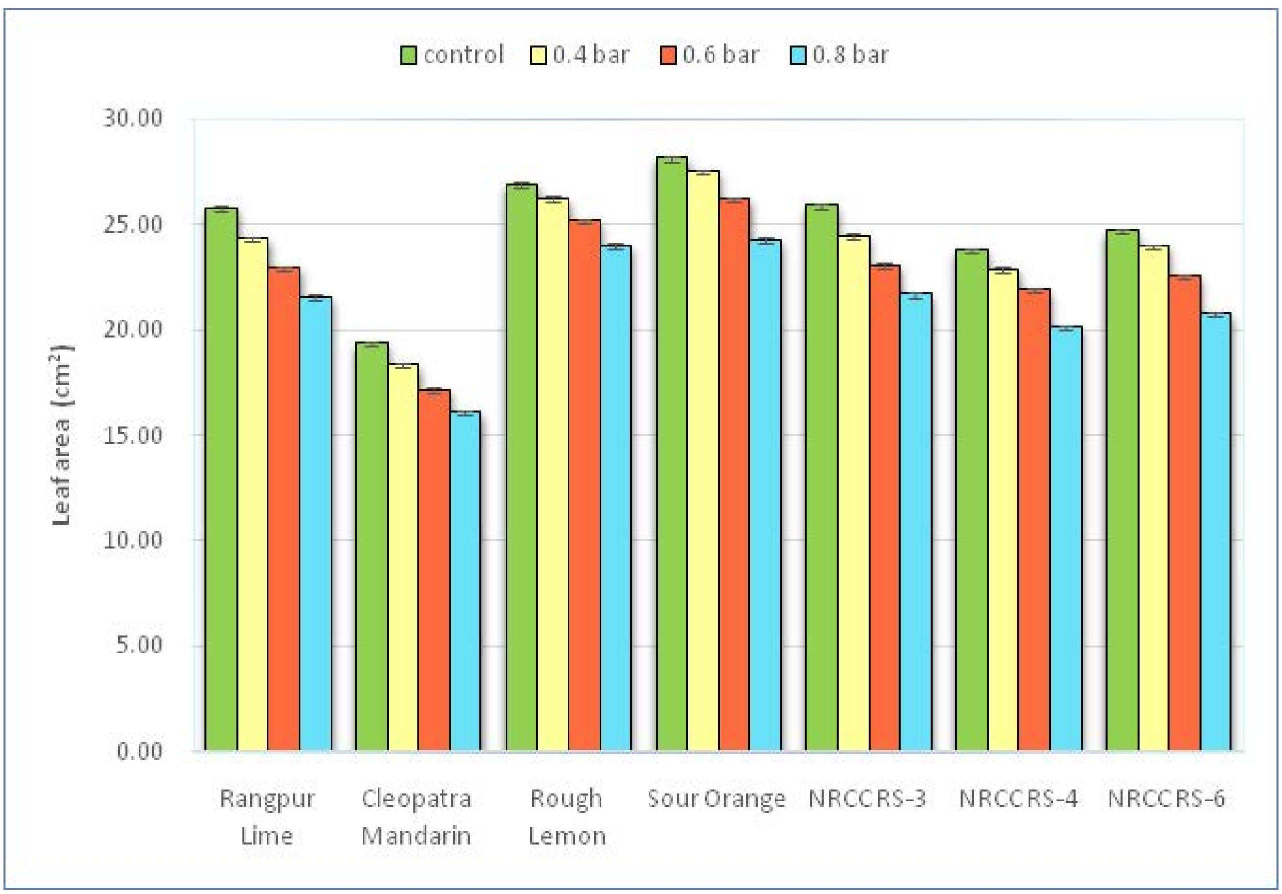
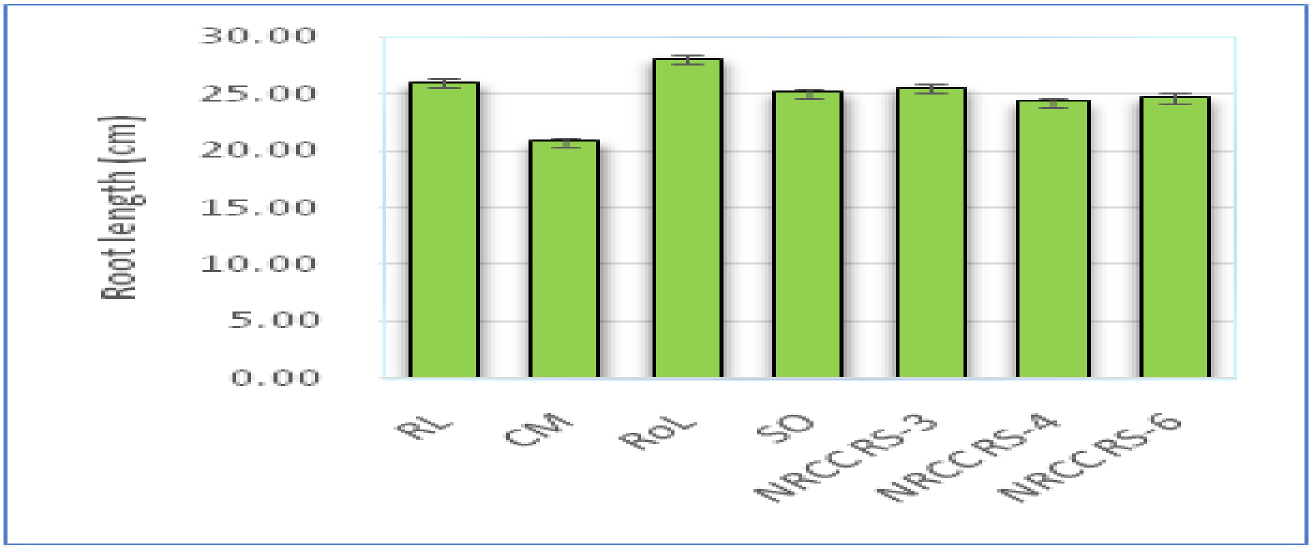


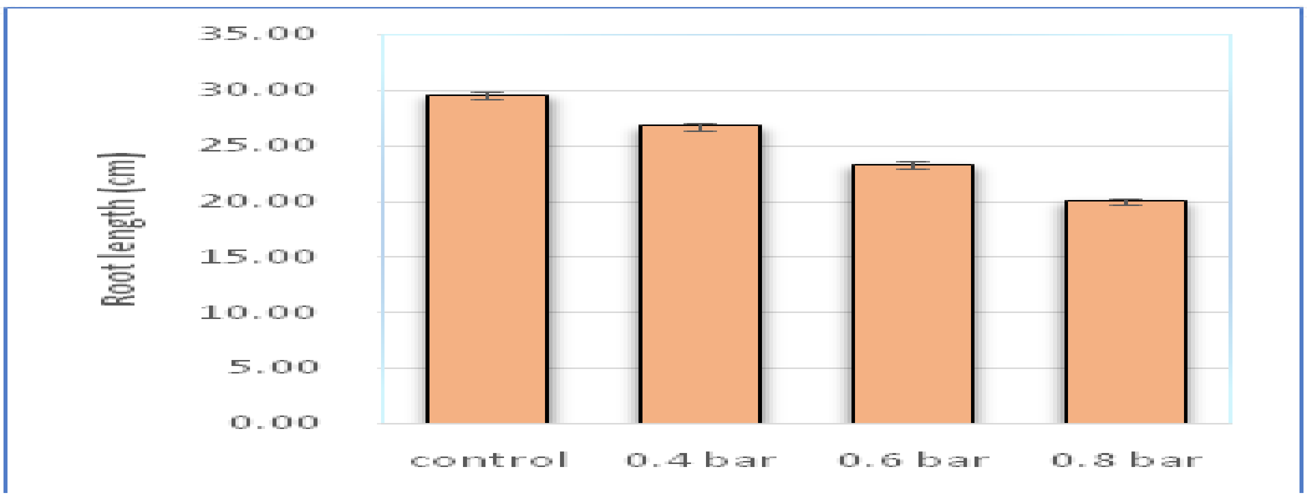
(c)

RL: Rangpur Lime; CM: Cleopetra Mandarin; RoL: Rough Lemon; SO: Sour Orange

Fig. 1a. Effect of water stress on leaf area (cm^2); **(b)** Leaf area (cm^2) of citrus rootstocks under water stress; **(c)** Interaction effect of citrus rootstock and water stress on leaf area (cm^2)



(a)



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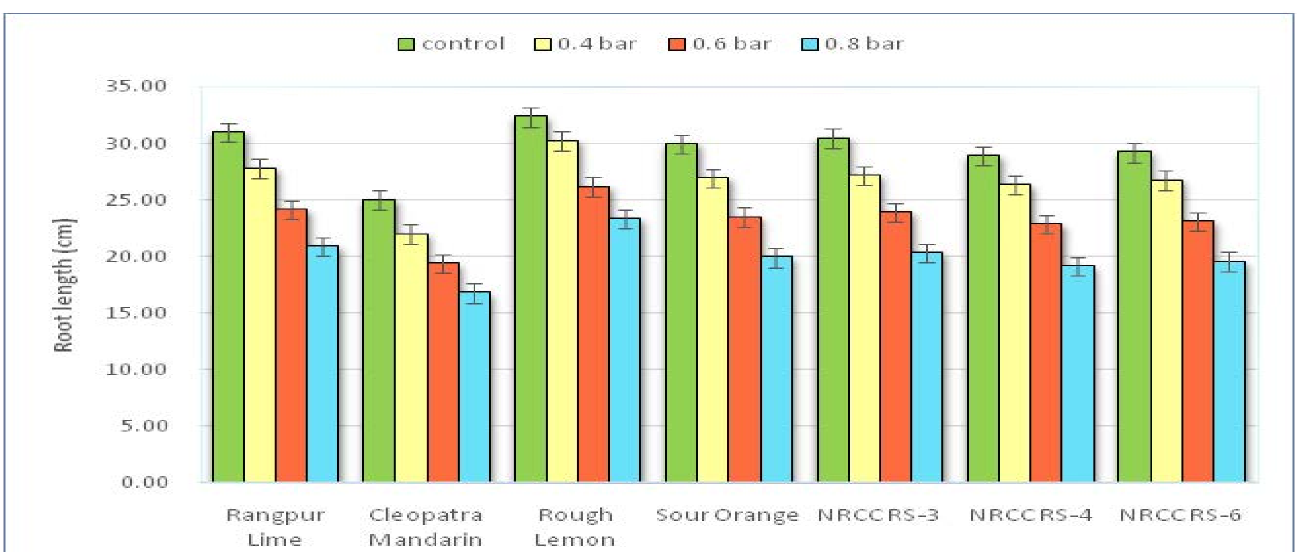

(c)

RL: Rangpur Lime; CM: Cleopetra Mandarin; RoL: Rough Lemon; SO: Sour Orange

Fig. 2a. Effect of water stress on root length (cm); **(b)** Root length (cm) of citrus rootstocks under water stress; **(c)** Interaction effect of citrus rootstock and water stress on root length (cm)

Conclusion

Our research shows that tolerant rootstocks are crucial for maintaining canopy growth and long-term productivity in water-limited environments. Water stress negatively affects citrus survival and growth, but the impact varies by rootstock. Rough lemon and Rangpur lime have lower mortality rates and better growth, demonstrating superior drought adaptation. While Sour Orange, NRCC RS-3 and NRCC RS-6 showed moderate drought adaptation. In contrast, Cleopatra mandarin and NRCC RS-4 are highly susceptible, making them unsuitable for arid areas. We recommend using Rough lemon and Rangpur lime in drought-prone orchards to enhance tree survival and stabilise yields. Future breeding should focus on rootstocks with improved hydraulic efficiency and deep rooting abilities to reduce yield losses from climate variability. These insights can help growers select the best rootstocks for sustainable and productive orchards.

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Evaluation of black cumin (*Nigella sativa* L.) varieties for seed yield potential under semi-arid conditions of northern Telangana

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ABSTRACT

Black cumin (*Nigella sativa L.*) is a valuable spice and medicinal crop however, in the semi-arid Northern Telangana Zone, there is a lack of comprehensive evaluation of improved black cumin varieties under dryland conditions. This study aimed to assess the performance of five varieties AN-1, AN-20, NS-32, NS-44, and a local check during the Rabi season of 2024-25 at the Horticultural Research Station, Adilabad. Significant variation was observed among the varieties for plant height, number of branches, capsules per plant, seeds per capsule, 1000-seed weight, and seed yield. AN-20 recorded the highest seed yield (1258.33 kg/ha), followed by AN-1 and NS-32, while the local check showed the lowest performance. These findings suggest that AN-20 and AN-1 are well-adapted to semi-arid dryland conditions and hold promise for commercial cultivation in the Northern Telangana region.

Introduction

Black cumin (*Nigella sativa* L.), a flowering plant of the Ranunculaceae family, is an ancient medicinal and culinary herb native to the Mediterranean region and widely cultivated across Asia, the Middle East, and parts of Africa (Xue *et al.*, 2016). The crop has gained global prominence for its diverse uses in culinary applications, cosmetics, pharmaceuticals, and traditional medicine systems. It thrives predominantly in arid and semi-arid environments owing to its low input requirements and adaptability to marginal soils (Sahin *et al.*, 2003). The seeds are small, angular, and black with a characteristic pungent aroma and flavor, making them popular ingredients in bread, pastries, pickles, and spice blends (Rasulloh *et al.*, 2018).

India is the leading global producer of black cumin, with an estimated cultivation area of approximately 9,000 hectares and annual production ranging between 7,000 and 8,000 tonnes (FAOSTAT, 2019; Pathak *et al.*, 2021). Major producing states include Rajasthan, Gujarat, Uttar Pradesh, Punjab, Bihar, Himachal Pradesh, Jammu and Kashmir, West Bengal, Assam, and Tamil Nadu. Despite this extensive cultivation, yield levels vary significantly across regions. For instance, experimental trials in Prayagraj, Uttar Pradesh, reported yields of up to 2.48 t/ha for improved genotypes such as Azad Kalonji (Singh *et al.*, 2023), compared to the national average of 0.8–1.0 t/ha, highlighting the potential for improvement through varietal selection and agronomic optimization.

Yield disparities among global producers are largely attributed to suboptimal agronomic practices, limited adoption of improved varieties, and poor post-harvest management

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(Anshiso and Teshome, 2019; Pathak *et al*., 2021). Numerous studies have documented considerable genetic variability in black cumin for yield and related traits. Singh *et al*. (2010) reported strong positive correlations between seed yield and traits such as plant height, number of capsules per plant, and 1000-seed weight, identifying them as key selection criteria in breeding programs. Bakhsh *et al*. (2015) also noted that genotypes with early flowering and high capsule density performed better under dryland conditions. Varietal evaluation studies in Rajasthan and Madhya Pradesh under rainfed conditions demonstrated that improved varieties out yielded local checks by 20–30% (Patel *et al*., 2018).

However, research on varietal performance under the semi-arid agro-climatic conditions of Telangana, particularly in the Northern Telangana Zone, remains limited. With increasing emphasis on dryland horticulture, black cumin presents a promising high-value crop option for these regions. Therefore, the present study aims to evaluate the performance of selected *Nigella sativa* varieties under the dryland conditions of Adilabad district in Northern Telangana.

Material and Methods

The field experiment was conducted during the Rabi season of 2024–25 at the Horticultural Research Station, Adilabad, located in the Northern Telangana Zone (Latitude 19.6480'N, Longitude 78.5321'E, at an elevation of 257 meters above MSL). The site falls under a semi-arid agro-climatic zone characterized by an average annual rainfall of approximately 850 mm. The average annual temperature is 30.08°C, and July is the wettest month. The predominant soil type is sandy loam in texture, neutral in reaction. Nutrient analysis indicated Organic Carbon 0.4%, and low in available nitrogen 200.6 kg/ha, medium in available phosphorus and potassium contents 18.2 and 206.4 kg/ ha respectively.

The weather conditions during the black cumin cropping period are presented in Table 1. October 2024 to April 2025 exhibited typical Rabi season weather patterns, with lower minimum temperatures in the winter months and rising temperatures toward the end of the cropping cycle. Relative humidity declined gradually after December 2024, while rainfall was negligible except in October and sporadically in March and April 2025

Table 1. Weather data during the black cumin cropping period (2024-25)

Month	Minimum temp. (°C)	Maximum temp. (°C)	Relative humidity (%)	Rainfall (mm)	Rainy days
Oct-24	23.1	34.0	84.9	35.6	3
Nov-24	14.6	30.9	82.9	0.0	0
Dec-24	14.0	29.9	79.5	5.6	1
Jan-25	12.8	31.3	74.9	0.0	0
Feb-25	15.3	34.1	55.7	0.0	0
Mar-25	23.8	37.6	67.0	6.0	4
Apr-25	28.0	41.0	69.9	13.78	3

Source: Automatic Weather Station (AWS), Agricultural Research Station, Adilabad

The experiment was laid out in a randomized complete block design (RCBD) with four replications. The treatments comprised five black cumin genotypes, including four improved varieties are AN-1, AN-20, NS-32, and NS-44 along with a local check. Varietal details such as maturity period, plant height, seed characteristics, average yield potential, and specific traits are presented in Table 2.

All experimental plots were managed using uniform cultural practices throughout the cropping cycle. During the Rabi season of 2024–25, land preparation for black cumin was completed on 14 October 2024, followed by sowing on 16 October 2024. Thinning operations were carried out on 18 November 2024. Manual weeding was done three times: the first on 6 November 2024, the second on 11 December 2024, and the third on 29 January 2025. The crop was harvested on 28 February 2025, and post-harvest drying was completed by 3 March 2025. A pre-emergence application of pendimethalin 30 EC @ 1 L/ha was used for weed control. The crop was raised in plots of 3.0 m × 2.0 m with a spacing of 30 cm × 10 cm, using a seed rate of 7 kg/ha, which resulted in an approximate plant population of 3,33,333 plants per hectare. For nutrient management, 10 t/ha of FYM was incorporated along with 40:20:20 kg/ha of NPK. The full dose of phosphorus and potassium, along with one-third of nitrogen, was applied as basal, while the remaining nitrogen was top-dressed in two equal splits at 30 DAS and at the flowering stage. Light irrigation was given immediately after sowing, followed by flood irrigation every 15–25 days. For pest management, 2% neem oil was sprayed to control sucking pests. The crop attained maturity within 125–135 days, after which harvesting was carried out.

Table 2. Varietal characters of black cumin included in the study

Variety	Source	Days to maturity	Seed colour	Average yield (kg/ha)	Special traits	Reference
AN-1	ICAR- NRCSS, Ajmer	135	Jet black	1129	Resistant to root rot	Meena *et al*., 2023; Kant *et al*. 2009
AN-20	ICAR-NRCSS, Ajmer	145–150	Black	1025	28.08% higher yield over other released varieties	Meena *et al*., 2023; Kant *et al*. 2009
NS-32	JNKVV, Jabalpur	170–175	Dark brown	1120	High oil content (36–38%)	Singh *et al*., 2024; Kant *et al*. 2009
NS-44	JNKVV, Jabalpur	150–155	Dark brown	850	Resistant to powdery mildew	Singh *et al*., 2024; Kant *et al*. 2009
Local	Adilabad (Farmer selection)	140–145	Black	-	-	-

During the course of the experiment, data were recorded on a range of growth and yield attributes. These included plant height at maturity (cm), number of primary and secondary branches per plant, days to first flowering, and days to maturity. Yield components such as number of capsules per plant, number of seeds per capsule, 1000-seed weight (g), and seed yield per hectare (kg/ha) were also measured. These parameters were selected to comprehensively evaluate the performance of black cumin genotypes under semi-arid dryland conditions.

The data recorded for various growth and yield parameters were subjected to analysis of variance (ANOVA) appropriate for a randomized complete block design (RCBD), using the GRAPES online statistical software developed by Gopinath *et al.* (2020). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% level of significance to determine the presence of statistically meaningful differences among the genotypes.

Results and Discussion

The results revealed significant differences among the five black cumin genotypes for all the agronomic and yield-related parameters evaluated under the semi-arid conditions of Adilabad (Table 3).

Among the tested genotypes, significant variation was observed in plant height. AN-20 recorded the highest plant height (64.5 cm), followed by AN-1 (53.25 cm) and NS-44 (47.72 cm). The observed variation in plant height can be attributed to genotypic differences and inherent growth characteristics, along with favorable cool temperatures during early vegetative growth, which promote elongation (Kant *et al*., 2009). Similarly, *Singh et al*. (2024) in black cumin reported that among all the tested genotypes Azad Kalonji had highest plant height followed by AN-20. According to Shweta *et al*. (2023) reported that high heritability (broad sense) for the total plant height in AN-1 and AN-20 varieties. A significantly highest number of primary (7.25) were recorded in AN-20 followed by AN-1 (6.20) and NS-44 (5.35) which was on par with NS-42 and significant highest secondary branches (9.85) was also recorded in AN-20, followed by NS-32. Branching habit is influenced by genetic potential and is also responsive to environmental conditions, sowing time, and crop management practices. These results are in agreement with the findings of Singh *et al.* (2024) reported that number of primary branches per plant and secondary branches highest in Azad Kalonji followed by local-2 and NS-44.

The highest number of flowers per plant was significantly observed in AN-20 (76.50), followed by AN-1 (69.50) and NS-44. The earliest flowering was recorded in AN-20 (47.57 days), followed by AN-1 (52.55 days) and a greater number of days to flowering was noticed in local check (76.75 days). In black cumin, flowering generally occurs on terminal branches, and early flowering is often associated with early germination and robust vegetative growth. An increase in branching also contributes to flower production, ultimately enhancing seed yield. Similar observations were reported by Singh *et al*. (2024) results indicated that earlier flowering in Azad Kalonji and number of flowers per plant found in Azad Kalonji followed by AN-20 and minimum number of flowers per plant recorded in NS-44.

With respect to reproductive traits, AN-20 recorded significantly highest number of capsules per plant (19.50), followed by NS-32 (17.00) which was on par with AN-1 (16.50). Singh *et al*. (2024), who also observed significant varietal differences for capsule formation. Significantly earliest days to maturity was observed in AN-20 (121.40 days), followed by AN-1 (134.05 days) which was on par with NS-32 and NS-44. These differences may be attributed to genetic variability among the genotypes. Comparable trends were reported by Singh *et al.* (2024) results showed that Azad Kalonji followed by AN-1.

Seed quality traits such as number of seeds per capsule and 1000-seed weight were also significantly influenced by genotype. AN-20 recorded the highest values (84.50 seeds per capsule) followed by NS-32 (78.50) which was on par with AN-1 (76.25). 1000-seed weight was significantly highest recorded in AN-20 (2.69 g) followed AN-1 (2.38 g) which was on par with NS-44 (2.26 g). NS-44 was on par with NS-32 (2.06 g). This improvement may be attributed to optimal climatic conditions during seed formation, particularly warm and sunny weather that favors seed development (Kant *et al.*, 2009). Similar results were Singh *et al.* (2024) reported that Azad Kalonji had highest number of seeds per capsule followed by AN-20 and 1000-seed weight was highest recorded in Azad Kalonji followed by local variety-2 and AN-20.

In terms of yield performance, AN-20 produced significantly highest seed yield (1258.33 kg/ha), followed by AN-1 (1124.99 kg/ha) and NS-32 (1024.99 kg/ha). The local check recorded the lowest yield (534.16 kg/ha), indicating its inferior performance under semi-arid conditions. Higher yields in AN-20, AN-1 and NS-32 were associated with early flowering, higher capsule numbers, and better seed weight. All varieties had an overlapped vegetative and reproductive phases. According to Kant *et al.* (2009), the advanced production technology of Nigella highlighted key features of different varieties. The average seed yield was reported as 800 kg/ha for variety AN-1 and 1000–1200 kg/ha for variety AN-20. Singh *et al.* (2024) reported that highest seed yield (t/ha) recorded in Azad Kalonji followed by AN-20. Hence, crop was harvested when 70 per cent capsules turned to brown. According to Shweta *et al.* (2023), the results indicated high heritability (broad sense) for growth and reproductive traits such as number of capsules, number of flowers, seed yield per capsule, and seed yield per plant, suggesting that AN-1 and AN-20 are high-yielding varieties. Moreover, high heritability coupled with high genetic advance for reproductive traits provides significant scope for the improvement of these traits to achieve higher yield. These findings are consistent with the reports of Meena *et al.* (2023) reported that AN-20 is recommended for cultivation in all nigella growing areas of Rajasthan.

Table 3. Performance of black cumin varieties under semi-arid conditions at Horticultural Research Station, Adilabad

Variety	Plant height (cm)	Primary branches/ plant	Secondary branches/ plant	Number of flowers/ plant	Days to 1st flower-ing	Number of capsules/ plant	Days to maturity	Number of seeds/ capsule	1000-seed weight (g)	Seed yield (kg/ ha)
AN-20	64.50^{a}	7.25^{a}	9.85^{a}	76.50^{a}	47.57^{d}	19.50^{a}	121.40^{c}	84.50^{a}	2.69^{a}	1258.33^{a}
AN-1	53.25^{b}	6.20^{b}	8.30^{cd}	69.50^{b}	52.55^{c}	16.50^{b}	134.05^{b}	76.25^{b}	2.38^{b}	1124.99^{ab}
NS-32	46.45^{c}	5.35^{c}	9.20^{b}	62.25^{c}	57.25^{b}	17.00^{b}	136.77^{b}	78.50^{b}	2.06^{c}	1024.99^{bc}
NS-44	47.72^{c}	5.42^{c}	8.57^{c}	68.25^{b}	60.00^{b}	13.50^{c}	138.80^{b}	71.95^{c}	2.26^{bc}	866.66^{c}
Local	43.00^{d}	5.60^{c}	7.95^{d}	61.50^{c}	76.75^{a}	12.25^{c}	150.00^{a}	70.50^{c}	1.82^{d}	534.16^{d}
SE(m)±	0.75	0.13	0.12	1.55	1.15	0.72	1.93	1.21	0.06	58.34
LSD (p=0.05)	2.31	0.39	0.38	4.78	3.58	2.22	6.03	3.74	0.19	181.71
CV (%)	2.94	4.25	2.81	4.59	3.91	9.13	2.84	3.18	5.56	12.12

Means followed by same letter in a column do not differ significantly at 5% LSD

Conclusion

The study revealed substantial genetic variability among black cumin varieties under semi-arid conditions of Northern Telangana. Improved varieties AN-20, AN-1, and NS-32 outperformed the local check and other genotypes in growth, phenological traits, and seed yield. AN-20 recorded the highest yield (1258.33 kg/ha), followed by AN-1 and NS-32, showcasing superior adaptability. These varieties exhibited desirable agronomic traits contributing to higher yield potential. Based on their performance, AN-20, AN-1, and NS-32 are recommended for commercial cultivation in the Adilabad region and similar agro-climatic zones. Further multi-location trials and participatory evaluations may help in validating these results for large-scale adoption by farmers.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Identification of best cultivar with suitable sowing time to maximize the pod yield of okra (*Abelmoschus esculentus*) in semi-arid regions of Haryana

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ABSTRACT

Recently released cultivars of okra were studied to standardize the sowing time for particular sowing window during 2021-22 to 2022-23 at the Experimental Research Farm, Vegetable Science, CCS HAU, Hisar (Haryana). In the present study, three cultivars namely, V_1- Hisar Naveen, V_2- Hisar Unnat and V_3- Varsha Uphar were sown on five different dates at an interval 15 days in Factorial RBD with three replications. The results compilation on the basis of two years of experimentation revealed that the okra cultivar, Hisar Naveen sown from 1st July under Haryana conditions produced maximum pod yield (112.55 q/ha) with B:C ratio (2.92), trailed by sowing of 15th July which produced the highest pod yield (110.40 q/ha) with B:C ratio (2.83). Therefore, for optimal okra production and the best benefit-cost ratio under the semi-arid conditions of Haryana, it is recommended to sow the Hisar Naveen okra cultivar between July 1st and July 15th for successful commercial cultivation.

Introduction

Okra (*Abelmoschus esculentus* L. Moench) is also known as ladyfinger. In India, it is very important export oriented rainy and spring-summer season vegetable crop. It ranks first in vegetable production and mainly cultivated in UP, Bihar, Haryana, Punjab, Gujarat, Maharashtra, Karnataka, Tamil Nadu, Odisha and West Bengal (Sood and Kaur, 2019). Globally, it is cultivated in sub-tropical, tropical, and low altitude areas of Asian, African and American countries (Raj *et al*., 2013 and 2014). The immature green pods are good source of carbohydrates, proteins, vitamin A and C. It also have K, Ca, Mg, and many more minerals, which are usually not found in our daily diet. Moreover, okra has good medicinal value for peptic ulcer because it is cheap source of plasma replacement for human body fluid (Makinde *et al*., 2022).

The selection of cultivars for a particular sowing time plays very important role to maximize the yield as it gives suitable environment for crop growth and fruit development (Bake *et al*., 2017). Proper sowing dates favours increase in fruit weight and number of fruits per plant which results in more production (Bake *et al*., 2017). Opposite to this, late sowing retards growth because of high temperature at the growth and development time, which affects reproductive stage and consequently reduce fruit yield (Ghannad *et al*., 2014). Moreover, late-sown vegetables attract more diseases and pests (Reddy and Reddi, 2014) and may resulting high infestation of viruses (Sastri *et al*., 2004). The cultivars found suitable for different planting time, as good high yielding

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cultivars grown at rude times may result less production (Ghannad *et al*., 2014) mainly because of unfavorable temperature, early stimulation of flowering, and rainfall.

For profitable cultivation of a vegetable, the high fruit yielding cultivar is the primary necessity of vegetable growers (Majoka *et al*., 2021; Oo *et al*., 2022 and Oo *et al*., 2023). Secondly, to explore the full potential of any cultivar, identify the best sowing time for flourishing its growth and ultimately high fruit yield production. Thus, to attain the highest yield of a variety, the identification of the specific planting time is required under a particular climate. The evaluation of different vegetable cultivars under changed dates of sowing delivers appreciates information to the researchers for further enhancement in fruit yield (Ngoc *et al*., 2017; Oo *et al*., 2023) and increase the availability of vegetables for large period. Therefore, keeping the above discussion in view, present research was conducted to find out the best sowing period for crop growth and immature pod production of okra cultivars *viz*., Hisar Naveen, Hisar Unnat and Varsha Uphar.

Material and Methods

The pod yield performance of okra cultivars under different dates of sowing was evaluated from 2021-22 to 2022-23 at the Experimental Research Farm, Vegetable Crops Sciences, CCS Haryana Agricultural University, Hisar, India. The experimental location having latitude of 29°10' N, longitude of 75°46' E and at an altitude of 215.2 m above mean sea level. This area is categorized as semi-arid region accompanied with dry and hot winds in May-June and dry severe cold in December-January. The average temperature of region is 44 - 48°C in summer and -2°C in winter escorted with chill frost (Majoka *et al*., 2021). The maximum rains received in July-September. In the present experiment, three cultivars namely, V_1- Hisar Naveen, V_2- Hisar Unnat and V_3- Varsha Uphar were planted during *Kharif* season on five different sowing dates at 15 days interval i.e. D_1:15 June 2022, D_2: 01 July 2022, D_3: 15 July 2022, D_4: 01 August 2022 and D_5:14 August 2022 in factorial RBD with three replications having plot size of 3.0 m x 2.7m with spacing 60cm x 30 cm. All the agronomic practices recommended by CCS HAU Hisar were followed to raise the good crop (Anonymous, 2023). The data were recorded from five selected plants in each treatment for pod yield per plant (kg), plant height (cm), and pods per plant and subjected to the Factorial RBD statistical analysis as per method prescribed by Panse and Sukhatme, 1985.

Results and Discussion

The results obtained during 2021-22 and 2022-23 on plant height (cm) and average pods/ plant are depicted in Table 1. During 2021-22, maximum plant height was observed 95.10 cm in Hisar Naveen sown on 15 July, while during 2022-23, maximum plant height was observed 97.30 cm in Hisar Naveen sown on 1 July, this difference might be due to seasonal variations in weather parameters. The average of both the years revealed that the sowing date of 15th July recorded significantly taller plants as compared to other sowing dates, which may be due to the occurrence of faster growth under suitable weather regimes, lead to the improved plant metabolic activities like photosynthesis. The early sown (15 June) crop got extra growing time as compared to late sown while it faced high temperature condition during early stage of growth. This might prevalent in the early stages of the vegetative growth, which led to the reduction in plant height. Likewise, the late sowings (1 August & 14 August) received less growing duration as compared to timely sowing while it faced high temperature condition. This might lead to less plant growth and development, thus the reduction in plant height was noticed. According to Das *et al*., 2018, reduction in plant height under late sown condition might be due to high air temperature faced by the crop which lead to stunted growth. Similar research observation were also conveyed by El-Waraky, 2014; Kumar *et al*., 2015 and Sood & Kaur, 2019. The pods/ plant were significantly reduced in early as well as late sowing. Okra sown on 15th July during 2021-22 and 1st July during 2022-23 was recorded the highest pods/ plant (24.10 and 24.70, respectively) due to the suitable weather conditions. These results are in agreement with Tandel *et al*. (2017). The highest number of pods (24.20) on average basis were attained on 1st July and 15th July which may be due to more number of nodes per plant and longer harvesting period accompanied with favorable weather conditions. The number of pods/ plant is one of very essential yield backing parameters and it directly effects the yield. The authors working on okra used different dates and verities reported similar results by Sonu *et al*. (2013), Dash *et al*. (2013) and Undie and Litio (2018).

Table 1. Effect of different dates of sowing on plant height and pods/ plant of okra

Sowing time	Cultivars	Plant height (cm)			Pods/ plant		
		2021-22	2022-23	Mean	2021-22	2022-23	Mean
D_1:15 June	V_1: Hisar Naveen	89.30	93.60	91.45	23.60	24.20	23.90
	V_2: Hisar Unnat	87.10	92.50	89.80	20.90	21.50	21.20
	V_3: Varsha Uphar	88.40	92.70	90.55	21.80	22.40	22.10

D_2: 01 July	V_1: Hisar Naveen	91.40	97.30	94.35	23.70	24.70	24.20
	V_2: Hisar Unnat	90.30	92.50	91.40	22.10	23.30	22.70
	V_3: Varsha Uphar	90.50	94.80	92.65	22.90	24.00	23.45
D_3: 15 July	V_1: Hisar Naveen	95.10	95.70	95.40	24.10	24.30	24.20
	V_2: Hisar Unnat	92.60	89.30	90.95	22.70	22.70	22.70
	V_3: Varsha Uphar	93.50	90.60	92.05	23.40	23.50	23.45
D_4: 01 August	V_1: Hisar Naveen	84.01	87.21	85.61	20.90	21.50	21.20
	V_2: Hisar Unnat	80.26	82.46	81.36	19.30	19.90	19.60
	V_3: Varsha Uphar	81.72	84.92	83.32	20.00	20.60	20.30
D_5:14 August	V_1: Hisar Naveen	62.71	64.91	63.81	17.70	18.30	18.00
	V_2: Hisar Unnat	48.28	50.48	49.38	15.10	15.70	15.40
	V_3: Varsha Uphar	59.97	62.17	61.07	16.20	16.80	16.50
	C.D. Factor (D)	3.26	1.54	-	0.50	0.49	-
	C.D. Factor (V)	1.83	1.19	-	0.40	0.38	-
	C.D. Factor (D x V)	NS	2.66	-			

Table 2. Mean performance on pod yield and B:C ratio of okra

Sowing time	Cultivars	Pod yield (q/ ha)			B:C ratio
		2021-22	2022-23	Mean	
D_1:15 June	V_1: Hisar Naveen	98.70	104.30	101.5	1.92
	V_2: Hisar Unnat	86.40	88.60	87.50	1.53
	V_3: Varsha Uphar	90.10	94.30	92.20	1.66
D_2: 01 July	V_1: Hisar Naveen	105.90	114.90	110.40	2.83
	V_2: Hisar Unnat	90.60	99.50	95.05	2.41
	V_3: Varsha Uphar	95.20	104.90	100.05	2.53
D_3: 15 July	V_1: Hisar Naveen	114.60	110.50	112.55	2.92
	V_2: Hisar Unnat	98.10	94.10	96.10	2.48
	V_3: Varsha Uphar	105.80	97.10	101.45	2.62
D_4: 01 August	V_1: Hisar Naveen	108.20	109.30	108.75	1.89
	V_2: Hisar Unnat	92.30	92.40	92.35	1.45
	V_3: Varsha Uphar	94.50	96.30	95.40	1.54
D_5:14 August	V_1: Hisar Naveen	85.40	90.30	87.85	1.45
	V_2: Hisar Unnat	73.60	78.20	75.90	1.13
	V_3: Varsha Uphar	78.90	81.00	79.95	1.23
	C.D. Factor (D)	6.36	3.35	-	-
	C.D. Factor (V)	4.93	2.13	-	-
	C.D. Factor (D x V)	NS	NS	-	-

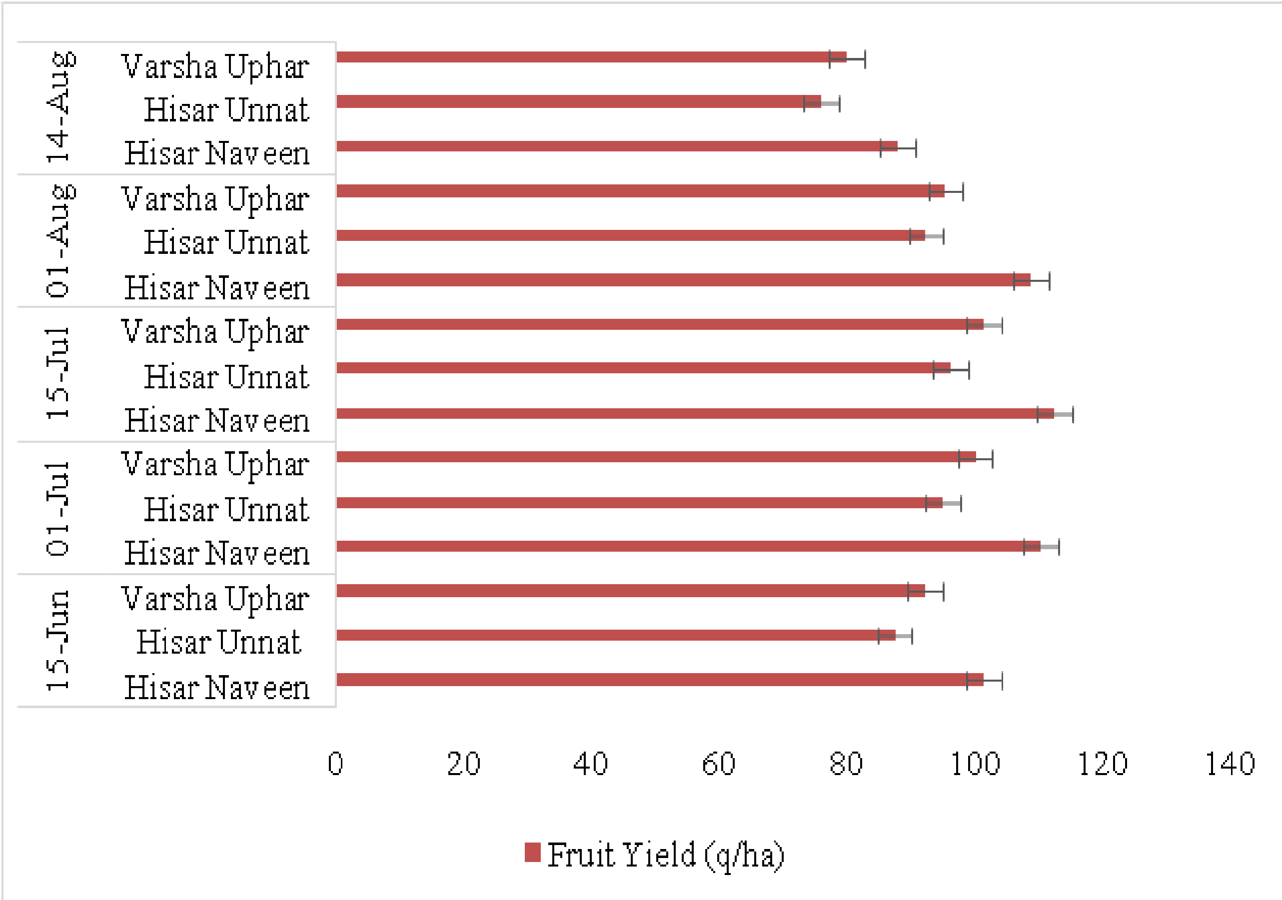

Fig. 1. Effect of sowing dates on pod yield of different okra cultivars

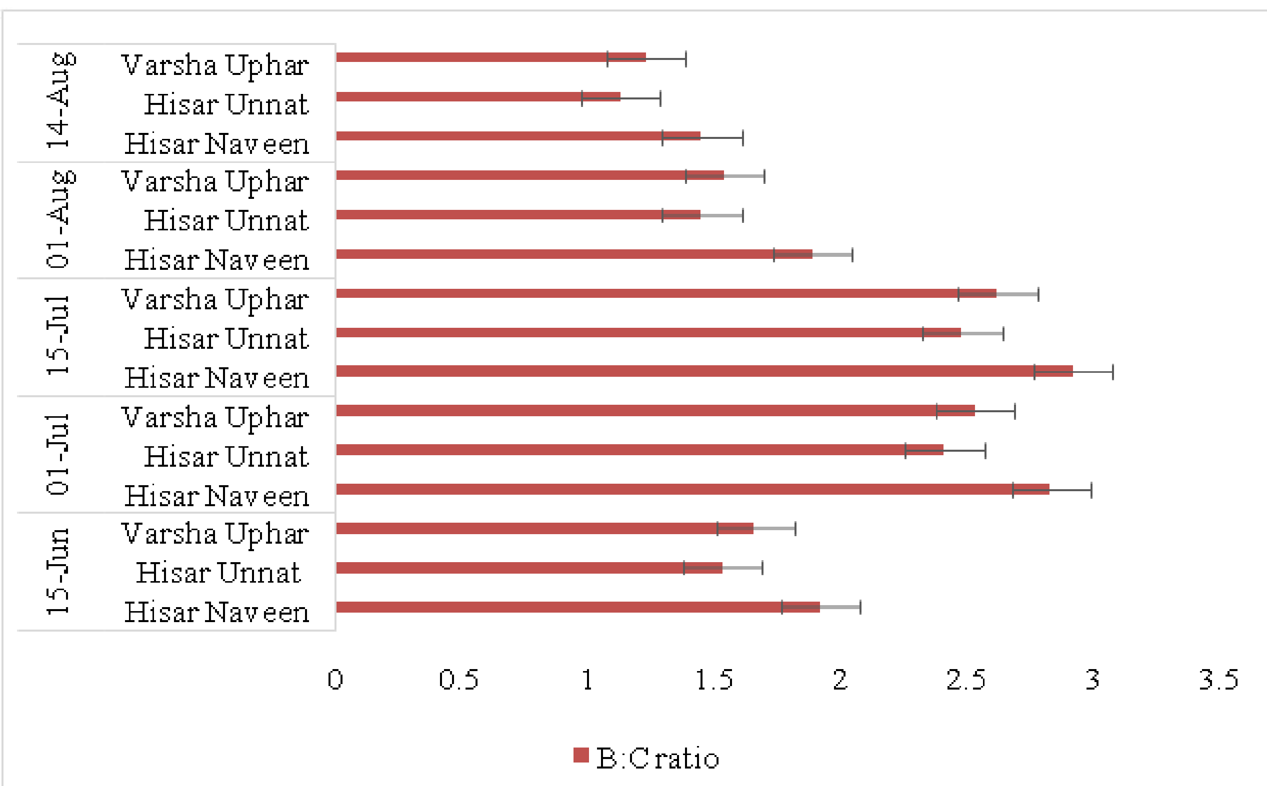

Fig. 2. Effect of sowing dates on pod yield of different okra cultivars

During 2021-22, the effect of change in dates of sowing on growth and pod yield of different okra cultivars found that maximum pod yield (114.60 q/ha) was obtained when okra cultivar Hisar Naveen sown on 15th July which was at par with sowing of 1st August under Hisar conditions. While, during 2022-23, results based on the effect of sowing dates on growth, development and yield of okra cultivars revealed that maximum pod yield (114.90 q/ha) was obtained when okra cultivar Hisar Naveen planted on 1st July which was at par with sowing of 15th July under Hisar conditions (Table 1 and Fig 1). The pod yield performance of the cultivars under different dates of sowing varied from year to year due to seasonal variations in weather parameters.

On the other side, 15th June sowing reflected overall less growth, and development and yield of okra plants due to extreme high temperature, which is not much conducive for okra cultivation and cause period for plant growth and development. Likewise, 1st August and 14th August sowing also faces the lack of moisture and high temperature conditions. The maximum pod yield mottled significantly amongst different sowing periods and interaction of sowing time with variety. This might be happened due to the prevailing favourable climate during the crop growth when crop was sown on 10th March. These findings were reported by earlier researchers i.e. Bake *et al*., 2017, Morwal and Patel, 2017, Das *et al*., 2018, Undie and Litio, 2018 in okra.

The results assemblage on okra discovered that the okra cultivar, Hisar Naveen sown on 1st July under Hisar conditions able to produce the maximum pod yield (112.55 q/ha) with B:C ratio (2.92), which is trailed by sowing of 15th July to produce good pod yield (110.40 q/ha) with B:C ratio (2.83). The maximum immature tender pod yield was recognized due to the favorable response environment in plant growth and pod yield attributes (Table 1 and Fig 2). Therefore, sowing of okra cultivar Hisar Naveen may be suggested from 1st July to 15th July to maximize the okra production and economize the commercial cultivation of okra under semi-arid conditions of Haryana.

Conclusion

The maximum yield of okra cv. Hisar Naveen was observed in the sowing date range of 1-15 July under semi-arid conditions of Haryana. The benefit cost ratio and overall economics was also found more in the same sowing period so the okra cultivar Hisar Naveen may be suggested for sown from 1st July to 15th July.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Genetic variability, heritability and genetic advance in bitter gourd (*Momordica charantia* L.)

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ABSTRACT

Greater diversity in the initial breeding stock increases the likelihood of developing desirable crop varieties. The key aim of germplasm conservation is to gather and safeguard genetic variation in native crop species for both current and future breeding efforts. The analysis of variance revealed significant differences among the hybrids across all traits studied, with average performance data presented for 10 genotypes that exhibited low, moderate, and high levels of phenotypic (PCV) and genotypic coefficient of variation (GCV). The greatest GCV was observed for sex ratio (20.93%) and the number of primary branches per plant (21.30%). Traits such as number of seeds per fruit (17.93%) and fruit yield per plant (17.53%) showed moderate GCV, whereas lower GCV values were recorded for days to first staminate flower anthesis (8.78%) and fruit circumference (7.74%). In general, PCV values exceeded GCV values. Heritability was high for days to first staminate flower anthesis (85%), moderate for vine length (53%), and low for number of seeds per fruit (25%). Traits like number of primary branches per plant exhibited high heritability along with high genetic advance, suggesting the predominance of additive gene action. Genetic advance expressed as a percentage of the mean was high for fruit yield per plant (41.79%) and number of primary branches per plant (40.55%). Moderate genetic advance was seen in traits like internodal length (18.67%), highlighting their considerable potential for improvement through direct selection.

Introduction

The bitter gourd (*Momordica charantia* L.) name itself indicate that bitter nature and it is due to momordicine, is an important cucurbit which was highly cross pollinated due to Monoecy condition and somatic chromosome number of 2n=2x=22. According to Singh *et al.* (2023), bitter gourds can be cooked, curried, stuffed, sliced, and fried. They can also be pickled, preserved, and dehydrated. They are also rich in therapeutic characteristics, such as carminative, purgative, and anti-diabetic effects. It is actually a tonic fruit that is used to treat diabetes, gout, and rheumatism (Khulakpam *et al.*, 2015).

Yield in bitter gourd is a complex trait influenced by multiple factors such as the number of primary branches per vine, number of nodes per vine, sex ratio, number of fruits per vine, and primarily, the average fruit weight. Heritability reflects the proportion of phenotypic variation that is attributed to genetic causes and provides essential guidance for genetic selection. In order to design an effective breeding program

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aimed at enhancing crop yield, it is crucial to gather sufficient information regarding the extent and nature of genetic variability, along with their associated heritability estimates. According to Dey *et al.* (2009), yield is a complicated trait that is impacted by a number of genetic factors interacting with the environment. In order to improve selection, it is necessary to provide a better understanding of the ancillary features. A crop's breeding strategy is largely determined by the type and extent of gene activities that contribute to the development of both quantitative and qualitative features. Selection efficiency improves when traits are chosen based on high heritability combined with high genetic advance over the mean. The magnitude of these estimates also indicates the potential for improvement through selection. The present study was conducted to estimate the components of variance, heritability, and genetic advance over the mean in bitter gourd.

Material and Methods

The experimental material for the present study was sourced from the Indian Institute of Vegetable Research (IIVR), Varanasi, consisting of 10 genotypes of *Momordica charantia* L. representing diverse morphological and yield characteristics. The genotypes included DVBTG-903, DVBTG-7, IC-06309, VRBTG-423, VRBTG-12-2, IC-068296, DVBTG-448, IC-068316, DVBTG-1004, and Green Long Jaunpuri. The experiment was carried out during 2022–23 at the Main Experimental Field, Department of Vegetable Science, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, using a Randomized Block Design (RBD) with three replications. A spacing of 1.5 meters between rows and 0.5 meters between plants was maintained. Recommended agronomic practices were followed to ensure a healthy crop. Data collection involved selecting six plants from each genotype in every replication, with the chosen plants tagged and properly labelled before the flowering stage to facilitate observation.

The traits recorded for analysis included days to first staminate flower anthesis, days to first pistillate flower anthesis, node number at first staminate flower appearance, node number at first pistillate flower appearance, internodal length (cm), sex ratio (male:female), vine length (m), number of primary branches per plant, days to first fruit harvest, fruit length (cm), fruit circumference (cm), average fruit weight (g), number of fruits per plant, fruit yield per plant (kg), and number of seeds per fruit. Additional traits such as days to flowering, days to ripening, plant height (cm), number of branches per plant, number of fruits per cluster, fruit width (cm), number of locules per fruit, number of fruits per plant, and fruit weight per plant were also recorded. After calculating the mean data for each character, Panse and Sukhatme (2000)'s standard method of analysis of variance was applied. According to Burton and Devane's (1953) formula, the genotypic and phenotypic coefficients of variation (GCV and PCV), heritability in the broadest sense (h^2), and genetic advancement as a percentage of mean were calculated.

Results and Discussion

A higher degree of diversity in the original breeding material guarantees a higher probability of generating the desired crop plant types. Therefore, the main goal of germplasm conservation is to gather and conserve the genetic diversity found in native crop species collections so that it can be used by both the current and future generations. The analysis of variance indicted the existing of significant differences among all the hybrids for all the traits studied. Mean performance of 10 genotypes for all character is presented in Table 1. The character exhibited low moderate and high PCV and GCV values in Table 2.

Highest genotypic coefficient of variation was recorded only two character i.e sex ratio (male: female) (20.93%) followed by number of primary branches per plant (21.30%). Moderate GCV was observed for number of seeds per fruit (17.93%), fruit yield per plant (17.53%), number of fruits per plant (17.19%), node at which first staminate flower appears (16.20%), node at which first pistillate flower appears (14.53%), fruit length (13.25%), vine length (13.16%), internodal length (12.20%) and average fruit weight (10.97%). Genotypic coefficient of variation was low for days to first staminate flowers anthesis (8.78%), fruit circumference (7.74%), days to first pistillate flower anthesis (6.39%) and days to first fruit harvest (6.01%). In general, PCV was higher than the GCV in the same direction. Rana and Pandit (2011) reported that in snake gourd, the genotypic coefficient of variation (GCV) was high for traits such as days to seedling emergence, fruit length, total number of male flowers, total number of seeds per fruit, total number of fruits per plant, and yield per plant. According to Bhati *et al.* (2023), the GCV values ranged from 4.64% to 23.40%.

The highest GCV was recorded for fruit diameter (23.27%), followed by fruit yield per plot (22.77%), number of fruits per plant (22.60%), fruit yield per hectare (22.50%), node number to first male flower (20.5%), and average fruit weight (20.14%). The lowest GCV was noted for days to germination (9.95%), number of leaves per plant (9.73%), vine length (9.49%), and number of primary branches per plant (6.39%). In terms of phenotypic coefficient of variation (PCV), the highest value was observed for fruit length (23.74%), followed by fruit diameter (23.34%), fruit yield per hectare (23.23%), fruit yield per plot (22.94%), number of fruits per plant (22.71%), node number to first male flower (21.11%), and average fruit weight (20.53%). Moderate PCV values were found for node number to first female flower (17.57%), total soluble solids (TSS) (13.09%), days to germination (10.73%), and vine length (10.25%). The lowest PCV values were recorded for number of leaves per plant (9.95%), number of primary branches per plant (7.28%), days to first male flower (5.40%), days to first female flower (5.34%), and days to first fruit harvest (4.85%).

Heritability estimates in narrow sense was high for three parameters while, moderate for five parameters and low for seven out of fifteen parameters taken in experiment. The high narrow sense heritability was observed for days to first staminate flowers anthesis (85%), days to first pistillate flower anthesis (79%) and node at which first staminate flower appears (70%), whereas, moderate heritability recorded by node at which first pistillate flower appears (58 %), vine length (53 %), days to first fruit harvest (52%), number of fruits per plant (49%) and fruit yield per plant (43%). It was heritability low for number of seeds per fruit (25%), fruit length (21%), number of primary branches per plant (18%), sex ratio (16%), average fruit weight (15%), fruit circumference (9%) and internodal length (7%). Bannatti *et al.* (2024) reported that high heritability (>60%) combined with high genetic advance as a percentage of the mean (>20%) was observed for traits such as number of primary branches per plant, days to first male flowering, node number at first male flower opening, sex ratio, node number at first female flower opening, vine length, fruit yield per vine, fruit length, average fruit weight, ascorbic acid content, fruit yield per hectare, beta carotene content, and exocarp thickness. This suggests that these traits are predominantly governed by additive gene action. Thus, there is considerable potential for direct selection to enhance these traits. According to Sagar *et al.* (2024), moderate heritability and high genetic advancement were observed for fruit yield per plant, average fruit weight, fruit length, and the number of primary branches per vine. Additionally, high heritability and high genetic advancement were found for vitamin C content, average fruit weight, number of primary branches per vine, and fruit yield per plant as a percentage of the mean.

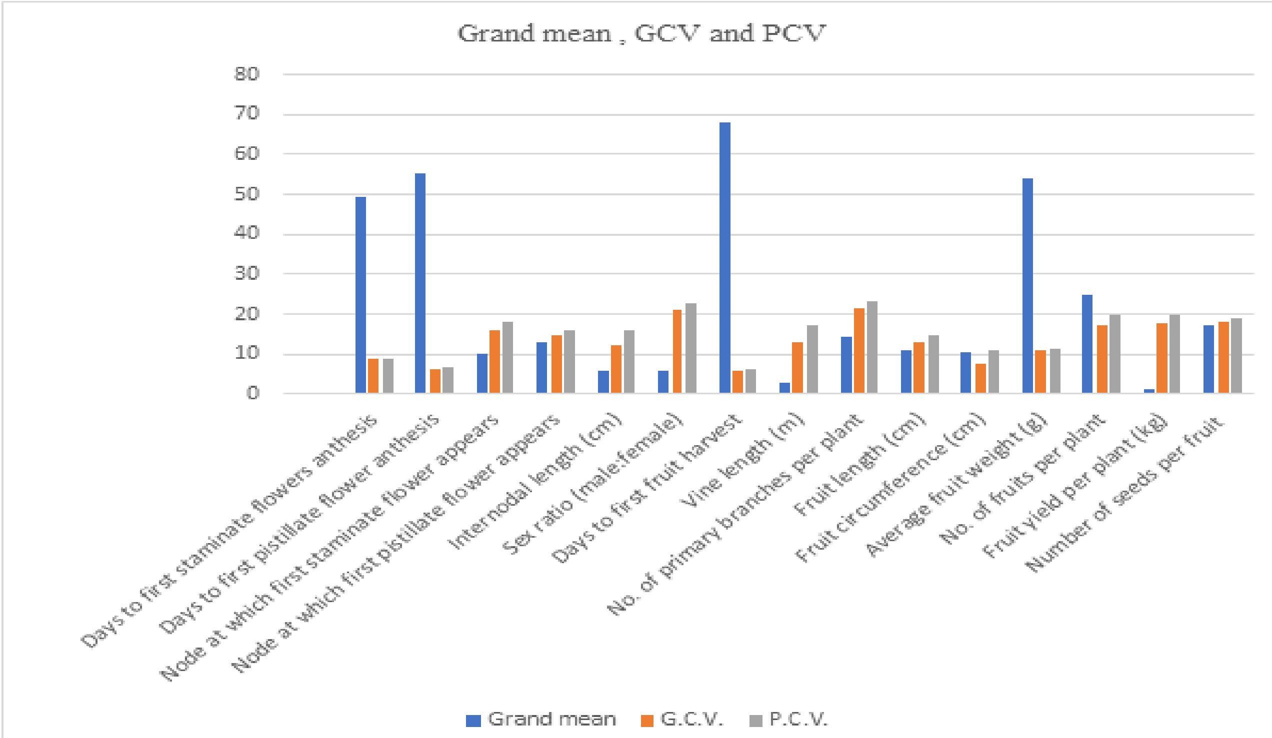
Genetic advance as per cent of mean was high for nine parameters i.e. fruit yield per plant (41.79%), number of primary branches per plant (40.55%), sex ratio (39.80%), number of seeds per fruit (34.53%), number of fruits per plant (30.77%), node at which first staminate flower appears (30.02%), node at which first pistillate flower appears (27.24%), fruit length (24.23%), average fruit weight (21.87%), vine length (20.88%), and whereas, moderate genetic advance as per cent of mean was observed for internodal length (18.67%), days to first staminate flower anthesis (17.67%), days to first pistillate flower anthesis (12.70%), days to first fruit harvest (11.98%) and fruit circumference (11.97%). Singh *et al.* (2014) high heritability coupled with high genetic advance as percent of mean was observed for fruit length, yield per plant, fruit diameter, fruit weight, branch per plant and seeds per fruit.

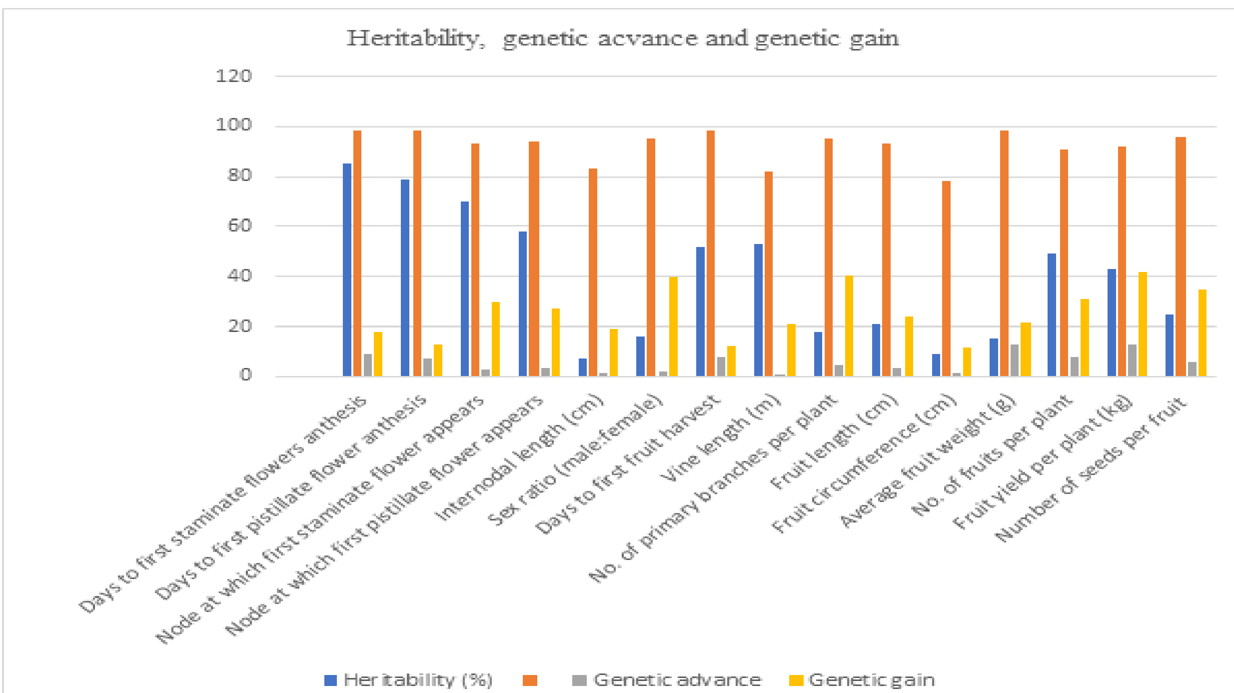
Table 2. Estimation of range, mean, genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic gain in bitter gourd

Characters	Range		Grand mean	G.C.V.	P.C.V.	Heritability (%)		Genetic advance	Genetic gain
	Min.	Max.				Narrow Sense	Broad Sense		
Days to first staminate flowers anthesis	43.60	61.26	49.43	8.78	8.98	85	98	8.77	17.67
Days to first pistillate flower anthesis	52.46	65.34	55.44	6.39	6.62	79	98	6.92	12.70
Node at which first staminate flower appears	7.60	14.53	10.21	16.20	18.01	70	93	2.96	30.02
Node at which first pistillate flower appears	9.44	18.48	13.07	14.53	15.97	58	94	3.34	27.24
Internodal length (cm)	5.12	6.97	6.05	12.20	16.03	7	83	1.13	19.12
Sex ratio (male:female)	4.01	7.98	5.95	20.93	22.68	16	95	2.07	39.80
Days to first fruit harvest	61.80	73.81	68.09	6.01	6.21	52	98	7.76	11.98
Vine length (m)	2.20	3.80	2.96	13.16	17.09	53	82	0.58	20.88
No. of primary branches per plant	11.60	18.40	14.11	21.30	23.04	18	95	4.65	40.55
Fruit length (cm)	8.62	13.28	10.93	13.25	14.93	21	93	3.11	24.23
Fruit circumference (cm)	8.61	12.06	10.69	7.74	10.86	9	78	1.28	11.37
Average fruit weight (g)	48.57	70.60	54.12	10.97	11.33	15	98	12.80	21.87
No. of fruits per plant	16.15	35.43	24.91	17.19	19.77	49	91	7.56	30.77
Fruit yield per plant (kg)	0.83	1.76	1.33	17.53	19.93	43	92	12.75	41.79
Number of seeds per fruit	11.45	25.26	17.45	17.93	19.17	25	96	5.60	34.53

Table 1. Mean performance of the 10 parents for 15 characters of bitter gourd

Genotypes	Days to first staminate flower anthesis	Days to first pistillate flower anthesis	Node at first staminate flower appears	Node at which first pistillate flower appears	Internodal length (cm)	Sex ratio (M:F)	Days to first fruit harvest	Vine length (m)	No. of primary branches/ plant	Fruit length (cm)	Fruit circumference (cm)	Average fruit weight (g)	No. of fruits/ plant	Fruit yield/ plant (kg)	Number of seeds/ fruit
DVBTG-903 (P_1)	43.60	52.54	9.00	12.66	6.07	6.83	66.06	3.33	13.37	9.43	9.03	49.06	31.30	1.53	18.60
DVBTG-7 (P_2)	44.65	53.93	12.66	13.70	6.97	7.73	73.07	3.80	16.63	11.03	8.61	49.96	35.43	1.76	13.92
IC-06309 (P_3)	47.16	54.06	8.27	12.10	5.23	4.19	63.18	2.71	12.06	8.62	12.06	48.57	24.80	1.19	15.60
VRBTG-423 (P_4)	51.00	53.26	10.91	12.58	5.12	4.01	73.46	2.66	12.36	9.61	10.63	57.36	22.26	1.27	11.45
VRBTG-12-12 (P_5)	50.90	53.60	7.60	12.53	6.93	7.15	64.89	3.30	18.40	11.70	11.33	54.41	31.03	1.68	16.69
IC-068296 (P_6)	45.33	57.06	13.51	15.93	5.86	4.71	66.20	3.07	15.13	12.70	11.66	70.60	22.66	1.59	25.26
DVBTG-448 (P_7)	50.24	52.46	7.90	9.44	5.60	6.40	61.80	2.20	12.80	11.83	11.76	50.93	16.15	0.83	17.80
IC-068316 (P_8)	53.24	57.33	8.36	11.17	6.43	7.98	65.24	3.32	15.86	9.68	10.93	49.16	22.53	1.10	15.99
DVBTG-1004 (P_9)	61.26	65.34	14.53	18.48	6.47	6.32	73.81	2.66	11.60	13.28	10.84	59.14	22.13	1.31	17.57
Green Long Jaunpuri (P_{10})	46.93	54.86	9.37	12.10	5.82	4.24	73.20	2.55	12.90	11.46	10.06	52.06	20.80	1.08	21.67
C.D.	2.251	2.382	0.388	0.464	0.171	0.154	2.616	0.11	0.427	0.313	0.268	2.229	0.669	0.032	0.588
SE(m)	0.752	0.796	0.13	0.155	0.057	0.051	0.874	0.04	0.143	0.105	0.09	0.745	0.223	0.011	0.196
SE(d)	1.063	1.125	0.183	0.219	0.081	0.073	1.235	0.05	0.202	0.148	0.127	1.053	0.316	0.015	0.278
C.V.	2.639	2.489	2.189	2.057	1.641	1.486	2.218	2.18	1.745	1.661	1.449	2.376	1.556	1.397	1.949





Conclusion

The maximum genotypic coefficient of variation was recorded for two traits: sex ratio (male: female) at 20.93% and number of primary branches per plant at 21.30%, with the phenotypic coefficient of variation (PCV) exceeding the genotypic coefficient of variation (GCV) in both cases. Furthermore, high heritability and genetic advance were observed for traits such as days to first staminate flower anthesis, days to first pistillate flower anthesis, and the node position of the first staminate flower. These findings indicate that selecting for these traits could be an effective approach to enhance bitter gourd yield. Thus, selection based on these attributes would be advantageous.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Enhancing the shelf life of tomato ketchup: An organoleptic analysis of natural and synthetic preservatives

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ABSTRACT

Tomato ketchup, a widely consumed condiment, requires effective preservation to maintain its shelf-life, taste, and quality. This study, conducted in 2025 at ICAR-KVK Panchmahal, Gujarat, compared the sensory attributes of tomato ketchup prepared with natural preservatives (NP) (vinegar and lemon juice) and synthetic preservatives (SP) (sodium metabisulphite). Sensory evaluation was conducted using a 5 point Hedonic scale among 40 farmers and 10 staff members of ICAR-KVK Panchmahal, Gujarat. The organoleptic assessment revealed that colour was slightly more preferred in SP ketchup, with 76% of respondents strongly liking it, compared to 74% for NP ketchup. Flavour and smell were rated higher for NP ketchup, with 72% and 84% of respondents strongly liked its flavour and aroma, respectively, while SP ketchup scored 68% and 80% on these parameters. Texture preference was comparable, with 52% of respondents strongly liking NP ketchup and 50% preferring SP ketchup, though the Weighted Mean Score (WMS) was higher for SP ketchup (4.26) than NP ketchup (4.12). General acceptability was higher for SP ketchup (WMS: 4.68) compared to NP ketchup (4.52), primarily due to its extended shelf-life (40 days at room temperature, 90 days refrigerated vs. 7 and 15 days for NP). NP ketchup was favoured for its natural taste. Production costs were lower for SP ketchup (₹92/kg) than NP (₹130/kg), though NP appeals to health-conscious consumers. While SP ketchup offers superior shelf stability and cost-effectiveness, NP ketchup is preferred for its flavour and natural ingredients, highlighting a trade-off between shelf-life, cost and sensory appeal.

Introduction

Tomatoes (*Solanum lycopersicum* L.) is widely consumed as vegetable and play an important role in nutrition because of well-established health benefits (Salehi *et al.,* 2019). It is used in various processed food products such as sauces, salads, soups, and pastes. Common nutrients reported in tomatoes are vitamins, minerals, fibre, protein, essential amino acids, monounsaturated fatty acids (MUFA), carotenoids and phytosterols (Lenucci *et al.,* 2006). Many types of antioxidant compounds i.e., alpha/beta/gamma/delta tocopherols, carotenoids, ascorbic acid, lycopene, and flavonoids are found in tomatoes. Generally, antioxidant compounds play important roles in the prevention of several human degenerative diseases, including CVD (cardio vascular diseases), diabetes, cancer, neurological diseases,

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and aging by minimizing oxidative stress. Oxidative stress (resulting from redox homeostasis imbalance between prooxidative and antioxidant systems) is a major player in the pathogenesis of many inflammatory, metabolic, cardiovascular, degenerative, and neoplastic diseases (Halliwell, 2015).

Tomato helps in improving vision, boosting immunity, and normalizing blood glucose level and cholesterol levels (Bhowmik *et al.,* 2012). The highest tomato producing states in India are Madhya Pradesh, Andhra Pradesh, Karnataka, Gujarat and Tamil Nadu. These states account for about 90% of total tomato production in the country. Tomato is highly perishable commodity as it has moisture content more than 90 percent (Dereje *et al.,* 2019). Shelf life of tomatoes is few days (less than 3 days) due to its high moisture content in tropical regions. So, post-harvest losses of tomatoes are great challenge in the developing countries where cold storage facilities are inadequate (Arah *et al.*, 2015). It is therefore, extremely important to process the tomatoes into value added products like paste, puree, juice and ketchup etc. to utilize for further consumption.

The processing of tomato helps to protect these losses that occur in between the harvest to final consumption stage. Thus, food preservation is a sound approach to utilize the tomato during off season by storing them in form of some product for off season use. There is also a great scope in the food processing sector through value addition of tomatoes in the form of puree, paste, juice and ketchup to generate income of farmers in developing countries. Hence, food preservation is useful technique for enhancing shelf life of the tomato. So, this study was conducted to analyse the sensory taste of tomato ketchups prepared with natural and synthetic preservatives.

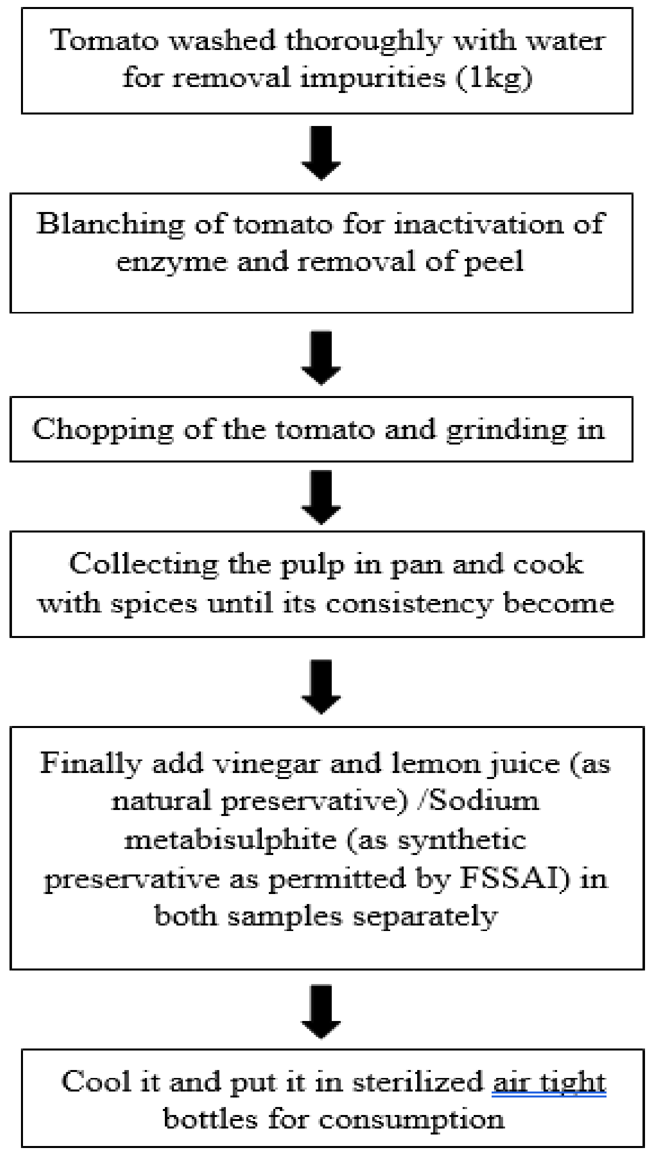
Material And Methods

The present study was conducted in year 2025 at ICAR-CIAH-Krishi Vigyan Kendra Panchmahal, Gujarat. Fresh tomatoes were purchased from the local market in Godhra, thoroughly washed with lukewarm water and salt to remove dirt and pesticide residues. Blanching was performed by boiling for less than one minute and immediately immersing the tomatoes in cold water. The tomatoes were then peeled, sliced, deseeded, and blended into a pulp. The pulp was cooked on low flame with water, spices (black pepper, cardamom), and salt until it thickened (half of initial concentration). Two formulations were prepared:

1. Natural Preservatives (NP): Vinegar (50 ml of 2% acetic acid concentration), lemon juice (20 ml) and salt (1%) were added.
2. Synthetic Preservatives (SP): Sodium metabisulphite (0.001%) was added as per FSSAI recommendations.

Both samples were cooled and stored in sterilized glass jars for sensory evaluation.

Flow chart for preparation of tomato ketchup



The effect of natural and synthetic preservatives was studied using a 5 point Hedonic scale of sensory evaluation (Birol *et al.*, 2015). The organoleptic quality scoring system is presented in Table 1.

Table 1. Hedonic scale (5 point) for sensory evaluation

Score	General/overall acceptability	Colour	Smell	Flavour	Texture
1	Strongly dislike	Very pale	Strongly dislike	Very poor	Strongly dislike
2	Dislike	Pale	Dislike	Poor	Dislike
3	Neutral	Moderate red	Neutral	Fair	Neutral
4	Like	Red	Like	Good	Like
5	Strongly like	Dark red	Strongly like	Very good	Strongly like

Sample size: The effect of natural and synthetic preservatives was analysed using a 5 point Hedonic scale of sensory evaluation. Data were collected from 50 untrained (40 farmers and 10 staff members of KVK Panchmahal, Gujarat) persons.

Statistical tools: Frequency, percentage, and weighted mean score (WMS) were used to evaluate the sensory responses. According to Agarwal (2006), weighted mean score was computed during the analysis of the data to calculate the likeliness of tomato ketchups with natural and synthetic preservatives. The weighted mean score was calculated by using following formula:

$$x = \frac{w_1 x_1 + w_2 x_2 + \cdots w_k x_k}{w_1 + w_2 + \cdots w_k}$$

Where:-

$w_1, w_2, \ldots\ldots\ldots w_k$ are the frequencies of responses for each score.

$x_1, x_2, \ldots\ldots\ldots x_k$ are the corresponding scores (1, 2, 3, 4, 5) on the 5-point Hedonic scale.

Results and Discussion

The organoleptic evaluation of tomato ketchup samples prepared with natural preservatives (NP) and synthetic preservatives (SP) was conducted using a 5 point Hedonic scale, with responses recorded from 40 farmers and 10 staff members of ICAR (CIAH) KVK Panchmahal. The results, as shown in Table 2, highlight variations in consumer preferences for colour, flavour, smell, texture, and general acceptability of both formulations. For colour, 74% of respondents strongly liked the NP formulation, whereas 76% strongly liked the SP formulation, as depicted in Fig. 1a. The like responses were 8% for NP and 4% for SP, while 10% and 14% of respondents remained neutral for NP and SP, respectively. Dislike levels were 8% for NP and 6% for SP, with no strong dislikes for either formulation. As shown in Fig. 1b for flavour, 72% of respondents strongly liked the NP formulation, compared to 68% for the SP. The "like" category had 14% for NP and 10% for SP, whereas neutral responses were 8% for NP and 16% for SP. Additionally, 6% of respondents disliked the NP formulation, while 4% disliked SP, and 2% strongly disliked the SP formulation. For smell, NP was strongly liked by 84% of respondents, compared to 80% for SP, as illustrated in Fig. 1c. Neutral responses were 4% for NP and 10% for SP, while both formulations had 4% dislikes and 2% strong dislikes. In terms of texture, 52% strongly liked NP, while 50% strongly liked SP. The like responses were 20% for NP and 26% for SP, while neutral responses were 20% for NP and 24% for SP. Notably, 4% of respondents disliked NP, while none disliked SP (Fig. 1d). The overall acceptability was higher for SP, with 84% strongly liked it, compared to 76% for NP as exhibited in Fig. 1e. Few respondents (2%) disliked or strongly disliked both formulations, mainly due to differences in shelf-life. Overall, the SP formulation was more preferred for its longer shelf-life, while NP was rated higher for its natural flavour and aroma. There was no significant ($p>0.05$) difference was found on organoleptic parameters of both ketchup formulations.

Table 2. Percent of respondents on organoleptic test scale for tomato ketchup samples

Sensory parameter	Dark red	Slightly red	Moderate	Pale	Very pale
Colour (NP)	74	8	10	8	0
Colour (SP)	76	4	14	6	0
Sensory parameter	Very good	Good	Fair	Poor	Very poor
Flavour (NP)	72	14	8	6	0
Flavour (SP)	68	10	16	4	2
Sensory parameter	Strongly like	Like	Neutral	Dislike	Strongly dislike
Smell (NP)	84	6	4	4	2
Smell (SP)	80	4	10	4	2
Texture (NP)	52	20	20	4	4
Texture (SP)	50	26	24	0	0
General acceptability (NP)	76	6	14	2	2
General acceptability (SP)	84	6	6	2	2

Shelf life of tomato ketchups with different preservatives

Table 3 presents the shelf life of tomato ketchups prepared using natural and synthetic preservatives under two storage conditions: room temperature and refrigeration. Ketchups made with natural preservatives such as vinegar, lemon juice showed a shelf life of 7 days at room temperature and 15 days under refrigerated conditions. On the other hand, those made with synthetic preservatives sodium metabisulphite lasted significantly longer 40 days at room temperature and 90 days when refrigerated. This clearly demonstrates that synthetic preservatives are more effective in extending the shelf life of tomato ketchup. However, natural preservatives are often preferred for being safer and more environmentally friendly, despite their shorter duration. Additionally, refrigeration helped improve the shelf life of both types of ketchups. These results are consistent with the findings of Thakur *et al.* (2018), who also reported superior shelf life with synthetic preservatives.

Table 3. Shelf life (days) of tomato ketchups

Tomato ketchup	At room temperature	At refrigerator temperature
Natural preservatives	07	15
Synthetic preservative	40	90

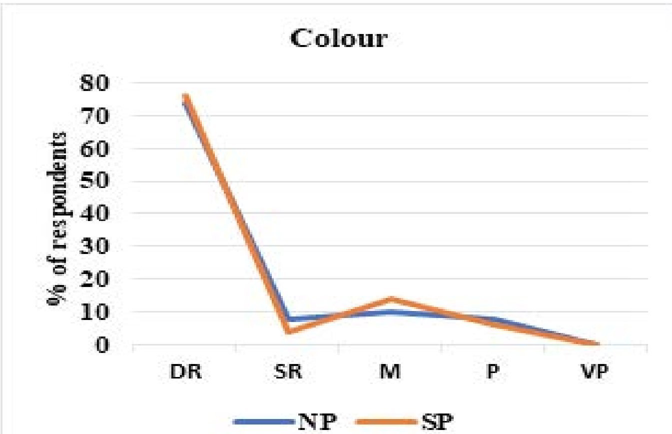


Fig.1a. Colour preference of both formulations of tomato ketchup

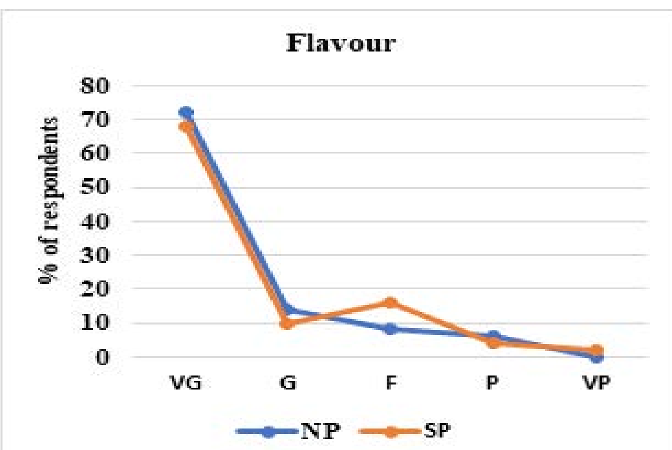


Fig.1b. Flavour preference of both formulations of tomato ketchup

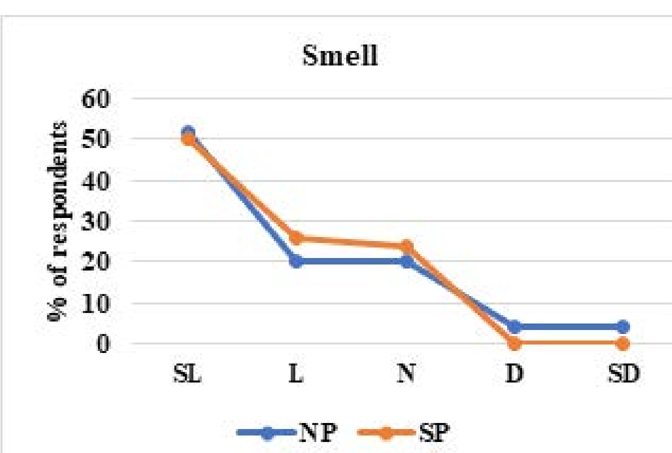


Fig.1c. Smell preference of both formulations of tomato ketchup

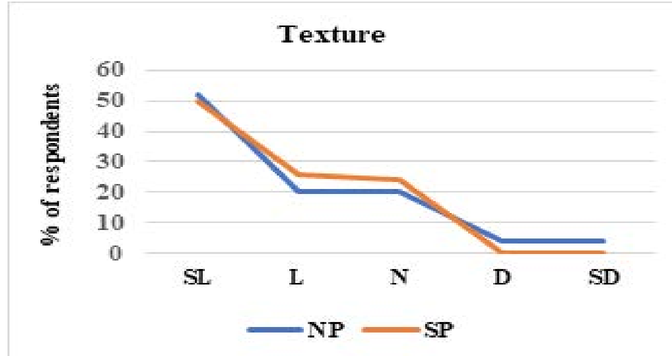


Fig.1d. Texture preference of both formulations of tomato ketchup

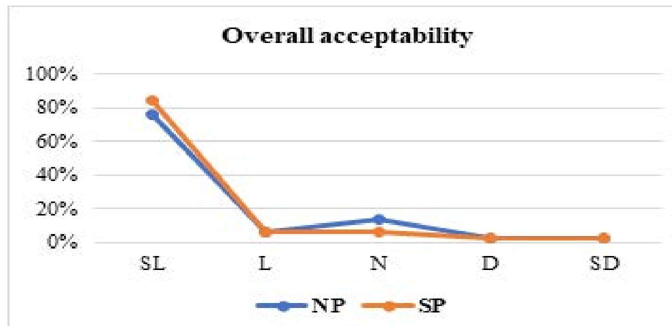


Fig.1e General acceptability of both formulations of tomato ketchup

Sensory evaluation of tomato ketchup based on weighted mean score

The weighted mean scores (WMS) for different sensory parameters of tomato ketchup formulations prepared with natural preservatives (NP) and synthetic preservatives (SP) were analyzed. The results, as presented in Table 4 & Figure 2 indicate variations in consumer preferences based on colour, flavour, smell, texture, and general acceptability. For colour, the WMS for NP ketchup was 4.48, while SP ketchup scored slightly higher at 4.50, showing a marginal preference for the synthetic formulation. In terms of flavour, NP ketchup received a higher score of 4.52, compared to 4.38 for SP ketchup, suggesting that consumers preferred the natural formulation due to its enhanced taste from ingredients like vinegar and lemon juice. For smell, both formulations scored high, with NP at 4.54 and SP at 4.56, indicating that consumers appreciated the aroma of both variants almost equally. Regarding texture, SP ketchup scored 4.26, which was slightly higher than 4.12 for NP ketchup, showing that the synthetic formulation provided a smoother consistency. These results show similarities with study of Tauferova, *et al.* (2015) that texture was the second most preferred parameter in consumer's choice. General acceptability of SP ketchup was rated highest, with a WMS of 4.68, while NP ketchup scored 4.52.

This suggests that although consumers liked the taste of the natural formulation, the synthetic variant was overall more preferred, likely due to its longer shelf life and smoother texture. Overall, while the natural preservative formulation was favoured for its flavour, the synthetic preservative formulation was preferred for its texture, colour and overall acceptability.

Table 4. Weighted mean score of respondents on sensory parameters

Sensory parameters	NP ketchup	SP ketchup
Colour	4.48	4.50
Flavour	4.52	4.38
Smell	4.54	4.56
Texture	4.12	4.26
General acceptability	4.52	4.68

NP: Natural preservatives and SP: Synthetic preservatives

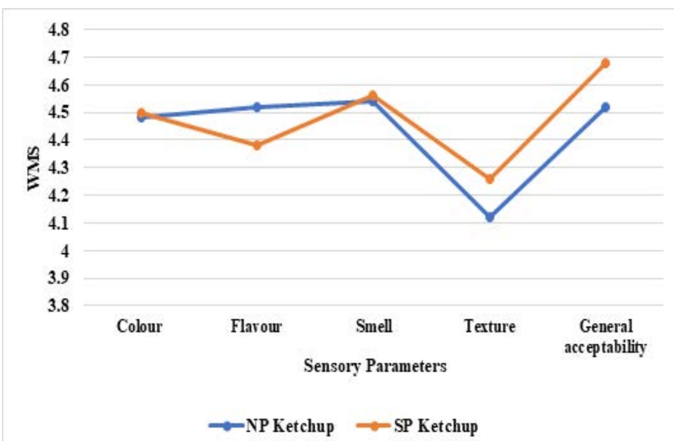


Fig. 2. Comparative analysis of tomato ketchup on sensory parameters using WMS

Comparative economics for tomato ketchup preparation using different preservatives

The production cost of tomato ketchup using natural and synthetic preservatives is compared. In both cases, the cost of tomatoes remains the same at ₹ 50 per kg. For natural preservatives, a combination of vinegar (₹ 20), lemon juice (₹ 20), and salt is used, making the preservative cost relatively higher. For synthetic preservatives, sodium metabisulphite is used, costing just ₹ 2 per gram, which is much more economical. The packaging cost, using a glass bottle, is constant at ₹ 40 for both types. When all factors are considered, the total production cost for ketchup with natural preservatives is ₹ 130 per kg, while that with synthetic preservatives is only ₹ 92 per kg. This shows that using synthetic preservatives significantly reduces the cost of production. However, natural preservatives may appeal more to health-conscious consumers. Thus, producers must balance between cost effectiveness and consumer preference when selecting preservatives for ketchup manufacturing, as shown in Table 5.

Table 5. Comparative economics for tomato ketchup preparation

Factor	Natural preservative	Synthetic preservative
Tomato	₹ 50/- kg	₹ 50/- kg
Preservative	Vinegar (₹ 20), Lemon (₹ 20), Salt	Sodium metabisulphite (₹ 2 per gram)
Glass bottle	₹ 40	₹ 40
Total production cost	₹ 130/- kg	₹ 92/- kg

Conclusion

The study revealed that synthetic preservative (SP) ketchup was preferred for its longer shelf life and had a higher general acceptability score (4.68) compared to natural preservative (NP) ketchup (4.52). However, NP ketchup was rated higher in flavour (4.52 vs. 4.38 for SP) and smell (4.54 vs. 4.56 for SP), likely due to the use of vinegar and lemon juice. Colour (4.48 for NP, 4.50 for SP) and texture (4.12 for NP, 4.26 for SP) showed marginal differences. Overall, SP ketchup was more acceptable (84% strongly liked it vs. 76% for NP), exhibited a longer shelf-life (40 days at room temperature and 90 days refrigerated), and had a lower production cost (₹92/kg). In contrast, NP ketchup had a shorter shelf-life (7 and 15 days) and a higher cost (₹130/kg), but was preferred for its natural flavour (72%) and aroma (84%), appealing to health-conscious consumers. No significant differences ($p > 0.05$) were observed in organoleptic parameters. These findings suggest consumer preferences vary based on priorities; natural quality versus shelf stability and cost.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Influence of VAM fungi on growth of jackfruit (*Artocarpus heterophyllus* L.) cv. Rudrakshi, soil parameters and microbial population of soil

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ABSTRACT

The soil application of various VAM treatments significantly influenced the growth of jackfruit (*Artocarpus heterophyllus* L.) cv. Rudrakshi. Among the treatments, T_6 (RDF + 70g VAM) was found to be significantly superior to all others with respect to plant growth and soil parameters. T_6 recorded the highest plant height (1.40 m), plant girth (148.42 mm), number of leaves per shoot (48.00) and number of shoots per plant (29.67). In addition, it also resulted in improved soil characteristics, including optimal pH (7.23) and population of fungi (10.67×10^3 cfu g^{-1}).

Introduction

The jackfruit (*Artocarpus heterophyllus* L.) is a valuable fruit tree in tropical and subtropical area belonging to the family Moraceae. It has a lot of potential for adding value. Both ripe and mature green jackfruit can be used to make over 100 processed items. As per NHB second advance estimates (2024-25), the total area in India under jackfruit cultivation is 1.86 lakh hectares, and production is 32.84 lakh metric tonnes (Anonymous, 2024-25).

Research highlights that soil microbes including VAM improves soil structure and microbial activity around the rhizosphere, creating favorable conditions for long-term growth and sustainability. Rhizosphere soil has been reported useful in improving the soil microorganism for plants and subsequently growth and development (Hodge *et al.*, 2001; Tippannavar and Singh, 2023 and Gahlot *et al.*, 2024). Hence, the study aims to evaluate the effect of VAM on jackfruit growth, soil properties, and soil microbial populations.

Material and Methods

The study was conducted during 2024–25 on jackfruit (*Artocarpus heterophyllus* L.) cultivar Rudrakshi, with the objective of evaluating the effect of Vesicular Arbuscular Mycorrhiza (VAM) on plant growth, soil parameters, and microbial population dynamics. The experiment consisted of 7 treatments, viz. T_0 (control), T_1 (RDF + 20g VAM), T_2 (RDF + 30g VAM), T_3 (RDF + 40g VAM), T_4 (RDF + 50g VAM), T_5 (RDF + 60g VAM) and T_6 (RDF + 70g VAM). The investigation was carried out at the Instructional Farm, Department of Fruit Science, College of Horticulture and Forestry, Jhalrapatan, Jhalawar. The age of the plants was two and a half years. The treatments were administered in the root zone of the plants at the start of the experiment. These treatments were applied after recording the initial growth and development parameters of the plants, just before the treatment application.

The experiment was laid out in a Randomized Block Design with three replications. The plant growth parameters

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were recorded initially during April, 2024 and then after every four-month interval till April, 2025. Thus, during the experiment, right from April, 2024 to April, 2025, observations were recorded four times (including initial and intermediate observations) during April, August, December, 2024 and April, 2025 for different plant parameters.

Soil parameters were recorded initially and at the termination of the experiment during April, 2025. The undisturbed soil samples were drawn from 0-30 cm depth with the help of auger from rhizosphere of plant. These soil samples were processed and stored in polyethylene bags till their analysis for various parameters. The pH and electrical conductivity of the soil were analyzed using the procedure described by Richards (1954). Soil organic carbon and microbial populations were estimated following the methods of Walkley and Black (1934) and Schmidt and Caldwell (1967), respectively.

Results and Discussion

The data presented in the Table 1 & 2 clearly demonstrate a significant effect of VAM application on growth parameters of jackfruit. A consistent increase in plant height was observed with the progressive application of higher VAM doses in combination with the recommended dose of fertilizer (RDF). There was a progressive increase in plant height across all treatments during the study period. The highest plant height was observed in T_6 (RDF + 70g VAM), which reached 1.40 m in April 2025. This represented an 18.64% **increase** over the initial height (1.18 m in April 2024) and was significantly higher than all other treatments. A similar trend was observed in plant girth. The maximum girth was recorded in T_6, reaching 148.42 mm by April 2025, showing a 23.40% increase over the initial measurement (120.7 mm in April 2024). This was significantly higher than all other treatments.

A progressive increase in the number of leaves per shoot was observed from April 2024 to April 2025 across all treatments. The maximum number of leaves per shoot was recorded in T_6 (RDF + 70g VAM), which reached 48.00 leaves per shoot in April 2025, showing a 453.63% increase over the control (T_0, 23.67 leaves per shoot). This was followed by T_5 (RDF + 60g VAM) with 42.33 leaves (429.12%), and T_4 (RDF + 50g VAM) with 40.33 leaves (425.81%). Similarly, the number of shoots per plant increased significantly with higher levels of VAM application. The maximum number of shoots per plant was observed in T_6, with 29.67 shoots in April 2025, representing a 128.23% increase over the control (14.00 shoots). This was followed by T_5 (28.67 shoots; 126.28%) and T_4 (26.33 shoots; 119.41%). These findings suggest that the application of VAM, particularly at 70g per plant (T_6), in conjunction with RDF, significantly enhances the vegetative growth of jackfruit. The results are in close conformity to the findings of Wu *et al.* (2010) and Kumari *et al.* (2017).

The study indicated that VAM significantly influenced the soil parameters like pH and population of fungi (Table 3). The minimum soil pH (7.33) was observed in treatments T_2 (RDF + 30g VAM) and T_5 (RDF + 60g VAM), which was comparable to T_6 (RDF + 70g VAM), with a pH of 7.34 at termination of the experiment. Throughout the various observation periods, the treatments had a non-significant impact on electrical conductivity. The amount of organic carbon in the soil varied considerably; however, it was not significantly affected by the various VAM treatments.

The treatment T_6 (RDF + 70g VAM) recorded the highest microbial population (Fungi: 10.67×10^3 cfu g^{-1} soil), which was significantly higher than all other treatments at the end of the experiment (April 2025). The bacterial population was not significantly affected by the various VAM treatments throughout the experiment. The beneficial effect of VAM on different soil parameters was also reported by several researches in different crops and the findings of this study are in line with those of Singh *et al.* (2010), Dutta and Kundu (2012), Sharma *et al.* (2017) and Nandish *et al.* (2020).

Table 1. Effect of VAM on height of plant and plant girth of jackfruit cv. Rudrakshi

Treatments	Plant height (m)*				Plant girth (mm)*			
	Apr-24	Aug-24	Dec-24	Apr-25	Apr-24	Aug-24	Dec-24	Apr-25
T_0 (Control) RDF	1.15	1.17 (1.73%)	1.21 (5.21%)	1.23 (6.95%)	120.08	122.06 (1.64%)	126.09 (5.00%)	130.14 (8.37%)
T_1 (RDF + 20g VAM)	1.16	1.19 (2.58%)	1.24 (6.89%)	1.28 (10.34%)	120.1	123.08 (2.47%)	128.12 (6.66%)	132.20 (10.06%)
T_2 (RDF + 30g VAM)	1.16	1.20 (3.44%)	1.26 (8.62%)	1.30 (12.06)	120.4	124.11 (3.30%)	130.14 (8.32%)	135.24 (12.56%)
T_3 (RDF + 40g VAM)	1.17	1.22 (4.27%)	1.29 (10.25%)	1.34 (14.52%)	120.8	125.14 (4.12%)	132.17 (9.97%)	138.28 (15.06%)

T_4 (RDF + 50g VAM)	1.17	1.22 (4.27%)	1.29 (10.25%)	1.35 (15.38%)	120.1	127.17 (5.78%)	134.21 (11.67%)	142.33 (18.40%)
T_5 (RDF + 60g VAM)	1.18	1.24 (5.08%)	1.31 (11.01%)	1.37 (16.10%)	120.3	128.17 (6.60%)	136.24 (13.31%)	145.37 (20.90%)
T_6 (RDF + 70g VAM)	1.18	1.25 (5.93%)	1.33 (12.71`%)	1.40 (18.64%)	120.7	129.24 (7.45%)	138.28 (14.97%)	148.42 (23.40%)
SEm (±)		0.002	0.004	0.004	-	0.013	0.004	0.003
CD (5%)		0.007	0.012	0.012	-	0.041	0.013	0.010

*Per cent increase in parentheses

Table 2. Effect of VAM on the number of leaves per shoot and the number of shoots per plant in jackfruit cv. Rudrakshi

Treatments	Number of leaves per shoot*				Number of shoots per plant*			
	Apr-24	Aug-24	Dec-24	Apr-25	Apr-24	Aug-24	Dec-24	Apr-25
T_0 (Control) RDF	6.33	10.33 (63.19%)	18.67 (194.94%)	23.67 (273.93%)	10.3	11.00 (6.48%)	13.33 (29.04%)	14.00 (35.52%)
T_1 (RDF + 20g VAM)	6.67	11.67 (74.96%)	26.67 (289.80%)	32.00 (379.76%)	10.7	13.33 (24.92%)	16.00 (49.95%)	19.33 (81.16%)
T_2 (RDF + 30g VAM)	7.0	13.00 (85.71%)	27.33 (290.42%)	34.33 (390.42%)	11.0	14.67 (33.36%)	18.33 (66.63%)	22.33 (103.00%)
T_3 (RDF + 40g VAM)	7.3	13.67 (86.49%)	28.67 (291.13%)	37.00 (404.77%)	11.3	15.67 (38.30%)	19.00 (67.69%)	24.67 (117.74%)
T_4 (RDF + 50g VAM)	7.7	14.67 (91.26%)	30.33 (295.43%)	40.33 (425.81%)	12.0	16.67 (38.91%)	21.33 (77.75%)	26.33 (119.41%)
T_5 (RDF + 60g VAM)	8.0	16.00 (100.00%)	32.33 (304.12%)	42.33 (429.12%)	12.7	17.67 (39.46%)	22.67 (78.92%)	28.67 (126.28%)
T_6 (RDF + 70g VAM)	8.7	17.67 (103.80)	35.33 (307.49%)	48.00 (453.63%)	13.0	18.33 (41.00%)	23.33 (79.46%)	29.67 (128.23%)
SEm (±)		0.304	0.549	0.321	-	0.477	0.192	0.236
CD (5%)		0.938	1.692	0.990	-	1.470	0.593	0.726

*Per cent increase in parentheses

Table 3. Soil parameters of jackfruit cv. Rudrakshi orchard as affected by soil application of VAM

Treatments	pH	Electrical conductivity (dS m^{-1})	Organic carbon (%)	Bacteria (× 10^5 cfu/ g soil)	Fungi (× 10^3 cfu/ g soil)
Initial value	7.37	0.45	0.30	3.07	3.00
T_0 (Control) RDF	7.36	0.44	0.31	3.07	3.00
T_1 (RDF + 20g VAM)	7.35	0.45	0.32	3.12	3.67
T_2 (RDF + 30g VAM)	7.33	0.47	0.34	3.26	4.67
T_3 (RDF + 40g VAM)	7.34	0.47	0.34	3.24	6.00
T_4 (RDF + 50g VAM)	7.34	0.48	0.34	3.23	7.33
T_5 (RDF + 60g VAM)	7.33	0.50	0.34	3.29	8.67
T_6 (RDF + 70g VAM)	7.34	0.51	0.35	3.36	10.67
SEm (±)	0.003	NS	NS	NS	0.35
CD (5%)	0.010	NS	NS	NS	1.08

Conclusion

Based on the findings from the field experiment, treatment T_6 (RDF + 70g VAM) proved to be significantly superior to all other treatments in terms of vegetative growth of jackfruit and soil parameters. The plant growth characters viz., plant height (1.40 m), plant girth (148.42 mm), number of leaves per shoot (48.00), number of shoots per plant, (29.67), increased significantly under T_6 (RDF + 70g VAM) treatment over other treatments. The treatment T_6 (RDF + 70g VAM) significantly improved the soil attributes such as pH (7.34) and microbial population (fungi 10.67 × 10^3 cfu g^{-3}) as compared to other treatments. Overall, the soil application of T_6 treatment (RDF + 70g VAM) in jackfruit cv. Rudrakshi plant was found highly effective to enhance the plant growth and soil attributes.

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Conflict of Interest

The authors declare no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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Research Article

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Effect of micronutrients and plant growth regulators on fruit set and retention in ber (*Ziziphus mauritiana* Lamk.)

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ABSTRACT

The determination of fruit set has been used in ber as a consistent indicator of the real productivity level. Due to short flower life, prevalence of self and cross incompatibility, pollen sterility and synchronous protandrous dichogamy, fruit set in the ber largely depends on sources of pollination, its related factors like effective pollination period, pollinators, environmental conditions, and the success in fertilization. Hence, any factor that can extend the effective pollination period, pollen germination and pollen tube growth such as the application of micronutrient or plant growth regulators, should be beneficial for fruit production. During 2020– 21, forty-one genotypes of ber were evaluated for fruit set at ICAR-CIAH, Bikaner. Simultaneously, a trial was conducted to find out the response of micronutrients and plant growth regulators on fruit set and fruit retention in the 'Gola' ber. Foliar sprays of micronutrients (Boron at 0.1% and Zinc at 0.5%) and graded doses (10, 20, and 30 ppm) of plant growth regulators (GA_3, NAA, kinetin, and benzyladenine) were applied at BBCH stage 54 (green bud) and 67 (flower fading *i.e.* most petal fall). The genotypes showed large variation in natural fruit sets ranging from 0.34 (Chochal) to 13.89% (Illaichi). About 88 per cent of genotypes under observation exhibited fruit set less than 6 per cent. Intervention with micronutrients and plant growth regulators applied at two different stages bring a significant response on fruit set in Gola ber. Among the various treatments evaluated, the highest fruit set was observed with the application of 0.1% boron (B) at BBCH stage 67 (11.41%), followed closely by the application of 10 ppm gibberellic acid (GA3) at the same stage (10.94%). Both treatments were statistically on par in terms of fruit set. However, the boron treatment demonstrated a superior fruit retention rate (80.38%) compared to GA3 (63.68%). In contrast, the water-sprayed control trees recorded significantly lower fruit set (3.77%) and retention (56.52%). In conclusion, the application of Boron (0.1%) at BBCH stage 67 is an effective approach to enhance fruit set and retention in ber cv. Gola under the hot arid regions of Rajasthan.

Introduction

Ber belongs to the family Rhamnaceae, which consists of about 45 genera and 950 species (Christenhusz and Byng, 2016). The genus *Ziziphus* includes approximately 170 species native to the tropics and subtropics. Of these, approximately 150 species are native to the Old World, including Europe, the Middle East, Africa, the Indian subcontinent, and Asia

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(Liu and Cheng, 1995), while about 25 species originate from the New World, covering the Americas and the Caribbean islands (Schirarend, 1991). Among these, *Ziziphus mauritiana*, *Ziziphus rotundifolia*, and *Ziziphus nummularia* are particularly well-adapted to dry and hot climates, thriving in harsh environments with degraded soils, high temperatures, and limited water availability. However, due to its greater economic significance, *Z. mauritiana* is extensively cultivated in the arid and semi-arid regions of Rajasthan.

Most angiosperm species produce hermaphroditic flowers (Renner, 2014), which favours self- pollination and consequently inbreeding depression. To counter this, plants with hermaphroditic flowers often evolve morphological, molecular, and/ or phenological adaptations that favours cross-pollination. The mechanisms preventing self-pollination in *Ziziphus mauritiana* are well- documented through studies on its morphology, physiology, genetics, and reproduction (Tel-Zur and Schneider, 2009; Asatryan and Tel-Zur, 2013; Asatryan and Tel-Zur, 2014).

Self-incompatibility is the inability of a fertile hermaphroditic plant to form zygotes following self-pollination (Allen and Hiscock, 2008). *Ziziphus mauritiana* exhibits self-incompatibility (Asatryan and Tel-Zur, 2013), which is governed by a gametophytic mechanism (Asatryan and Tel-Zur, 2013). An additional mechanism that reduces self-fertilization in *Ziziphus mauritiana* is dichogamy. Its flowers exhibit synchronous protandrous dichogamy, i.e., flowers of an individual plant mature in synchrony, and anther dehiscence precedes stigma receptivity, with little or no over-lapping between the sexual stages (Islam and Simmons, 2006; Asatryan and Tel-Zur, 2013; Tel-Zur and Schneider, 2009).

Due to the prevalence of self and cross incompatibility and synchronous protandrous dichogamy, fruit set in the ber largely depends on sources of pollination, its related factors like effective pollination period, pollinators, environmental conditions, and the success in fertilization. Further, the life of an individual ber flower is very short and many flowers are not pollinated during their respective period. Consequently, despite a very profuse flowering, fruit set in ber is very low even under open pollination. Natural fruit set in ber varies from 2-18 per cent (Vashishtha and Pareek, 1979). Therefore, the determination of fruit set has been used in ber as a consistent indicator of the real productivity level. Hence, any factor that can extend the effective pollination period, pollen germination and pollen tube growth such as the application of micronutrient or plant growth regulators, could be beneficial for fruit production.

Some micronutrients (Zn & B) and plant growth regulators (auxin, cytokinin, gibberellins) are known for their positive influence on fruit set by affecting pollen germination and pollen tube growth. However, their concentration, targeted stage as well as interaction with climatic variables have an influence on their response. The present experiment was conducted to find out the response of micronutrients and plant growth regulators on fruit set in Gola cultivar of ber under hot arid region.

Material and Methods

The present study was carried out at the ICAR–Central Institute for Arid Horticulture (CIAH), Bikaner, Rajasthan, located at 28°06' N latitude, 73°20' E longitude, and an elevation of 240 m above mean sea level. The site lies within the Western dry region of India, characterized by extremely hot summers, with maximum temperatures reaching up to 50 °C, and moderately cold winters, with minimum temperatures occasionally dropping to −3 °C. During the flowering and fruit set period (September–October) of 2020, the mean monthly temperature was 28.90 °C, about 0.06 °C higher than the decadal average for the same months (2010–2019).

During 2020–21, 41 genotypes of ber were evaluated for fruit set. Three trees of each genotype were selected, and two proleptic branches on each tree were tagged in two directions (East-South and North-West) to observe natural fruit set. Each tree was treated as one replication. Simultaneously, a trial was conducted to find out the response of micronutrients and plant growth regulators on fruit set and fruit retention in the 'Gola' ber. Foliar sprays of micronutrients (Boron at 0.1% and Zinc at 0.5%) and graded doses (10, 20, and 30 ppm) of plant growth regulators (GA_3- gibberellic acid, NAA-naphthaleneacetic acid, kinetin, and benzyladenine) were applied at BBCH stage 54 (green bud) and 67 (flower fading *i.e.* most petal fall). The experiment was set up in factorial randomized block design with three replications of two trees per replicate. For assessing fruit set and retention, two uniform and healthy proleptic branches were selected from each tree in two directions (East-South and North-West). The total number of flowers on each selected branch was counted. At 15 days after the last bloom (DALB), the number of fruits set was counted. Subsequently, the number of fruits retained until harvest was counted. The fruit set and retention data were expressed as percentages using the following formulas for treatment comparison:

$$\text{Fruit set (\%)} = \frac{\text{No. of fruit set per branch at 15 DALB}}{\text{No. of flowers per branch}} \times 100$$

$$\text{Fruit retention (\%)} = \frac{\text{No. of fruit at harvest}}{\text{No. of fruit at 15 DALB}} \times 100$$

The collected experimental data were subjected to statistical analysis based on the analysis of variance (ANOVA) using the programme R Software. Significant differences at p=0.05 level was obtained using Duncan's multiple range test.

Result and Discussion

Experiment 1

The present study revealed a significant variation in natural fruit set among 41 ber (*Ziziphus mauritiana*) genotypes, ranging from as low as 0.34% in the genotype Chochal to as high as 13.89% in Illaichi. This wide range highlights the inherent genetic diversity present within the ber germplasm concerning reproductive success and adaptability under prevailing environmental conditions. The variation in fruit set among different genotypes corroborates earlier findings by Vashishtha and Pareek (1979), who also reported significant genotypic influence on fruit setting patterns in ber.

About 88% of the genotypes exhibited fruit set percentages below 6%, indicating that a substantial proportion of the studied genotypes may have limited reproductive efficiency under natural pollination in the hot arid climate. This low fruit set could be attributed to various factors including floral biology, pollen viability, stigma receptivity, pollinator activity, and environmental stressors such as high temperatures and low relative humidity.

On the other hand, a few genotypes demonstrated relatively higher fruit set, suggesting a better adaptation to arid conditions. Notably, Mehrun (7.07%), Rashmi (7.24%), and Umran (7.85%) recorded satisfactory levels of fruit set. The highest fruit set was observed in Illaichi (13.89%), indicating its potential as promising genotype for cultivation and future breeding programme. These genotypes might possess favorable floral traits or higher compatibility with the existing pollinator fauna, which could be contributing to their better performance.

Among the 41 genotypes evaluated, the average fruit set was significantly higher on the east– south side of the trees (4.7%) compared to the north–west side (3.4%). This variation may be attributed to differences in light interception and canopy microclimate. The east–south orientation receives more favorable sunlight during the morning and early afternoon, promoting optimal photosynthetic activity and maintaining suitable temperature conditions during the critical period of pollination and fertilization. During the fruit set phase (September–October), the sun's apparent path in September remains nearly balanced, rising close to the east and setting in the west, whereas in October it becomes lower in the sky and shifts toward the south in Bikaner. Consequently, improved light availability and moderated thermal conditions on the east–south side likely enhanced pollen viability, stigma receptivity, and overall fruit set.

The determination of natural fruit set serves as a reliable indicator of the reproductive potential and yield capacity in ber. Unlike other yield components that may vary due to management practices or environmental fluctuations, fruit set reflects the inherent reproductive efficiency of a genotype under natural pollination conditions. Therefore, genotypes exhibiting consistently higher fruit set are likely to possess greater yield stability and adaptability across diverse environments.

Table 1. Range of natural fruit set in different ber genotypes under the hot arid region.

Range (%)	Genotype(s)
0 – 2	Chochal, C. Bawal, Nazuk, Khatti
2 – 4	Gola, Banarsi Kadaka, Chhuhara, Sanaur, ZG-3, Jogia, Kissmiss, S. Rohtak, Kala Gola, Dharki No. 1, Safeda Selection, Tikadi, Aliganj, Jogia, Nanki, Laddu, Nilgiri, Ponda
4 – 6	Seb, Banarsi Pavindi, Mundia, Kathaphal, Lakhan, Thar Malti, Kheera, Kali, Dadan, Thornless, Banarsi, Kaithli, Gularvasi, Meharwali
6 – 8	Rashmi, Mehrun, Badami, Umran
>12	Illaichi

Experiment 2

Fruit set

The present study revealed that the fruit set (%) in ber cv. Gola was significantly influenced by the type and concentration of chemical treatments, as well as the stage of application (Figure 1; Table 2). Among the two stages evaluated, the flower fading stage (BBCH 67) exhibited a greater response to chemical treatments, resulting in a significantly (P = 0.0008) higher fruit set (5.89%) compared to the green bud stage (5.49%) (Figure 1). This suggests that the reproductive physiology of ber is more receptive to external stimuli closer to anthesis or immediately post- anthesis, likely due to enhanced metabolic and hormonal activity in the floral tissues during this period. Among the chemical treatments, boron (B) at 0.1% showed the most pronounced effect (10.3%; $P \leq 0.0001$), particularly when applied at BBCH 67, resulting in the highest fruit set of 11.4%, which was significantly superior ($P \leq 0.0001$) to the untreated control (3.77%) (Table 2). This enhanced fruit set aligns with the essential role of boron in reproductive development, as it forms borate cross-links in rhamnogalacturonan-II (RG-II) pectin that are critical for pollen tube growth, transmitting tissue integrity, and successful fertilization. The gene *NpGUT*1, responsible for RG-II biosynthesis and borate cross-linking, has been shown to be crucial for the development of male and female reproductive tissues and for guiding pollen tubes to the ovary during fertilization. Disruption of the boron–RG-II complex or the associated *NpGUT*1 gene results in sterility and defective reproductive tissue development (Iwai *et al.*, 2006). Reproductive tissues have a higher demand for boron than vegetative tissues (Rerkasem and Jamjod, 2004), likely due to the elevated concentration of the RG-II complex in the cell walls of pollen tubes (Matoh *et al*., 1997). Consequently, boron deficiency has a more severe impact on reproductive processes than on vegetative growth. In monocots, the putative boron transporter OsBOR4 is specifically expressed in floral tissues, and its disruption leads to impaired reproductive competence due to slower or reduced pollen tube growth in rice (Tanaka *et al*., 2013). Similarly, the expression of VvBOR1 (putative boron transporters in dicot) in floral tissue rises sharply at anthesis and expression can be directly linked to the accumulation of boron in grape berries during development (Pérez-Castro *et al*., 2012). Inadequate boron levels also disrupt microsporogenesis, resulting in reduced pollen production, smaller pollen grains, and lower pollen viability (Huang *et al*., 2000). Moreover, boron promotes pollen germination and pollen tube elongation, as demonstrated in apple (Sharafi and Raina, 2020) and almond (Agnes *et al*., 2000), highlighting its vital role in ensuring successful fertilization and fruit set.

The application of plant growth regulators (PGRs) also showed promising results, with a clear dependence on both the type and concentration used. GA_3 at 10 ppm, when applied at BBCH stage 67, resulted in a fruit set of 10.94%, which was statistically at par with the boron treatment (Table 2). Similarly, benzyladenine (BA) at 30 ppm and 20 ppm, applied at the same stage, produced fruit sets of 10.1% and 9.04%, respectively. Kinetin at 10 ppm, also applied at BBCH 67, was effective as well, resulting in a fruit set of 9.25 per cent.

Higher doses of BA (30 ppm) proved more effective than lower concentrations, indicating a positive response to increased levels. This suggests that higher concentrations of BA may further enhance fruit set in ber. Interestingly, lower concentrations (10 ppm) of GA3, NAA, and kinetin were generally more effective than higher doses, suggesting a threshold beyond which these compounds may not produce favorable physiological responses or could even inhibit normal reproductive development due to hormonal imbalance. However, NAA exhibited contradictory and even negative effects, especially when applied at BBCH 67. The fruit set in these treatments ranged from 0.9 to 1.28%, which was significantly lower than the control. This implies that NAA, at least at the tested concentrations and timings, may interfere with natural hormonal balance or cause excessive abscission in ber. Similarly, the application of zinc (Zn), regardless of timing, did not result in any significant improvement in fruit set, suggesting its limited role under the tested stage and conditions.

These findings are consistent with earlier research demonstrating the importance of plant growth regulators like GA3 (Garmendia *et al*., 2019; Lindo-García *et al*., 2020; Choudhary *et al*., 2020; Das *et al*., 2020; Jayachitra and Richard Kennedy, 2021; Priya *et al*., 2023; Narayan and Deen, 2024) in improving fruit set in fruit crops. The negative response of NAA, however, warrants further investigation into its concentration- dependent effects and interaction with endogenous hormones during the flowering and early fruiting stages in ber.

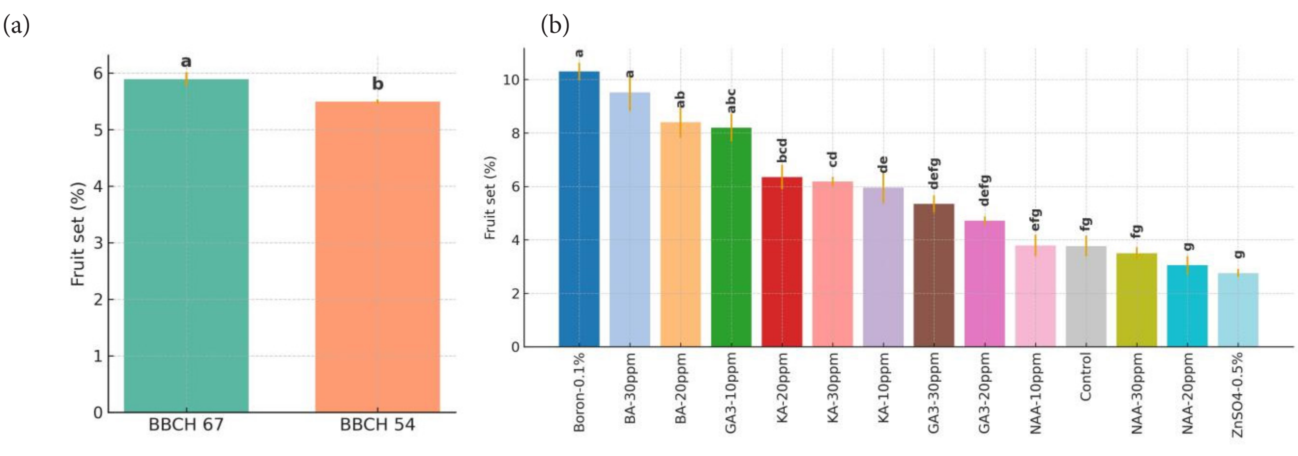

Fig. 1. Effect of targeted phenological stage (a), chemical treatments, and their concentrations (b) on fruit set in ber cv. Gola

Fruit retention

The findings presented in Figure 2 and Table 2 clearly show that fruit retention in ber cv. Gola was also significantly influenced by the stage of application ($P \leq 0.0001$), the type of chemical treatment ($P \leq 0.0001$), and their interaction ($P \leq 0.0001$). The highest fruit retention was recorded with the application of NAA at the flower fading stage (BBCH 67). Interestingly, several treatments that produced lower or even negative effects on initial fruit set subsequently exhibited higher retention at physiological maturity. This inverse relationship between fruit set and retention may reflect an internal self-regulatory mechanism within the tree, wherein an excessive initial fruit load intensifies competition among developing fruits for assimilates, mineral nutrients, and hormonal signaling, ultimately leading to enhanced fruit abscission (Bangerth, 2000; Goren *et al*., 2004). In contrast, a moderate fruit set allows for more efficient assimilate partitioning and stronger sink development in individual fruits, thereby improving their capacity for retention and continued growth. These findings are consistent with established physiological concepts that final yield in fruit crops is determined primarily by sink strength and assimilate availability rather than the initial number of fruits formed (Forshey and Elfving, 1989).

However, two notable exceptions to this trend were observed: the application of boron (B) at 0.1%, whether at the green bud stage (BBCH 54) or the flower fading stage (BBCH 67), and KN (10 ppm) applied at BBCH 67. These treatments not only significantly enhanced fruit set but also maintained a high proportion of fruit retention until harvest. This dual benefit suggests a more balanced influence on both reproductive processes and carbohydrate partitioning.

Additionally, the application of benzyladenine (BA) at either BBCH 54 or 67 effectively improved fruit set, though the retention rate was lower compared to that observed with B (0.1%) and KN (10 ppm). This indicates that while BA may stimulate initial fruit development, its ability to support sustained retention may be limited, possibly due to a lack of support for sink strength or inadequate influence on hormonal balance and resource allocation during the later stages of fruit development.

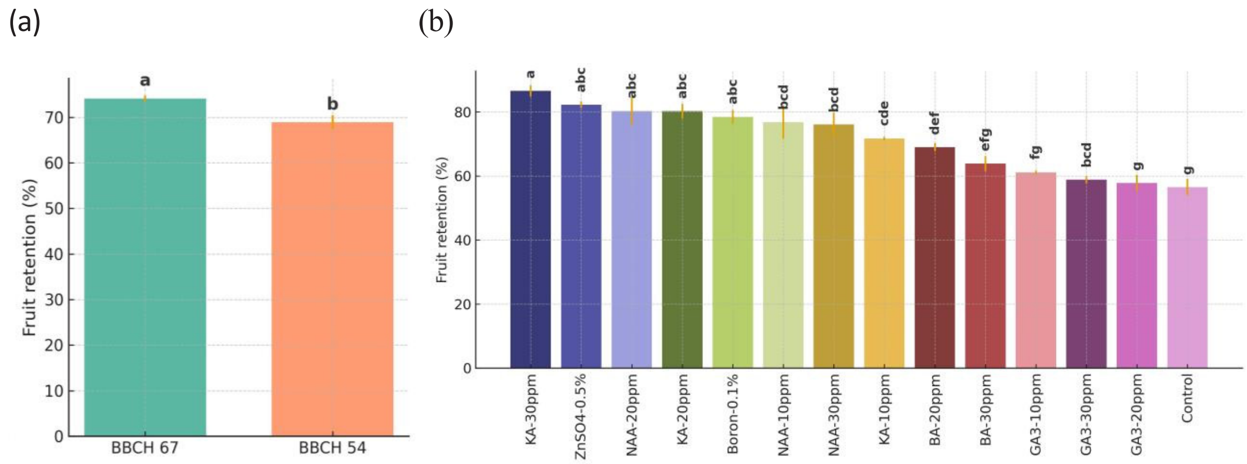

Fig. 2. Effect of targeted phenological stage (a), chemical treatments, and their concentrations (b) on fruit retention in ber cv. Gola

Table 2. Interaction effects of application stages and chemical treatments on fruit set and retention in ber cv. Gola

Stage	Treatments	Fruit set (%)	Fruit retention (%)
	Boron- 0.1 %	9.18 ± 1.04^{d}	76.60 ± 1.87^{efg}
BBCH stage 54	ZnSO4- 0.5%	3.42 ± 0.24^{jk}	79.85 ± 2.28^{def}
	GA3-10 ppm	5.45 ± 0.38^{hi}	58.52 ± 1.35^{mno}
	GA3-20 ppm	3.35 ± 0.16^{jk}	55.53 ± 2.99^{o}
	GA3-30 ppm	3.78 ± 0.32^{j}	57.80 ± 1.37^{mno}
	NAA- 10 ppm	6.45 ± 0.54^{fg}	65.08 ± 2.73^{jkl}
	NAA- 20 ppm	5.19 ± 0.63^{i}	65.36 ± 3.62^{jkl}
	NAA- 30 ppm	5.73 ± 0.61^{ghi}	63.25 ± 2.31^{klm}
	KA- 10 ppm	2.66 ± 0.54^{kl}	71.13 ± 1.77^{ghij}
	KA- 20 ppm	6.98 ± 0.49^{ef}	81.81 ± 2.86^{def}
	KA- 30 ppm	6.13 ± 0.89^{fgh}	90.75 ± 4.48^{ab}
	BA- 10 ppm	3.59 ± 0.42^{j}	75.54 ± 2.01^{fgh}
	BA- 20 ppm	7.77 ± 0.72^{e}	70.22 ± 1.70^{hij}
	BA- 30 ppm	8.93 ± 0.51^{d}	65.71 ± 2.56^{jkl}

BBCH stage 67	Boron- 0.1 %	11.41 ± 0.50^{a}	80.38 ± 2.45^{def}
	ZnSO4- 0.5%	2.11 ± 0.17^{lm}	84.69 ± 4.28^{bcd}
	GA3-10 ppm	10.94 ± 0.66^{ab}	63.68 ± 2.61^{klm}
	GA3-20 ppm	6.10 ± 0.30^{fgh}	60.03 ± 2.46^{lmno}
	GA3-30 ppm	6.93 ± 0.64^{ef}	59.87 ± 1.74^{lmno}
	NAA- 10 ppm	1.12 ± 0.30^{n}	88.57 ± 10.30^{bc}
	NAA- 20 ppm	0.90 ± 0.09^{n}	95.24 ± 8.25^{a}
	NAA- 30 ppm	1.28 ± 0.15^{mn}	88.89 ± 9.62^{ab}
	KA- 10 ppm	9.25 ± 0.64^{cd}	72.26 ± 2.72^{ghi}
	KA- 20 ppm	5.72 ± 0.70^{ghi}	78.65 ± 2.52^{def}
	KA- 30 ppm	6.23 ± 0.52^{fgh}	82.36 ± 1.05^{cde}
	BA- 10 ppm	3.51 ± 0.35^{jk}	70.37 ± 1.63^{ghij}
	BA- 20 ppm	9.04 ± 0.44^{d}	67.74 ± 4.24^{ijk}
	BA- 30 ppm	10.10 ± 0.99^{bc}	62.06 ± 2.87^{klmn}
Control		3.77 ± 0.39^{j}	56.52 ± 2.61^{no}
Pr > F		< 0.0001	< 0.0001

Conclusion

In conclusion, the observed variation in fruit set among genotypes can be primarily attributed to inherent genetic differences. Identifying and utilizing genotypes with superior fruit set potential offer a viable strategy to enhance ber production in challenging environments. The present study demonstrates that the application of micronutrients and plant growth regulators can effectively improve fruit set in ber cultivated under hot arid conditions. These findings highlight the significance of using suitable micronutrient and growth regulator treatments to enhance fruit set and ensure effective fruit retention. Furthermore, internal physiological factors such as crop load and assimilate availability play a crucial role in determining the final yield outcome. Among the treatments evaluated, boron (0.1%) application at the BBCH 67 stage proved particularly effective in improving both fruit set and retention under variable crop load conditions. Future research should focus on elucidating the physiological and molecular mechanisms governing fruit set in diverse genotypes and assessing their performance under different agro-climatic conditions and in controlled pollination trials to confirm their breeding value.

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Conflict of Interest

The authors have no conflict of interest.

Data Sharing

All relevant data are within the manuscript.

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