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CURRENT HORTICULTURE

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Announcement

4th Indian Horticulture Summit Cum–International Conference – 2026

Date: January 28–30, 2026

Venue: Rani Lakshmi Bai Central Agricultural University (RLBCAU), Jhansi, Uttar Pradesh, India

The 4th Indian Horticulture Summit cum–International Conference–2026 is being organised by the Society for Horticultural Research and Development (SHRD) and will bring together eminent scientists, academicians, researchers, students, farmers, entrepreneurs, policymakers, and industry stakeholders to exchange knowledge, share research advancements, and discuss future strategies for sustainable horticultural development.

The summit aims to provide a national and international platform for deliberation on genetic resources, diversity, conservation, and crop improvement of indigenous and underutilized horticultural crops. These crops, traditionally cultivated by local communities and well-adapted to diverse agro-climatic conditions, hold immense potential to enhance nutritional security, climate resilience, sustainable livelihoods, and agri-based entrepreneurship.

Abstracts are invited under the following major themes:

1. Genetic resources, diversity, exploration, evaluation, conservation, and their use in crop improvement
2. Genomics for improvement of indigenous and underutilized horticultural crops
3. Conventional breeding for crop improvement
4. Recent advances in the production technology of indigenous and underutilized horticultural crops
5. Post-harvest management, processing, value addition, and Agri-Export Zones (AEZs)
6. Clean planting material and high-yielding seeds
7. Protected cultivation and precision farming
8. Diseases and pest management of horticultural crops
9. Climate-resilient horticultural production
10. Entrepreneurship development and Farmer-Producer Organisations (FPOs)

Kindly visit **https://currenthorticulture.com/shrd/** for detailed information regarding the Summit, important dates, registration, and guidelines.
Researchers, students, and professionals are encouraged to **submit their abstracts and apply for various awards** through the conference portal for active participation.

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Research Review Article

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Multiple nutrient stress in fruit crops : road to soil health-mediated quality production — a review

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Abstract

Fruit crops by the virtue of their extended juvenility , sharply delineated crop phenological growth stages , and ability to produce biomass per unit use of inputs, higher than cereal crops , are infact more mechanistically tailored to tolerate multiple nutrient stress. Productivity of fruit crops depends essentially on two premier facts, nutrient balance and biological activity , provided optimum soil moisture is maintained . Though , fruit crops are highly microbes -responsive , but combination of microbes-mycorrhizas produced much better crop responses , an indication of nutrient-constraint-neutral production system. Of late, paradigm shift from inorganic to organic manures-inorganic nutrients -microbes mediated associative crop response have aided in developing the far sustainable and climate -resilient fruit production system. Our long term data (2007-19) accrued on response of organic manures versus inorganic fertilizers demonstrated that important soil quality indices like soil microbial diversity, soil microbial biomass nutrient, and organic carbon partitioning displayed significant changes, but without much difference in quantum of fruit yield (but coupled with a-grade size fruits) when compared with purely inorganic fertilizer schedule. Combination of inorganic fertilizers -vermicompost -microbial consortium aided in saving 30-40% of crop nutrient requirement without any compromise on fruit yield or quality , besides lower rate of CO2 release compared to inorganic fertilizers , an evidence of carbon deposited in passive soil organic carbon pool, in addition to reducing the fertilizer doses by 30-40% and elevating the post-harvest shelf life of citrus fruits. We further introduced the concept of "rhizosphere hybridization" to harness the value -added benefits of nutrient -microbe synergy, besides providing better crop responsiveness to microbial consortium suiting to wide range of perennial fruits under both optimum as well as soil water deficit stress. Role of biochars (more recalcitrant carbon source) and arbuscular mycorrhizas-mediated glomalins (glycoproteins) have to be increasingly brought into the regular practice while addressing the multiple nutrient stress backed up with crop phenology -based 8-10 pulse fertigation schedules . These attempts could be translated into developing a robust toolbox (catering to 4R X 4W principles) for addressing multiple nutrient stress on a mutually exclusive basis , provided current methods of diagnosis of soil fertility constraints en-route precision diagnosis.

Key words: Fruit crops, Carbon sequestration, Customized fertilizer mixture, Integrated soil fertility management, Nutrient-microbes synergy, Microbial consortium, Multiple nutrient stress, Nutrient schedules, Organic manures evaluation

Globally, fruit crops occupy an area of 65.29 million ha with a production of 883 million tons (average productivity of 13.52 tons/ha) and fresh fruit market of USD 726.20 billion to further expand at an annual growth rate of 6.58% from 2024 onwards (FAO, 2023). The world trade of fruits is dominated by apple-pears, bananas, berries -grapes, and citrus fruits accounting 74.20% of fresh fruit market, with other fruits contributing only 25.80%. Approximately 1.7 million (2.8%) human deaths worldwide are attributable to micronutrient deficiency induced through suboptimum consumption of fruits and vegetables, and regarded as one of the top 10 selected risks for global mortality (WHO, 2021).

In the current era of climate change on continuous rampage triggering an upsurge in aridity , nutrient-efficient plants will play a major role in sustaining the crop yield compared to yesteryears , amidst newer challenges like shrinking land and water resources available for fruit crop production (often comes from competitive cereal-based land uses) , higher cost of inorganic fertilizer inputs, declining trends in crop yields globally, and increasing environmental concerns (Srivastava , 2013c; Srivastava and Pongener , 2023). Furthermore, at least 60% of the world's arable lands have mineral deficiencies or elemental toxicity problems and, on such soils, fertilizers and lime amendments are essential for achieving improved crop yields (Pathak and Nedwell, 2011). In the light of climate change related issues, fruit trees besides being severely challenged by multiple nutrient deficiencies, are widely claimed to play an important role in carbon cycle of terrestrial ecosystems and sequestering atmospheric CO_2 (Lobell *et al.*,2005; Guimãraes *et al.*, 2014) as a part of sustaining the ongoing growth of fruit industry. According to Wu *et al.* (2012), net C- sink and C- storage in biomass of apple orchard ranged from 19 to 32 Tg C and from 230 to 475 Tg C in 20- years period, amounting to 4.5% of total net C sink in the terrestrial ecosystems in China. In an estimate, Lakso (2010) observed that an acre of apple

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orchard fixed about 20 tonnes of CO_2 from the air each season, and provided over 15 tonnes of CO_2, equivalent to over 5 billion BTU of cooling power. The atmospheric carbon fixing ability of fruit crops under soil waster deficit stress is, hence considered quite instrumental in negating the impact of multiple nutrient stress.

In sustaining the productivity potential of fruit crops under soil water deficit conditions, there will be an increasing importance of nutrient efficient cultivars (higher yields per unit of nutrients applied or absorbed than standard cultivars under similar agroecological conditions) that are higher producers under multiple nutrient stress (Srivastava, 2013a; Malhotra and Srivastava, 2015) . In the past, much research has been conducted to identify and/or breed nutrient efficient plant species or genotypes/cultivars within different fruit species, but the success in releasing nutrient efficient cultivars has been far limited (Dong *et al*., 2023). The main reasons for limited success are the genetics of plant responses to nutrients and plant interactions with environmental variables, not so well understood even today (Fageria *et al*., 2008). Fruit crops by the virtue of their perennial nature of woody framework (nutrients locked therein), extended physiological stages of growth, differential root distribution pattern (root volume distribution), growth stages from the point of view of nutrient requirement, and preferential requirement of some nutrients by specific fruit crop, collectively make them different than the annual crops (Srivastava and Singh, 2008a ; Srivastava and Malhotra, 2017).

Rengel *et al*. (1996) observed that the total number of bacterial colony forming units increased in the rhizosphere of Zn-efficient genotypes of wheat under Zn-deficiency and in Mn-efficient genotypes under conditions of Mn-deficiency. In contrast, a Zn-deficiency treatment acted synergistically with the number of fluorescent *Pseudomonas* in the rhizospheres. These studies provide strong clues that fruit crops exposed to varying nutrient stresses recruit plant growth promoting microorganisms, playing an important role in producing crop responses through number of mechanisms comprised of biological nitrogen fixation, growth hormone production, phosphate solubilization , siderophore production, hydrolytic enzymes production, and antagonistic activityAnother group of microorganisms, popularly known as arbuscular mycorrhizal fungi (Wu *et al.,* 2013 ; 2014; Zhang *et al.,* 2015) are equally effective in substantially improving the nutrient acquisition capacity of fruit crops, in addition to enriching the rhizosphere biologically in a much activated form (Liu *et al*., 2014; Huang *et al*.,2014; Zou *et al*., 2014).

A still bigger question emerges, whether rhizosphere competent microbes could collectively contribute towards improved resilience of plant's rhizosphere (Wang et al., 2014). And if those microbes are so successful in promoting growth response, addition of starter nutrients in such combination may further magnify the magnitude of response called nutrient-microbe synergy. Our earlier studies have shown that rhizosphere effective microbes have the tendency to play multiple roles (Keditsu and Srivastava, 2014 ; Wu *et al*., 2013) to overcome various biotic and abiotic stresses while interacting with an environment. Mineral fertilizers on the other hand as a main stream of direct nutrient supply, their application can enhance the soil biological activity via increases in system productivity, crop residue return, and soil organic matter (Khandelwal *et al.,* 2013). Therefore, a sound understanding of nutrient-microbe synergy could possibly lay a solid foundation in unlocking the productivity potential of perennial fruit crops, besides safeguarding the soil health, both physico-chemically as well as biologically. In this background, systematic efforts were made to analyse the relationship between inorganic nutrients (macronutrients versus micronutrients) -organic manures (manures versus green manure) - microbial inoculants (single versus microbial consortium) and fruit crops as a holistic approach to address multiple nutrient stress jeopardizing the production sustainability , either under optimum soil moisture or water deficit stress during any growth stage of crop .

Nutrient-microbes relationship, a toolkit to neutralize multiple nutrient stress

The microbial communities associated with plants are known as the plant microbiome or phytobiome, comprised of an array of microorganisms such as bacteria , fungi, oomycetes, viruses, and different microbial habitats known by the terms like rhizosphere, phyllosphere, and endosphere (Berg, 2009). The phytobiome is an emerging field of research aimed at generating a system slevel understanding of plant-microbe interactions which influence plant health and plant productivity. The study of phytobiomes is currently in its infancy, and most research focuses on profiling plant microbiomes in different hosts and environments. The interactions between the microbiome and plant are highly complex and dynamic. The interactions among plant and microbes can be beneficial (mutualistic), neutral (commensalism), or detrimental (parasitic). Consequently, the plant microbiome dramatically affects plant health and productivity (Guttman *et al*., 2014). Hence, soil microbial count-related traits are more sensitive to soil fertility parameters.

Microbes and macronutrients bioavailability: The rhizosphere supports large and active microbial populations capable of exerting beneficial, neutral, or detrimental effects of plant growth. Plant growth promoting microbes have been reported to enhance plant growth directly by a variety of mechanisms; fixation of atmospheric N that is transferred to the plant, production of siderophores that chelate Fe and make it available to the plant root, solubilization of minerals such as P, and synthesis of phytohormones (Dobbelaere *et al*,. 2003). Direct enhancement of mineral uptake due to increases inspecific ion fluxes at the root surface in the presence of PGPR has also been reported (Bertrand *et al.*, 2015 ; Tilak *et al.*, 2005). Okon and Labandera-Gonzalez (1994) evaluated worldwide data accumulated over the previous 20 years on field inoculation with *Azospirillum,* and concluded that these bacteria are capable of promoting the yield of crops in different soils and climatic areas. *Azospirillum* spp. are involved in the biological fixation of N and the increased activity of glutamate dehydrogenase and glutamine synthetase (Ribaudo *et al.*, 2006 ; Thaler *et al.*, 2003). *Azospirillum brasilense* produces high quantities of extracellular indole-3-acetic acid (IAA), increasing root elongation, root surface area, and root dry matter (Molla *et al.,* 1984). However, considering the vital role of microbes in the maintenance and buildup of soil fertility, their utility is indispensable.

The phosphate-solubilising microorganisms popularlyknownasPSMinvolvephosphate sources, mainly of two types, : i. mineral (fluorapatite, hydroxyapatite, tircalcium phosphate, mono- and dicalcium phosphate, rock phosphate, and iron phosphate) and ii. organic nature (phytin, lecithin, hexose monophosphatic ester, phenyl phosphate, and calcium glycerophosphate) according to Joseph *et al.* (2015). Various species of *Trichoderma* as dual purpose microbe (phosphate solubilizer as well as microbial antagonist) were also effective in the promotion of growth and yield in various crops (Kalayu , 2019). Both the species of *Trichoderma,* viz., *T. harzianum* and *T. virens* promoted growth of variety of fruit crops (Joseph *et al.,* 2015 ; Chen *et al.* , 2023) . On the other hand, application of *Trichoderma* was not conducive to increased yields of some annual crops (Wang *et al.*, 2022), suggesting some kind of inconsistency in response. Unfortunately, many studies carried out in the past have not been given due consideration due to exploitation of the potassium solubilising ability of microbes. Latest critical reviews (Bist *et al.*, 2020 ; Afify, 2022) stated that although K is released from silicates by microorganisms, the process is not active enough to complete provision of the plants with this element.

Microbial solubilisation of micronutrients: Microorganisms attached to soil mineral surfaces ably create micro-environments where concentration of ligand, acidity and redox activity is substantially improved compared to the bulk soil, thus effecting mineral exchange reactions (Rogers and Bennett, 2004; Barker *et al.*, 1997). The so-called fluorescent pseudomonads *Pseudomonas aeruginosa*, *P.fluorescens*, and *P.putida* produce a water- soluble yellow-green fluorescent (under UV light) pigment called pyoverdine (Meyer and Abdallah, 1997). This pigment is responsible for the characteristic fluorescence of the cell and has also been identified as an iron-chelating siderophore (Schalk and Guillon , 2012).

Another important factor for the colonization of plant roots, especially under iron-limiting condition, is the synthesis of siderophores from *Pseudomonas*, which are iron-chelating compounds (Cornelius and Dingemans, 2013). Pseudomonas siderophore have a high affinity for iron, and when they chelate this micro-nutrient, they make it less available for other microorganisms, including plant pathogens (Ahmad *et al.*, 2008 ; Olanrewaju *et al.*, 2017). The synthesis of siderophores is, therefore, important to confer an advantage in the competition for nutrients and space with regard solubilization of micronutrients in the rhizosphere .The bacterial genera viz.,, *Azotobacter, Azospirillum*, *Bacillus*, *Gluconacetobacter*, and *Pseudomonas,* have all been identified as Zn solubilizers (Lindsay and Norvell, 1978). Arbuscular mycorrhizae and the genus Trichoderma are the two groups of fungi possessing Zn-solubilizing activities in soil (Li *et al.*, 2015). Recently, the discovery of Zn nanoparticles from the cell-free culture filtrates of *Pseudomonas*, *Bacillus*, and *Azospirillum* strains suggested that these microbes might solubilize Zn by producing nanoparticles to mobilize nutrients in the rhizosphere (Sultana *et al.*, 2020).

Endophytes are generally known as non-pathogenic microbes that colonize inside plant tissues including roots . The beneficial effects of root endophytes on plant growth has been extensively discussed (Gouda *et al.*, 2016; White *et al.*, 2019) . Besides plant growth, there is emerging evidence showing the involvement of endophytic fungi in biofortification. The symbiotic mechanism involves extensive interactions between plants and endophytes . Plants excrete metabolites to initiate the symbiosis with these fungi. Endophytes can enhance the accumulation of nutrients including Fe, Zn, vitamin-B, vitamin- C, flavonoids, and saponins. In addition, endophytes can also enhance the accumulation of nitrogen and minerals in crops. Since the adverse effects of nitrogen fertilizer on the environment has been well known , microbe-mediated biofortification could be a “greener” alternative to provide (Khan *et al.*, 2009).

Trichoderma species are not only found to solubilize phosphorus but other important nutrients- through various mechanisms. They react to limiting iron conditions by using a high-affinity iron uptake system based on the release of iron chelating molecules called siderophores. This chelated iron is not available to plant pathogens, whose activity is thereby reduced (Baker *et al*,. 2003), while plant roots can take up chelated irons either directly or after reduction of Fe^{3+} by plasma membrane reductases (Welch *et al.,* 1993).

Mycorrhizal dependence of fruit crops :Soil microorganisms are a major driving force in soil fertility transformations (Xuan *et al*., 2011; Srivastava , 2023). And of them, arbuscular mycorrhizal fungi (AMF) are the ubiquitous root symbiotic fungi that belong to the phylum Glomeromycota, possess a distinctive role in soil processes such as nutrient cycling and soil structural improvements (Rillig , 2004) , including the gobal carbon dynamics (Hawkins *et al*., 2023) due to their widespread presence in soils. AMF fungi can form mutualistic relationships with over 80% of land's plants, namely, arbuscular mycorrhizas (AMs). This symbiosis is the most common mycorrhizal association in natural ecosystems , and partly undertakes the absorption and delivery of mineral nutrition and water from the soil to the host plant by mycorrhizal hyphae (Begum *et al*., 2019). Therefore, AMs are critical for plant health, survival, and restoration in fruits -based agro-ecosystems (Liu *et al*., 2024).

The rhizosphere properties governing the crop performance are characterized by changes in soil fertility (available nutrients), nature of proteins binding soil particles into different aggregate sizes commonly known as water-stable aggregate and soil carbon pool (Ngullie *et al*., 2015) . Different species or communities of AMF have been observed to promote soil aggregation to varying degrees . However, the mechanisms involved are still inconclusively understood. Extensive hyphae of AMF enmesh soil particles and increase soil water repellency , thus, facilitating the formation and stabilization of soil aggregates. These hyphae also release an insoluble N-linked glycoprotein, called as glomalin, which contains ~60% carbohydrates and showed 3–10 times higher soil aggregating ability than hot-water-extractable carbohydrates (Wu *et al*., 2015).

Glomalin in soils is defined as glomalin-related soil protein (GRSP) (Rillig, 2004). Studies have proven the highly positive correlate on of GRSP with aggregate stability, irrespective of soil types (Wu et al., 2014). In citrus rhizosphere, we have found significantly positively correlation of GRSP with water stable aggregates at the size of 0.25–0.50 mm in field (Wu *et al*., 2017), and the contribution of GRSP to soil aggregate stability lied on water stable aggregates fractions (Wang et al., 2014). Recently, GRSP was classified into three fractions : fraction 1 of Bradford-reactive soil protein (BRSP) (highly labile GRSP, corresponding to easily-extractable glomalin-related soil protein), fraction 2 of BRSP (relatively more recalcitrant in soil, corresponding to difficultly-extractable glomalin-related soil protein), and total BRSP (fraction 1 + fraction 2 = T-BSRP) according to studies by Wu *et al*. (2015).

Plants can synthesize specific microbial structure according to their metabolic requirement and consequently the root exudates to varying composition, thereby, influencing rhizosphere properties on various accounts (Wu *et al.,* 2017). On the other hand, besides GRSP, AMF also develop an extraradical hyphae network to enmesh soil aggregates and induced more SOC to cement aggregates (Wu *et al*., 2014; 2015) . In principle, fruit crops have been observed highly AM-dependent crops evident from various kinds of soils-plant health -related parameters . Mycorrhizae have also been helpful in improving the uptake of diffusion limited micro nutrients such as P, Zn, Cu, Mn, and Fe by the host plants on account of their ability to dissolve and promote absorption of these nutrients . This is accomplished primarily by extension of root geometry through symbiotic association in which fungus utilizes carbohydrates produced by the host plants, and plants in turn benefit by increased nutrients uptake,

Organic manures-based fruit production system

Organic manures play a critical role in both short-term nutrient availability and long-term maintenance of soil organic matter vis-a-vis production sustainability, especially in small holder farming systems (Srivastava and Bora, 2023) via improvements in agrobiology-driven soil fertility changs. Despite this importance, there is little predictive understanding for the management of organic inputs in different fruit-based agro-ecosystems. Crop yields are a fundamental factor of economic success, and depend very much on balanced fertilization to address multiple nutrient constraints (Srivastava and Singh , 2004a) . A crucial question is how to guarantee optimum nutrition along with production on a sustained basis by organic measures only. An array of microorganisms present in manure and manure extracts such as *Trichoderma, Rhizobacteria,* and fluorescent *Pseudomonas* are known to stimulate plant growth (Bora and Bora , 2020) . Such composts having microbes of twin utility hold more promise in integrated nutrient management package (Srivastava and Singh , 2008c) .

Agronomic response of organic manures : The nutrient composition of different organic manures (Srivastava *et al*., 2002 ; 2019) and green manure (at flowering stage) showed a large variation in their nutrient value viz., FYM (1.42% N, 0.14% P, 1.20% K, 640 ppm Fe, 108.2 ppm Mn, 94.2 ppm Cu and 227.0 ppm Zn); vermicompost (1.91%

N, 0.16% P, 0.88% K,2850 ppm Fe, 113.2 ppm Mn, 67.0 ppm Cu and 72.4 ppm Zn); and poultry manure (2.15% N, 0.14% P,1.32% K, 28560 ppm Fe, 115.4 ppm Mn, 45.6 ppm Cu and 325.0 ppm Zn). The yield of green manure (sunhemp) on Typic Ustochrept soil varied from 5.17 to 11.12 tons/ha, adding 101.97 -229.68 kg N/ha, 4.1-9.28 kg P/ha, 87.55 -197.20 kg K/ha, 1.24 - 2.78 kg Fe/ha, 300.24-676.28 g Mn/ha,116.90-263.32 g Cu/ha, and 112.27-252.88 g Zn/ha into the soil (Kohli *et al.*, 1998; Srivastava and Singh, 2009a). A long term replicated trial laid out with different organic manures and green manuring treatments using Nagpur mandarin as test crop. Different treatments consisted of T_1 (Farmyard manure as FYM). T_2 (Vermicompost), T_3 (Poultry manure), T_4,(Green manuring - Sunhemp), and T_5(Inorganic fertilizers) : The requirement of organic manure was computed on N-equivalent basis using recommended doses of fertilizers (600 g N - 200 g P_2O_5, 100 g K_2O - 200 g $FeSO_4$, - 200 g $ZnSO_4$,) as guiding principle. The results obtained are summarized briefly as below:

Maximum increase in canopy volume was recorded with green manure (24.94 m^3) statistically on par with vermicompost (23.72 m^3) and , inorganic fertilizers (22.46 m^3) with farmyard manure (18.72 m^3) displaying the most inferior response. These observations suggested green manure and vermicompost as two most effective treatments (Table 1). The magnitude of different treatments on yield response was of comparatively lower order including those with inorganic fertilizers. Quality-wise, the maximum size of fruit was recorded with green manuring and vermicompost , while treatments carrying farmyard mansure , poultry manure or inorganic fertilizers , though display on-par response, but magnitude of response was far inferior over either vermicompost or green manure treatment. A constant increase, although at a slow rate, in organic carbon buildup was observed in all the treatments. After 6- years of consistent manuring , maximum organic carbon of 0.86% was observed with

Table 1. Response of organic manures vs inorganic fertilizers on growth, yield, and fruit quality (pooled data 2008-14)

Treatment	Net increase in canopy volume (m^3)	Fruit yield (kg/plant)	Quality parameters (%)		
			Juice content	TSS	Acidity
Farmyard manure	18.72d	11.92cd	44.82c	9.21b	0.82a
Vermicompost	23.72b	26.20a	47.02a	9.86a	0.86a
Poultry manure	17.50e	12.05c	44.36cd	8.69d	0.84a
Green manure	24.94a	18.96b	46.05ab	9.02c	0.79a
Inorganic fertilizers	22.46c	11.49de	44.15de	8.79de	0.80a
C.D. (P=0.05)	1.14	5.20	1.28	0.14	NS

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments . CD stands for critical difference.
Source: Srivastava *et al.* (2002).

vermicompost treatment which was significantly higher than rest of the treatments viz., farmyard manure (0.68%), poultry manure (0.72%), green manure (0.86%) or inorganic fertilizers (0.61%).The maximum buildup of 0.38% was computed with vermicompost treatments compared to 0.28% with either green manuring treatment or only 0.10% with exclusive use of chemical fertilizers.

The available pool of nutrients was significantly affected by different organic manuring treatments (Table 3). Net increase in available N over initial value was observed in the order 123.8 mg/kg N and 7.9 mg/kg P, respectively, with K- depleting to 50.8 mg/kg with vermicompost treatment. This magnitude of increase in available N (120.7 mg/kg) and P (2.2 mg/kg) was not observed even with straight inorganic fertilizers, and decrease in available K was similarly on the declining side (Srivastava *et al.*, 2007). The availability of DTPA-extractable micronutrients displayed an overall improvement with all the treatments except inorganic fertilizers . These response in available supply of micronutrient indicated that all the organic

Table 2. changes in plant available pool of nutrients (mg/kg) in response to long-term application of organic manures (pooled data : 2008-14)

Treatment	Macronutrients			Micronutrients		
	N	P	K	Fe	Mn	Zn
Farmyard manure	196.2e	14.2d	207.0d	17.1bc	12.1d	0.82cd
Vermicompost	226.2a	21.3a	286.2a	22.2a	26.8a	1.08a
Poultry manure	210.3c	15.3c	190.1e	14.cd2	16.2c	0.94b
Green manure	219.4b	16.1b	243.7b	17.1b	18.3b	0.90bc
Inorganic fertilizers	204.7d	14.2d	238.3c	14.0de	10.8e	0.80de
C.D. (P = 0:05)	2.8	0.80	4.3	1.0	0.80	0110

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2002), Srivastava and Singh (2005) manures have excellent mobilizing capacity of otherwise unavailable micronutrients in soil (Srivastava *et al*., 2007) . Except Cu, all the micronutrients attained a concentration within optimum range, irrespective of different treatments (Table 3) .

The studies so far carried out provided two cardinal explanations *viz.*, i. organic manures (vermicompost, green manure, and farmyard manure as FYM) hold good promise to meet crop nutrient requirement, and ii. Qualitywise , fruits from organic manuring were not inferior to those from inorganic fertilizers (Srivastava and Singh , 2009b ; Srivastava *et al*., 2008). In such studies, it is more important to see the response of legacy carbon of soil (passive soil carbon stock) on production sustainability by working out the periodicity of organic manuring as a part of crop manuring holiday under both soil moisture limiting and optimum moisture availability to simulate the nutrient release pattern . The crop responses of different organic manures under two divergent soil moisture conditions are likely to originate through intensity of recalcitrance of carbon (Agegnehu *et al.,* 2017; Mousavi *et al*., 2023).

Optimising nutrient (organic and inorganic)-microbe synergy: our experiences

The long-term experiments conducted around the world indicated that chemical fertilizer alone is not enough to improve or maintain soil fertility at high levels and the soil acidification problem caused by over-application of synthetic N fertilizers can be reduced if more fertilizer N is applied as NO_3 relative to ammonium- or urea-based N fertilizers (Pathak and Nedwell, 2011). Organic amendments comprising manures have helped in increasing the fruit yield coupled with quality, effectively replacing mineral fertilizers in the nutrient management of commercial fruit tree orchards through associated changes in soil C pool, microbial pool and available nutrient pool of soil. Nutrient (nutrient as well as inorganic source)-microbe as tripartite association on the other hand is better known in fruit crops (Singh and Banik, 2011; Srivastava and Ngullie, 2009 ; Khehra and Bal, 2014) with respect to both agronomic response as well as soil health. An array of fruit crops have been reported to respond to the synergies originated through combination of organic nutrient- microbe-inorganics (Table 7) either under soil water deficit or an optimum soil moisture conditions. And such associations have invariably witnessed substantially higher productivity than any single component alone. However, there is a greater need to expand such plant response advantages using more rhizocompetent microbes preferably in consortium mode, plant response as well as soil health response both have to be sustained on a long term basis (Srivastava and Bora, 2023) .

Our long term studies on microbial consortium (mixture of *Bacillus pseudomycoides* , MF113272 ; *Acinetobacter radioresisten s,* MF113273 ; *Micrococcus yunnanensis* , MF113274 ; *Paenibacillus alvei,* MF113275 ; and *Aspergillus flavus* , MF113270), inorganic fertilizers, and vermicompost- mediated integrated soil fertility management (ISFM) in relation of sustained quality production of Nagpur mandarin (*Citrus reticulata* Blanco) under field condition during 2007-16 were initiated with five treatments viz., Module I (T_1)- 100% RDF (recommended doses of fertilizers: 600 g N – 200 g P – 300 g K - 200 g $ZnSO_4$ – 200 g $FeSO_4$ – 200 g $MnSO_4$/tree/year), Module II (T_2) -75 % RDF + 25% vermicompost; Module III (T_3)-75% RDF + 25% vermicompost + microbial consortium; Module IV(T_4)-50% RDF + 50% vermicompost; and Module V (T_5) – 50 % RDF + 50% vermicompost + microbial consortium. These modules representing various forms of ISFM were evaluated in terms of vegetative growth, fruit yield, fruit quality, plant available pool of nutrients in soil, leaf nutrients composition, soil carbon stock, and soil microbial load on a black clay soil (Typic Ustochrept) , and presented below through pooled data (Table 4- 7) :

Table 3. Nutrient profile of index leaves in response to long-term application of different organic manures (Pooled data: 2008-14)

Treatments	Macronutrients (%)			Micronutrients (mg/kg dry)drymatter)		
	N	P	K	Fe	Mn	Zn
Farmyard manure	2.38c	0.091d	1.20e	106.2d	28.2e	19.2bc
Vermicompost	2.63a	0.114a	1.34c	121.2a	40.3a	23.1a
Poultry manure	2.10e	0.080e	1.24d	118.1b	32.8d	20.4b
Green manure	2.52b	0.100b	1.54a	108.4c	36.1b	19.2bc
Inorganic fertilizers	2.28d	0.094c	1.45b	99.6e	34.0c	17.0d
C.D. (P = 0:05)	0.08	0.008	0.08	2.2	1.2	1.0

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2002), Srivastava and Sigh (2005)

Response ISFM modules on plant growth, fruit yield, and quality: All the ISFM-based treatments displayed significant response on changes in canopy volume (Table 4). Maximum cumulative increase in canopy volume was observed with module-III (18.67 m^3) followed by module-IV(17.16), Module-V(16.93 m^3), on part with module-II (16.70 m^3) and canopy volume with either module-III or module-V which were better than either module-II or module-IV compared to module-I which comprised of only inorganic fertilizers. Module I- T_1 (11.50 m^3). Incorporation of microbial consortium either with module-III or with module –V invariably induced higher canopy volume suggesting better response on fruit yield was observed to be significantly affected by different ISFM-based treatments (Table 5).The maximum fruit yield of 88.8 kg/tree was observed with treatment module-V which was better than 83.2 kg/tree with T_4 or 80.5 kg/tree with module-III than 71.0 kg/tree with treatment module-II. However, all these modules were observed far superior in magnitude of response when compared with 100% RDF as module-I (67.7 kg/tree). Hence, different ISFM-based modules (71.0-88.8 kg/tree) were much better than exclusive inorganic fertilizer treatment like module (67.7 kg/tree).

Different fruit quality parameters, except peel thickness (Table 5) displayed significant response in relation to different treatments. There was much high fruit weight with different ISFM-based treatments modules I-V 101.4-114.6 g compared to inorganic RDF module-I (101.4), showing that incorporation of both organic manure as well as microbial cultures improved the efficiency of organic fertilizers. The other three fruit quality related parameters such as juice content, acidity, and TSS expressed the similar pattern of response. While on the other hand, acidity observed a significant reduction with those superior treatment, e.g. module-III (0.86%) and module-V (0.80%) compared to module-II (0.93%) and module-IV(0.91%) highlighting the favorable changes in different fruit quality in response to different ISFM-based treatments.

Response of ISFM modules on response on soil health: Rational soil use practices must allow economically and environmentally sustainable yields, which will only be reached with the maintenance or

Table 4. Growth attributing parameters in response to different vermicompost - based modules of ISFM (Pooled data :2007-16)

ISFM modules	Plant height(m)	Tree spread (m)		Canopy volume (m^3)	Cumulative increase in canopy volume over 2007-08 (m^3)
		E-W	N-S		
Module I	3.82 (2.02)	2.52 (1.27)	2.50 (1.20)	13.04e (1.54)	11.50e
Module II	5.09 (2.10)	2.98 (1.39)	2.89 (1.25)	18.51bc (1.81)	16.70cd
Module III	3.87 (2.13)	3.00 (1.27)	3.22 (1.23)	20.28a (1.61)	18.67a
Module IV	3.76 (2.10)	3.73 (1.30)	2.93 (1.30)	19.78ab (1.62)	17.16ab
ModuleV	3.86 (1.87)	2.97 (1.18)	2.96 (1.22)	18.33cd (1.40)	16.93bc
C.D. (P=0.05)	0.49	0.38	0.51	1.18	1.32

Figures in parentheses indicates the value obtained in 2007-2008

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source: Srivastava *et al.* (2019)

Table 5. Fruit yield and quality parameter in response to different vermicompost based modules of ISFM- treatments (pooled data:2007-16)

ISFM module	Yield (kg/tree)	Fruit weight (g/fruit)	Peel thickness (mm)	Fruit quality parameters			
				Juice content (%)	TSS (^{0}Brix)	Acidity (%)	TSS/ Acid ratio
Module I	67.7e	101.4e	4.1a	40.2cd	8.4cd	0.96a	8.92de
Module II	71.0d	104.1d	3.0bc	39.6de	8.6bc	0.93ab	9.23cd
Module III	80.5c	106.2c	3.4b	41.5bc	9.5a	0.86cd	10.05b
Module IV	83.2b	109.1b	3.4b	42.7b	8.4cd	0.91bc	9.56bc
Module V	88.8a	114.6a	3.0bc	44.2a	9.3ab	0.80de	11.62a
C. D. (P=0.05)	2.1	1.4	0.50	2.1	0.30	0.10	1.10

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source : Srivastava *et al.* (2019) recovery of the soil health (Lehman *et al.*, 2020) . Thus, a healthy soil has been defined as "The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran and Zeiss, 2000). To understand and use soil health as a tool for production sustainability, physical, chemical, and biological properties must be employed to verify the soil use and management within a desired timescale.

The soil microbial load in terms total bacterial count and fungal count in response to different ISMF-based treatments showed variable higher soil microbial load with module III and module V compared to either module II or module IV including module I . In our study changes in soil fertility indices with regard to available macro- as well as micronutrients were observed highly significant, but of variable nature in response to different treatments (Table 6). Module-I involving exclusive inorganic fertilizers registered lowest test values as against treatment like module-V registering maximum values, validating the supremacy of those treatments which carry all the three components of ISFM. The soil properties such as soil pH and soil EC were not affected by any of the ISFM-based treatments (Table 8). While, amongst different fractions of soil carbon viz., organic-C (SOC), inorganic-C (SiC), and total-C (TC) only SOC and TC were significantly affected . These observations showed that changes in soil carbon stock are more governed by organic fraction than inorganic fraction.

Maximum SOC and TC of 7.43 g/kg and 9.14 g/kg were observed with module-V. Likewise, module-III much SOC and TOC than module-II, displaying the significant role of microbial consortium in improving the carbon sink capacity of soil. Different ISFM-based modules were also observed to aid in improving the total soil N stock, being maximum with treatment like module- III- V(0.741-0.748%) compared to rest of the treatments like module-I, module-II or module-IV (0.721-0.738%). However, soil C:N ratio in the range of 12.00-12.32, without displaying significant changes in response to different treatments (Table 7). These modules provided us the strong clues about the effectiveness of developed microbial consortium . We further laid out the field experiment to evaluate in 10-year-old Nagpur mandarin (*Citrus reticulata* Blanco raised on *Citrus jambhiri* Lush rootstock) , how much nutrients saving can be achieved through microbial consortium , with treatments comprising, i. 50% RDF + 50% RDF equivalent vermicompost + microbial consortium, ii. 45% RDF + 45 % RDF equivalent vermicompost + microbial consortium, iii. 40% RDF + 40% RDF equivalent vermicompost + microbial consortium, iv. 35% RDF + 35% RDF equivalent vermicompost + microbial consortium, and v. 30% RDF + 30% RDF equivalent vermicompost + microbial consortium. Incorporation of microbial consortium in ISFM showed a minimum of 30% of RDF (35% RDF + 35% RDF equivalent vermicompost + microbial consortium) could be saved without any compromise on either fruit yield , quality or soil fertility status (Srivastava *et al.*, 2019).

Customized micronutrient mixtures: development and field evaluation

A number of principles are involved in developing customized fertilizers, which include: soil fertility-based variogram measuring spatial variability, defining different production management zones along with soil fertility gradient, nutrient budgeting based on nutrient removal and addition, nutrient logging data relation to phenology of a crop and blending nutrients- based spatial and temporal crop specific nutrient removal pattern (Srivastava and Das, 2017) . Needless to elaborate on advantages of customized fertilizers than straight fertilizers. Unfortunately, not much inroads have been made with respect to developing specialty fertilizers or these fertilizers customized as per crop nutrient demand

Table 6 . Changes in soil fertility status in response to different modules of ISFM-based treatments (Pooled data: 2007-16)

ISFM modules	Plant available nutrients (mg/kg)						
	Macronutrients			DTPA-micronutrients			
	$KMnO_4$-N	Olsen-P	NH_4OAc-K	Fe	Mn	Cu	Zn
Module I	140.0e	9.32a	185.2e	10.35e	10.54e	2.2a	0.98
Module II	143.5d	9.27a	196.6d	12.57d	11.54cd	2.3a	1.00
Module III	155.7bc	9.15a	203.6c	15.18bc	12.45c	2.7a	1.10
Module IV	161.0b	9.57a	209.2b	16.56b	11.67b	2.8a	1.18
Module V	178.5a	9.55a	212.6a	19.50a	12.93a	2.5a	1.32
CD (P=0.05)	6.2	NS	1.3	1.32	1.01	NS	0.46

Means separated by different letters using Duncans Multiple Range Test show significant difference between different treatments. CD stands for critical difference.

Source: Srivastava *et al.* (2019) depending upon soil and climate (Srivastava *et al.*, 2010). We made some sincere efforts to highlight some efforts to develop specialty fertilizers and customize them like citrus, with the help of other fruit crops :

Specialty fertilizer, a tool for site specific nutrient management (SSNM) : Conventionally designed long term fertilizer trials revealed that: i. omission of limiting macro- or micronutrients led to their progressive deficiencies due to heavy removals; ii. Sites initially well supplied with P, K or S become deficient when continuously cropped using N alone and iii. Fertilizer rates considered optimum still resulted in nutrient depletion at higher productivity levels, if continued, become sub-optimum rates (Tiwari *et al.*, 2007a) . There is a strong necessity to keep overall nutrient balance in relation to total crop load (Tiwari 2007b). Most of the existing fertilization guidelines have been derived from experimental data on yield responses to individual nutrients after controlling for other soil conditions by way of randomization. But , soil conditions in farm fields, former being more heterogeneous in soil fertility, is distinctly very different from those in the experimental fields, and soil data collected from a farm fields cannot be analyzed using the statistical method developed for experimental data (Srivastava *et al.*, 2006) .

Knowing the nutrients required for all stages of growth, and understanding the soil's ability to supply those needed nutrients, are critical to profitable crop production. The recommendations on fertilizer application may not, however, produce the same magnitude of results when practiced on an orchard of large area, because of its inability to accommodate large spatial variation in soil fertility (Srivastava *et al.*, 2006). Application of uniform single rate of nutrients, hence, most often result in over-application of nutrients at some sites and under-application at other sites, cumulatively leading to reduced fertilizer use efficiency (Jeyabaskaran *et al.*, 2021). Under such circumstances, SSNM as a dynamic concept of nutrient management exploits indigenously and spatially available nutrients within bigger orchards requiring differential fertilizer treatments in patches so as to improve the orchard efficiency (average yield of specified trees in relation to average orchard yield) in ultimate terms (Srivastava and Singh , 2008a). The success of SSNM during the last 15- years has been prominently realized on a number of fruit crops viz., avocado (Salaza-Garcia and Lazcano-Ferrat 2003), citrus (Srivastava *et al.* 2006 ; 2009) etc. to cite few success stories. In this background, the present review attempts to highlight certain pertinent issues on the necessity of developing SSNM concept as rationale of fertilizer use to harness better fertilizer use efficiency with emphasis on perennial crops.

The following steps are involved in arriving at fertilizer requirement based on the principles of SSNM (Srivastava 2013b): step i.: estimating target yield; step ii. estimating nutrient requirement to get target yield, step iii. estimating indigenous nutrient supply from soil (based on our earlier studies dealing with progressive nutrient response experiment), step iv : calculating fertilizer requirement. Working out the nutrient requirement : defined as the amount of nutrients added for producing the target yield minus the amount of indigenous nutrient (soil and other sources)and fertilizer recovery (%) defined as the percentage of nutrients absorbed by a crop out of the total amount of fertilizers applied (Srivastava *et al.*, 2014) .

Future gains in productivity and input- use-efficiency will require soil and crop management technologies that are knowledge-intensive, and are tailored to specific characteristics of individual farms or fields to manage the variability that exists between and within them (Tiwari 2007a). The SSNM approach is one such option that has been tried successfully in India using different approaches. In subsequent sections we discuss the principles and strategies that could be effectively used developing customized fertilizers use strategy, leading to development of specialty fertilizers. We developed a specialty micronutrient mixtures for Nagpur mandarin grown in central India and evaluated during 2012-20 in Vertic Ustochrept (Soil facing multiple nutrient deficiencies in form of N, P,Fe, MN, Zn and B. The treatments involving a total of four treatments viz.,$T_{1:}$ Micronutrient mixture (Citrus special, IIHR Bangalore, T_2 : Macronutrients (Soil application) + Micronutrients (Foliar application); T_3 : Micronutrient mixture-1(Soil application) + Macronutrients (Soil application) and T_4 : Micronutrient mixture-2 (Soil application) + Macronutrients (Soil application) were tested in field with 6 replications. The responses were evaluated in terms of vegetative growth, changes in soil fertility status and nutrient composition of index leaves to identify the best treatment during the fifth year of evaluation. The results obtained are as follows:

Response on vegetative growth and quality: Vegetative growth response using different growth contributing parameters were evaluated and expressed as canopy volume, responded significantly to the different treatments, as in preceding years. Among all the treatments, the most striking increase in canopy volume over 2018 – 19 was observed with the treatment T_4 (0.96 m^3) followed by the treatment T_3 (0.92 m^3), T_2 (0.85 m^3) and T_1 (0.46m^3). These responses in canopy volume suggested the superiority of both the micronutrient mixtures (T_3 and T_4) over conventionally used fertilizer (T_1 and T_2) application. Similarly, the yield response with treatments T_4 (58.2 kg tree or 16.2 tons /ha) and T_3 (46.3 kg /tree or 12.9 tons /ha) were of much higher magnitude over T_2 (42.4 kg/ tree or 11.8 tons/ha) and T_1 (40.4 kg/ tree or 11.1 tons/ha), suggesting that our prepared mixtures have out-yielded the conventionally used fertilizer doses (Fig. 1).

Changes in soil fertility and plant nutrition: The soil fertility and leaf nutrients composition were significantly available nutrients, with an exception of DTPA-Cu a affected by different treatments. Amongst plant available nutrients , with the exception of DTPA-Cu , all the nutrients viz., $KMnO_4$-N, Olsen-P, NH_4OAc-K, DTPA-Fe, DTPA-Mn, and DTPA-Zn showed a signification response of different treatments. The treatments T_4 observed significantly higher plant available macronutrient than treatment T_3 compared to treatments T_2 . These observations suggested the far superior response of micronutrient mixtures (Treatment T_3 and T_4) than treatments involving T_1 and T_2. The treatment T_4 and T_3 registered a significantly higher plant available micronutrient than T_2 and T_1. Similar responses were observed in leaf nutrient status, where T_4 treatment showing the best response over T_3, T_2 or T_1 . Our observations strongly lend support shortly support towards better efficacy of micronutrient mixtures compared to conventionally used fertilizers (Fig 1) Hence our long term studies showed that micronutrient mixture developed by simply mixing straight micronutrient fertilizers such as ferrous sulphate , manganese sulphate , zinc sulphate and borax in ratio of 1:1:0.50:0.20 that stoichiometrically coincided with the similar concentration ratio of micronutrients present in fruits. Interesting, our developed micronutrient mixture at the rate of 100g/plant overtaken the response of these micronutrients when applied at the rate of 100g ferrous sulphate , 100g manganese sulphate , 100g zinc sulphate and 50g borax/plant/year (total micronutrients at the rate of 350g /plant proved far inferior over 100g customized micronutrients mixture) .

Changes in fruit quality index: Fruit quality index developed for citrus fruits displayed varying response. The treatment T_4 showed a maximum index value (69/100) followed by T_3 (66/100) , T_2 (62/100), and T_1 (59/100) in decreasing order. These observations suggested the far significant response of customized micronutrient mixtures compared to straight fertilizers involving treatment T_1 (Srivastava , 2012 ; Srivastava and Pandey , 2021) .

Microbial response of rhizosphere hybridization

Soil region adhering to plant root system is claimed to display the maximum microbiome diversity, responsible for changes in soil bio-physico-chemical properties influenced by root growth and their elevated activity, popularly known as rhizosphere . The term "Rhizosphere" was coined by German scientist, Hilter (1904) from two Greek words, i.e. rhiza (root) and sphere (field of influence). There are three broad classifications describing three different tiers of rhizosphere properties, viz., i. root tissues enclosing endodermis and cortical layers (endorhizopshere), ii. root surface adhering soil particles and microbes (rhizoplane), and iii. soil immediately adjacent to root (ectorhizosphere). Plant roots release various organic compounds through exudation, secretion, and deposition, starting from the

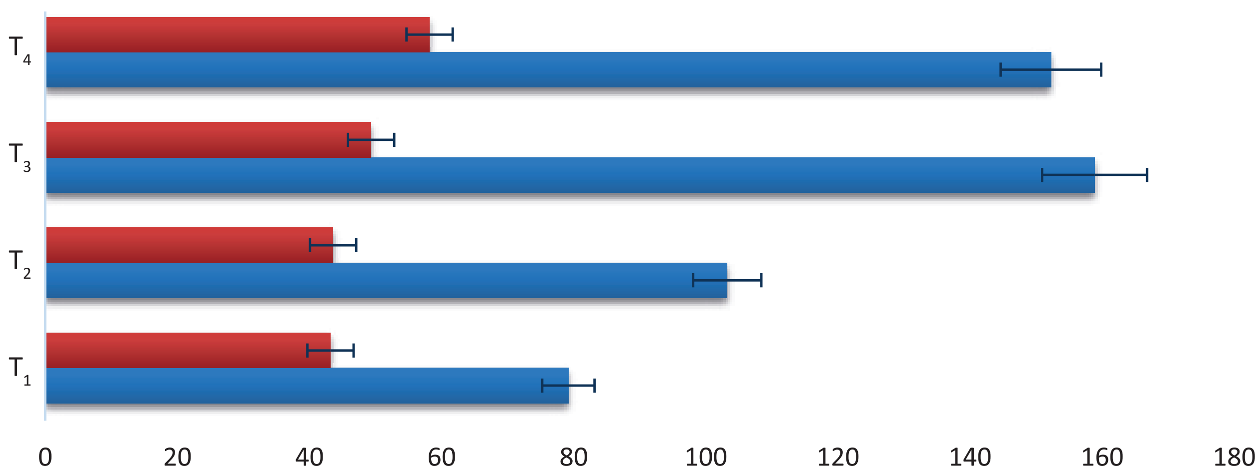

Fig. 1. Response of customized micronutrient mixtures on changes in canopy volume and fruit yield of Nagpur mandarin (2007-2019)
T_1 – Micronutrient mixture (Citrus special, IIHR Bangalore); T_2 -Macronutrients (Soil application) + Micronutrients (Foliar application; T_3- Micronutrient mixture-1 (Soil application) + Macronutrients (Soil application); T_4- Micronutrient mixtur-2 (Soil application) + Macronutrients (Soil application)
Source : Srivastav and Pandey(2021)

seed germination to growth of an adult plant, thereby, transforming rhizosphere biologically more active than bulk soil (Moshiri *et al.*, 2019). In this process, plant recruits active microbial communities within rhizosphere along and within the rootzone.

While addressing this important issue, comparative studies (Wang *et al.*, 2022; Xie *et al.*, 2024) on monoculture versus intercropping cultivation patterns of fruit crops have shown significant differences in reshaping the microbial communities and metabolism of beneficial microbes alongside microbial antagonists. The evidences accrued through worldwide studies are strong enough about a strong possibility of microbial communities conditioned by root exudates of main crops and intercrops undergoing mutational changes via different trophic interactions , thereby giving birth to another term (Fig 2 as a conceptual framework) , we propose as "Rhizosphere Hybridization" . Rhizosphere hybridization is hence a concept that involves combining the microbial diversity of different crop rhizospheres to improve the rhizosphere function of targeted crops for improvised plant growth and development. In this background information, efforts were made to take stock of the work done on the rhizosphere microbiome of different promising tree plants that could be fitted into the concept of rhizosphere hybridization and put forth some future lines of research on an issue, very limited clues are presently available at the international arena.

Rhizosphere hybridization is new concept to modify the rhizosphere ecology to create an optimum environment for PGPMs to show the positive effect of plant agronomy . The concept of "rhizosphere hybridization" is therefore, advocated to harness the value- added benefit of nutrient-microbe synergy, besides providing dynamism to microbial consortium suiting to wide range of perennial fruits (Srivastava and Singh , 2006) . Our studies on response of different treatments involving rhizosphere soil of three perennial trees viz., *Ficus racemosa* L. (Umber tree), *Ficus benghalensis* L. (Banyan tree), and *Ficus religiosa* L. (Pipal tree) along with rhizosphere soil of healthy and highly productive sweet orange trees in sweet orange buddlings showed differential response in terms of agronomic parameters, changes in soil physical properties, and pool of plant available nutrients (Cheke *et al.*, 2018). However, hybridized rhizosphere of sweet orange and *Ficus racemosa* L. out-smarted the response over other rhizosphere hybridization treatments . These studies lend some support to the fact that inoculation of soil or crops with rhizospheric or endophytic microbes, respectively, can enhance the micronutrient contents in various plant tissues including roots, leaves, and fruits (Fig. 3). In field , the rhizosphere hybridization can be

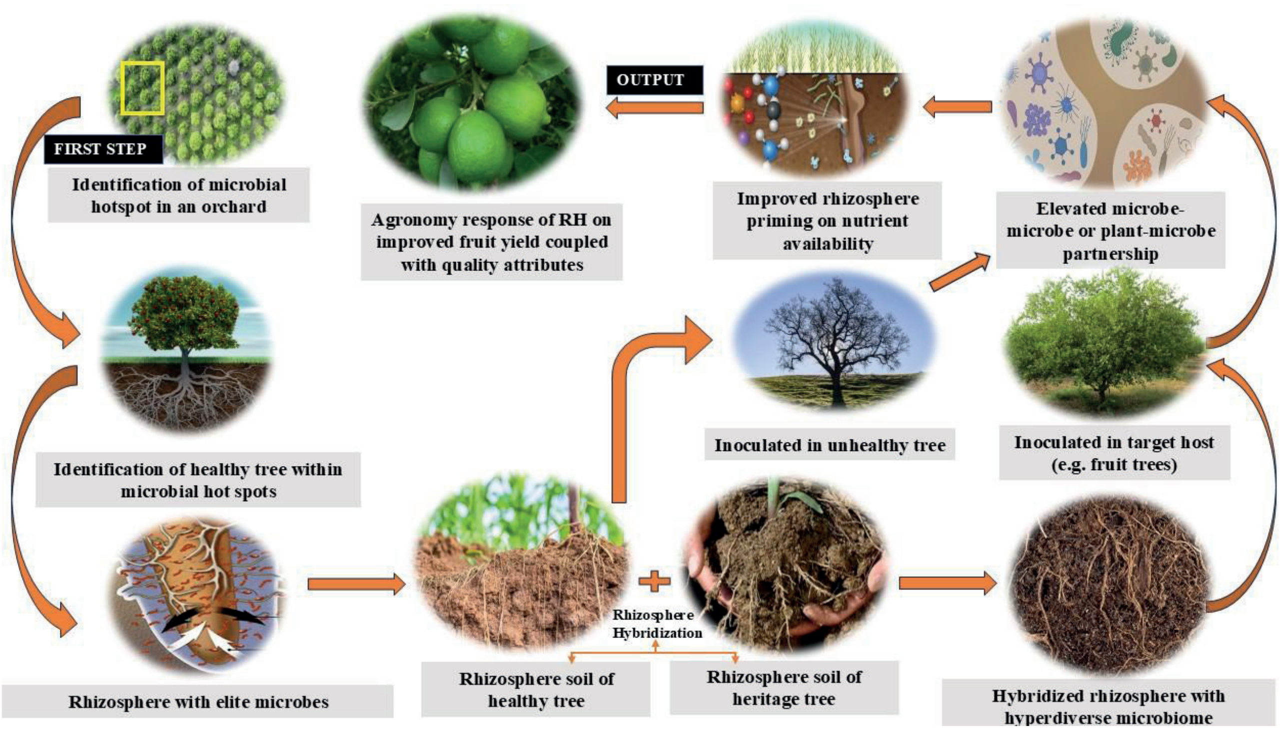

Fig.2. Schematic representation of rhizosphere hybridization proposed for using agrobiology-driven rhizosphere fortification of microbes in citrus (Srivastava *et al.*, 2025)

implemented by collecting rhizosphere soil of healthy trees and injected into weaker trees to rationalise distribution of microbes across field /orchard as a part of natural farming with agro-ecology exploited as its best .

Strategies and opportunities

No doubt , magnitude and distribution of nutrient stress are likely to expand with soil water deficit stress (Shirgure and Srivastava, 2003), warranting for a reoriented strategies to sustain the fruit production when compared with optimum soil moisture condition (Shirgure *et al.*, 2001) and optimum fruit load (Srivastava *et al.*, 2000). Despite many cutting edge technologies, addressing a variety of core issues on role of soil management-based nutrient- use -efficiency (integrating right dose of fertilizers in right place at right crop growth stage using right source as 4R and right amount of irrigation water in right place at right crop growth stage using right source as 4W) using sensor-based subsurface fertigation amidst multiple nutrient deficiencies (Meshram *et al.*, 2025a ; 2025b) in raising the productivity of perennial fruits is the major research and developmental issue. Microbes are most diverse soil organisms, yet very little is known about them (Hota *et al.*, 2020). Until recently, research has focused on those organisms that are culturable. However a wealth of information is now being collected from both culturable and, as yet, unculturable organisms. Functions of the soil microbial population impact many processes and, therefore, productivity , if mechanisms involved in the plant-microbe interaction are better understood. Researchers are still looking forward to schedule function-specific microbial inoculation , in line with nutrients partitioning as per crop critical growth stages . If fertigation (as a prudent option to neutralize soil water deficit stress) is a nutrient saving exercise , biofertigation could still be a better option, provided value -chain of microbial inoculants is precisely developed.

fertilizers, an understanding on nutrient acquisition and regulating the water relations would help switch orchards to CO_2 sink (expanding carbon capturing capacity of rhizosphere) so that a more sustainable fruit-based integrated crop production system under biotic and abiotic stress could be evolved. Role of mycorrhizas

in providing an additional resilience to rhizosphere's ability of carbon accredition through within rhizosphere and associated development of plant's antioxidant profile

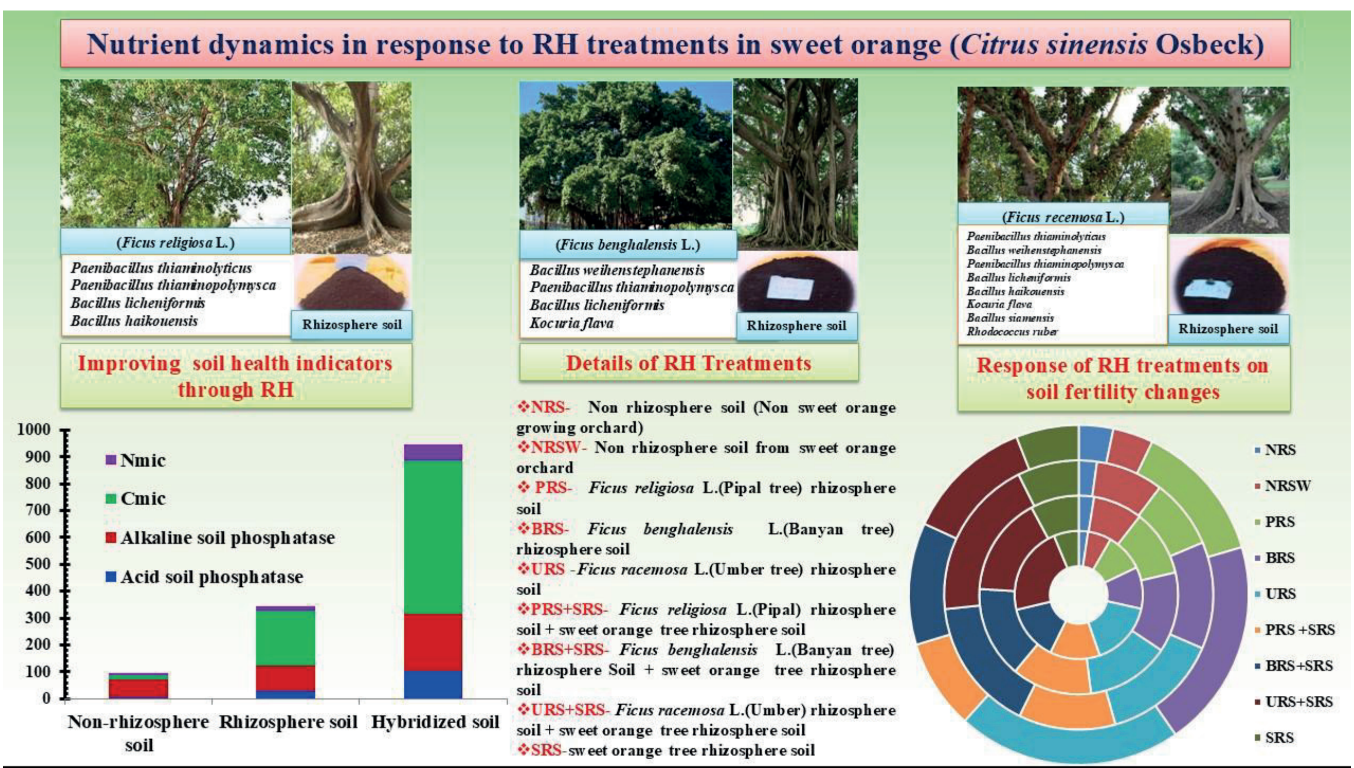

Fig. 3: Diagrammatic representation on response of RH in sweet orange (*Citrus sinensis* Osbeck) grafted on Rangpur lime (*Citrus limonia* Osbeck) rootstock for improved rhizosphere health indicators (microbial biomass nitrogen, Nmic; microbial biomass carbon, Cmic; alkaline soil phosphatase; and acid soil phosphatase) and soil fertility changes (inner most circle represents organic carbon, followed by $KMnO_4$-N, Olson-P, and NH_4OAc-K as we move on from inner circle). Hybridized soil (URS + SRS) involving inoculation of rhizosphere of *F. recemosa* (URS) into the rhizosphere of sweet orange trees (SRS) proved to be far superior over either of two. Based on data used generated through studies by Cheke *et al.* (2018) and Srivastava *et al.* (2021)

as a defense mechanism should divert the research studying strong mycorrhizal dependency of fruit crops. Rhizosphere specific AMF-based microbial consortium (mass multiplication technology, however still a lot desired to be addressed) would add a new dimension in providing newer options for raising the productivity potential of fruit crops. The framework on soil biodiversity effects from field to fork comprises: i. recognizing both direct and indirect mechanisms of soil biodiversity effects on crops properties, ii. identifying postharvest processes that affect biodiversity legacy effects on crop properties; and iii. pinpointing biodiversity-related crop properties that influence the efficacy and success of operations occurring in the agrifood chain..

In addition, another novel concept called "Rhizosphere Hybridization" where we succeeded in developing a microbially hybridized rhizosphere (Hota *et al.*, 2020 ; Sivastava *et al.*, 2022; Srivastava *et al.*, 2025) by inoculating rhizosphere soil from healthy plants into the rhizosphere those unhealthy plants , eventually resulted in complete recuperation from untimely decline in productivity (Dzvichu *et al.*, 2023) on account of aided biochemical preparedness of thus treated plants (Srivastava , 2023 ; Srivastava and Singh , 2004b) . These strategies are anticipated to develop a resilience to soil water deficit stress without nutrient constraints jeopardizing the possible gains in crop-response linked productivity. The work related to microbial inoculants for mass production, formulation coupled with innovative marketing, interaction and signaling with the plant and soil environment need further redressal to reorient nutrient-microbe synergy in fruit scientists. In another persuit to develop a nutrient-efficient fruit crop, engineering microbial genepool could play an important role by combining nutritional physiology with functional genomics and simultaneously solve the recurrent problem of crop response under soil water deficit stress.

The fall out of a generalized fertilizer s recommendation over large areas of small-scale farming very frequently leads to the possibility of over or under-application of nutrients, by and large, coupled with its economic and environmental consequences . The more apparent consequences of falling productivity and nutrient efficiency, multi-nutrient deficiencies, increasing pace of nutrient mining, and falling farm income are highlighted by earlier researchers (Srivastava and Singh , 2004b ; 2009a). The environmental impacts are not very apparent yet, probably because of the generally low nutrient application rates, except few crops of very high commercial importance. The SSNM using crop-customized fertilizers on the other hand, is another approach for feeding crops with nutrients, as and when they are needed, considering inherent spatial variability associated with fields under crop production. The most important step towards the calibration of site specific fertilizer requirement is the estimation of the indigenous nutrient supplies, which we define as the cumulative amount of nutrient originating from all indigenous sources . The major challenges for SSNM research and extension in future will be two-folds: i. to retain the demonstrated potential of the approach and ii. to build upon what has already been achieved while reducing the complexity of the technologies as it is disseminated to farmers . However, Zhang *et al.* (2010) suggested that the regionalized maps are practical alternative to site-specific soil nutrient management approaches in areas where it is not practical to implement SSNM due to small field size or other constraints to use intensive soil sampling and chemical analyses (Srivastava and Patil, 2014 ; Srivastava *et al.*, 2015 ;Srivastava and Singh , 2001 ; 2002). These strategies would go a long way in offering some fruitful solution in mitigating multiple nutrient deficiencies (regardless of soil moisture) using specialty fertilizers, with an eye on the soil agroecology playing a pivotal role in ensuring a sustained productivity in the backdrop of climate change as an approach of slogan-to-solution for future redressal of soil health-mediated multiple nutrient stress in fruit crops. .

REFERENCES

Afify A H (2022) Silicate bacteria on a bio-fertilizer. *Journal of Agricultural Chemistry and Biotechnology* **13** : 75-83.

Agegnehu G, Srivastava A K and Bird M I (2017) The role of biochar and biochar-compost in improving soil quality and crop performance : a review. *Applied Soil Microbiology* 119:156-70.

Ahmad F , Ahmad J , and Khan M S (2008) Screening of free-living rhizospheria bacteria for their. multiple growth promoting activities. *Microbiological Research* **163**: 173-100.

Baker B, Zambryski P, Staskawicz B and Dinesh Kumar S P (1997) Signaling in plant- microbe interactions *Science* **276**: 726-28.

Bashan Y , Holguin G and de-Bashan L E s (2004) *Azospirillum*-plant relationships :physiological , molecular , agricultural, environmental advances (1997-2003). *Canadian Journal of Microbiology* **50** : 225-28.

Begum N , Qin C, Ahanger M A , Raza S , Khan, M I , Ashraf M , Ahmed N and Zhang L (2019) Role of arbuscular mycorrhizal fungi in plant growth: implications in abiotic stress tolerance. *Frontiers in Plant Science* **10**: 01068.

Bertrand J-C, Document P, Guyoneaud R, Marrot B, Martin-Laurent F, Matheron R, Moulin P and Soulas G (2015)

Applied microbial-ecology and bioremediation. In: *Environmental Microbiology. Fundamental and Applications.* Springer -Verlag , pp. 659-753.

Bist V , Niranjan A , Ranjan M , Lehri A, Seem K and Srivastava S (2020) Silicon solubilising media and its implication for characterisation of bacteria to mitigate biocristras. *Frontiers in Plant Science* **11**: 00028.

Bora P and Bora, L C (2020) Disease management in host crops through microbial interventions: an overview. *Indian Journal of Agricultural Sciences* **90**(8): 1389-1396.

Cheke A , Patil V K and Srivastava A K (2018) Studies on rhizosphere hybridization and nutrient dynamics in sweet orange seedlings from pot culture experiment. *Journal of Pharmacognosy and Phytochemistry* **7**: 3077-82.

Chen F, Ma J , Yuan Q and Yu Z (2023) Phosphate solubilising microorganisms as a driving force to assets mine phytoremediation. *Frontiers in Bioengineering and Biotechnology* **11**: 1201067.

Cheng W and Gershenson A (2007) Carbon fluxes in the rhizosphere. In: The rhizosphere-an ecological perspective, 2nd ed.; Eds. Cardon, Z.G.; Whitbeck, J.L., Eds.; Publisher: Academic Press, San Diego, California, USA, pp 31-56.

Cornelius P and Dingmans J (2013) *Pseudomonas aeruginosa* adopts its iron uptake strategies in function of the type of infections. *Frontiers in Cell Infection and Microbiology* **3**: 00075.

Dong ZH, Srivastava AK, Tan QL, Raiz M, Lv XL, Liu XD, Gao Y and Chen M (2023) Effect f different spring and summer fertilization on fruit yield , quality and nutrient-use-efficiency of Nehwall orange (*Citrus sinensis* Osbeck) orchard of China. *Journal of Plant Nutrition* **46**: 2144-54.

Doran S F and Zeiss M R (2000) Soil health and sustainability : managing the biotic components of soil quality . *Applied Soil Ecology* **15**(1) : 3-11.

Dzuvichu M, Alila P , Jamire S, Kanauzia S P and Srivastava A K (2023) Yield response of rhizosphere hybridization in khasi mandarin . *International Journal of Innovative Horticulture* **12**(1): 102-108.

FAO (2023) Statistical Year Book of Food and Agricultural Organization, FAO. State div. Metalink: P3.Reu.FAO, ESS.FRD.AHSci.p.108-113.www.fao.org.docrep/017/i3138e/i3138e05.pdf.

Frageria N K, Baligar, VC and Li Y C 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. *Journal of Plant Nutrition* **31**: 121-157.

Gouda S , Das G, Sen S K, Skin H-S and Patra J K (2016) Endophytes: A treasure house of bioactive compounds of medicinal importance. *Frontiers in Microbiology* **7**:1538.

Graham J H and Fardelmann D (1986) Inoculation of citrus with root fragment containing chlamydospores of the mycorrhizal fungus *Glomus intraradices*. *Candian Journal of Botany* **64** :1739-44.

Guimaraes V, Danielle M I S , Gonzaga G and Jose de O.Melo Neto (2014) Manangemnt of soil organic matter and carbon storage in tropical fruit crops. *Revista Brasileira de Engenharia Agricola e Ambiental*. **18** : 83-93.

Guttman D S, Mc Hardy A Cand Schulze- Lefert P (2014) Microbial genome- enabled insights into plant-microorganism interactions. *Nature Review Genetics* **15**: 797-813.

Hiltner L (1904) Über neuere erfahrungen und probleme auf dem gebiete der Bodenbakteriologie unter besonderer Berücksichtigung der Gründüngung und Brache. *Arb DLG* **98**: 59-78.

Hota D, Srivastava A K, Dahat S and Dubey S (2020) Rhizosphere engineering through microbes enhancing agronomic performance of acid lime. *Progressive Horticulture* **52**: 120-123.

Huang Y-M , Srivastava, A K , Zou Y-N, Ni Q-D, Han Y and Wu, Q-S (2014) Mycorrhizal -induced calmodulin mediated changes in antioxidant enzymes and growth response of drought -stressed trifoliate orange. *Frontiers in Microbiology*. **5**: 682-28.

Jeyabaskaran K J, Shirgure P S, Srivastava A K, Pandey V and Uma S (2021) Fertigation in horticulture : a guarantee to economized quality production . *Indian Journal of Fertilizers* **17**: 364-83.

Joseph M H, Dhargave T S , Deshpande C P and Srivastava A K (2015) Microbial solubilization of phosphates; *Pseudomonas* versus *Trichoderma*. *Annals of Plant and Soil Research* **17**(3): 227-32.

Keditsu R and Srivastava A K (2014) Substrate dynamics : developments and issues. *Annals of Plant and Soil Research* **16**(1): 1–8.

Khan K Mohd , Mishra P K , Sharma T, Verma S K , Misra P and Ramteke PW (2009) Screening of microbial strains for succinic acid production . *Annals of Plant and Soil Research* **11** : 67-68.

Khandelwal R , Choudhary S K , Goshyla J and Singh P (2013) Effect of fertilizer and biofertilizer on growth , yield , and economics of cowpea. *Annals of Plant and Soil Research* **15**: 177-78.

Khehra S and Bal J S (2014) Influence of organic and inorganic nutrient sources on growth of lemon (*Citrus limon* (L.) Burm.) cv Baramasi. *Journal of Experimental Biology and Agricultural Sciences* **2**: 126–29.

Kloepper J K , Leong J, Teintze M and Schorth M N (1980) Enhanced plant growth by siderophores produced by plant growth promoting rhizobacteria. *Nature* **28**: 885-86.

Kohli R R , Srivastava A K and Shivankar V J (1998) Organic culture in citrus cultivation. *Indian Horticulture* **43**; 12-15.

Meshram D T , Srivastava A K , Thirugnanavel A , Meshram N M , Jagannadham P T K , Utkhede A D and Pangul, C S (2025a) Agronomic response of subsurface versus surface drip irrigation in Nagpur mandarin (*Citrus reticulata* Blanco) on Indian Vertisol. *Frontiers in Horticulture* **4**: 1552283.

Meshram D , Srivastava A K , Utkhede A , Pangul C and Ziogas V (2025b) Response to sensor- based fertigation of Nagpur mandarin (*Citrus reticulata* Blanco) in Vertisol of central India. *Horticulturae* **11**: 508.

Lakso A l. (2010) Estimating the environmental footprint of New York apple orchards. *New York Fruit Quarterly* **18**:26-28.

Lehman J, Bassio, D N, Kogel-Kanbner I and Rillig M C (2020) The concept and future prospects of soil health . *Nature Reviews Earth and Environment* **1** : 544-53.

Li R-X , Cai F, Pang G, Shen Q-R, Li R and Chen W (2015) Solubilisation of phosphate and micronutrients by *Trichoderma harzianum* and its relationship with the promotion of tomato Plant growth. *PLosOne* **10**(6) :e0130081.

Lindsay W L C and Norvell W (1978) Development DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of American Journal* **42** : 421-28.

Liu Z , Cheng X F , Zou Y N, Srivastava A K , Alqahtani M D and Wu Q-S (2024) Negotiating soil water deficit in mycorrhizal trifoliate orange: a gibberellin pathway. *Environmental and Experimental Botany* 219:105658.

Liu C-Y ,Srivastava AK and Wu, Q-S (2014) Effect of auxin inhibitor and AMF inoculation on growth and rot morphology of trifoliate orange (*Poncirus trifoliata*) seedlings. *Indian Journal of Agricultural Sciences* **84**(11): 342-46.

Lobell D B , Field,C B, Chahill, K N and Bonfils C (2005) Impacts of future climatic changes on California crop yields: Model projections with climate and crop uncertainities . *Agricultural and Forest Meteorology* **141**: 208-18.

Malhotra S and Srivastava A K (2015.) Fertilizer requirement of Indian horticulture :an analysis. *Indian Journal of Fertilizers* **11**(7) :16-25.

Meyer J M and Abdallah M A (1997) The Fluorescent pigment of *Pseudomonas fluorescens*: Biosynthesis, purification and physico-chemical properties. *Microbiology* **107**: 319-28.

Molnar Z, Soloman W, Mutum L and Janda T (2023) Understanding mechanisms of Fe- deficiency in the rhizosphere to promote plant resilience. *Frontiers in Plant Science* **12** :1945-48.

Moshiri F, Ebrahimi H, Ardakani M R, Rejali F and Mousavi S M (2019) Biogeochemical distribution of Pb and Zn forms in two calcareous soils affected by mycorrhizal symbiosis and alfalfa rhizosphere. *Ecotoxicology and Environmental Safety* **179** : 241-48.

Mousavi S M, Srivastava A K and Cheraghi M (2023) Soil health and crop response of biochar: an updated analysis. *Archives of Agronomy and Soil Science* **69**(7): 1085-10.

Ngullie E, Singh A K, Sema A and Srivastava A K (2015) Citrus growth and rhizosphere properties. *Communications in Soil Science and Plant Analysis*. **46**(12): 1540-50.

Olanrewaju U O S , Glick BR and Babalola O O (2017) Mechanism of action of plant growth promoting bacteria. *World Journal of Microbiology and Biotechnology* **33**:197-10.

Ortas I, Refique M, Akpinar C and KacarY A (2017) Growth media and mycorrhizal special effect on acclimatization and nutrient uptake of banana plantlets. *Scientia Horticulturae* **217**: 55-60.

Pathak H and Nedwell D B (2011) Nitrous oxide emission from soil with different fertilizer , water levels , and nitrification inhibiyots. *Water , Air and Soil Pollution* **129**: 217-28.

Rengel Z , Gutteridge R , Hirsch P and Hornby D (1996) Plant genotype , micronutrient fertilization , and take-all infection influence bacterial populations in the rhizosphere of wheat . *Plant and Soil*. **183**: 269-77.

Ribaudo C M , Krumpholz E M, Cassan F D, Bottini R, Contour M L and Curia JA (2006) *Azospirillium* sp. promotes root hair development in Taranto plants trash a mechanism that involves ethylene. *Journal of Plant Growth Regulation* **25** :175-85.

Rillig M C (2004) Arbuscular mycorrhizae, glomalin and soil aggregation. *Canadian Journal of Soil Science* **85**: 355-363.

Salaza-Garcia S and Lazcano-Ferrat I (2003) Site-specific fertilization increased yield and fruit size in 'Hass' Avocado. *Better Crops International* **17**(1): 12-16.

Schalk I J and Guillon L (2012) Pyoverdine biosynthesis and secretion of *Pseudomonas aeruginosa*: implication of metal homeostasis. *Environmental Microbiology* **15** (6):1661-73.

Shirgure P S and Srivastava A K (2003) differential fertigation response of Nagpur mandarin (*Citus reticulata* Blanco) on an alkaline Inceptisol under subtropical climate. *Tropical Agriculture* **80**: 91-96.

Shirgure PS, Srivastava A K and Singh S (2001) Fertigation and drip irrigation in Nagpur mandarin (*Citrus reticulata* Blanco) .*South Indian Horticulture* **49**: 95-97.

Singh S R and Banik B C (2011) Response of integrated nutrient management on flowering. *Fruits* **42**:151–54.

Srivastava A K (2012) Integrated nutrient management in citrus. (*In) Advances in Citrus Nutrition,* Srivastava A K. (Ed). Springer-Verlag, The Netherlands, pp.369-389.

Srivastava A K (2013a)Nutrient deficiency symptomology in citrus: An effective diagnostic tool or just an aid for post–mortem analysis. *Agricultural Advances*. **2** :177-94.

Srivastava A K (2013b) Site specific nutrient management in citrus. *Scientific Journal of Agricultural (Agricultural Advances)*. **2**: 1-15.

Srivastava A K (2013c) Nutrient diagnostics in citrus: Are they applicable to current season crop. *Agrotechnology* **2**: 104-05. (Doi.10.4172/2168P-9881.1000e104).

Srivastava A K (2023) Integrating natural farming with agroecology for soil health care under fruit production system. *Annals of Plant and Soil Research* **25**(4) :524-33.

Srivastava A K and Bora P (2023) Multiple dimensions of agroecology in sustaining agriculture. *Indian Farming* **73**(6) : 524-33.

Srivastava A K and Das S N (2017) Nutrient optima-based productivity zonality and rationale of fertilizer use in citrus. In ; Sustainable Management of Land Resources. Apple Academic Press, USA. pp. 717-38.

Srivastava A K, Das AK, Jagannadham PT K, Bora P, Ansari FA and Bhate R (2022) Bioprospecting soil and plant health management amidst huanglongbing threat in citrus; a review. *Frontiers in Plant Science* **13** :858842.

Srivastava A K , Das S N , Malhotra S K, Majumdar K (2014) SSNM-based rationale of fertilizer use in perennial crops; a review. *Indian Journal of Agricultural Sciences* **84**(1) : 3-17.

Srivastava A K, Majid S M , Bora P , Hota D, Malhotra S K, Pandey V and Vasileios Z (2025) Rhizosphere to rhizosphere hybridization : new initiatives in fruit crops. *Frontiers in Horticulture* **4**: :1584807.

Srivastava A K and Malhotra S K (2017) Nutrient use efficiency in perennial fruit crops- a review. *Journal of Plant Nutrition* **40**(13): 1928-1953.

Srivastava A K, Malhotra S K and Krishna Kumar N K (2015) Exploiting nutrient-microbe synergy in unlocking productivity potential of perennial fruits: A review. *Indian Journal of Agricultural Sciences* **85**(4) :459-81.

Srivastava A K and Ngullie E (2009) Integrated nutrient management :theory and practice. *Dynamic Soil, Dynamic Plant* **3** : 1-30.

Srivastava A K , Paithankar D H, Ventataramana KT, Hazarika B and Patil P (2019) INM in fruit crops: sustaining quality production and soi health. *Indian Journal of Agricultural Sciences* **89**(3):379-395.

Srivastava A K and Pandey V (2021) Speciality fertilizer centric site specific nutrient management in fruit crops: principles and achievements. *Indian Journal of Fertilizers* **17**(5) : 458-474.

Srivastava, A K and Patil P (2014) Soil fertility indexing in acid lime grown on smectite rich soils. *Annals of Plant and Soil Research* **16** : 25-28.

Srivastava A K and Pongener A (2023)Asian citrus:a meta-analysis on soil fertility and plant nutrition constraints. *Annals of Plant and Soil Research* **25**: 345-52.

Srivastava A K and Singh S (2001) Development of optimum soil property limits in relation to fruit yield and quality of *Citrus reticulata* Blanco cv. Nagpur mandarin. *Tropical Agriculture* **78** : 174-81.

Srivastava A K and Singh S (2002) Soil analysis based diagnostic norms for Indian citrus cultivar. *Communications in Soil Science and Plant Analysis* **33**: 1689-1706.

Srivastava A K and Singh S (2004a) Soil and plant nutritional constraints contributing to citrus decline in Marathawada region, India. *Communications in Soil Science and Plant Analysis* **35**: 2537-50.

Srivastava A K and Singh S (2004b) Zinc nutrition, a global concern for sustainable citrus production. *Journal of Sustainable Agriculture* **25**: 5-42.

Srivastava A K and Singh S (2005) Diagnosis of nutrient constraints in citrus orchards of humid tropical India. *Journal of Plant Nutrition* **29** : 1061-76.

Srivastava A K and Singh S (2006).Citrus nutrition and biochemical markers. *Journal of Plant Nutrition* **29**(5): 827-55.

Srivastava A K and Singh S (2008a) Analysis of citrus orchard efficiency in relation to soil properties. *Journal of Plant Nutrition* **30**: 2077-90.

Srivastava A K and Singh, S (2008b) DRIS norms and their field validation in Nagpur mandarin (*Citrus reticulata* Blanco). *Journal of Plant Nutrition* **31**: 1091-97.

Srivastava A K and Singh S (2008c) Citrus nutrition research in India : Problems and prospects. *Indian Journal of Agricultural Sciences* **78**: 3-16.

Srivastava A K and Singh S (2009a) Citrus decline : Soil fertility and plant nutrition. *Journal of Plant Nutrition* **32** : 197-45.

Srivastava, A K and Singh S (2009b) Zinc nutrition in 'Nagpur' mandarin on Haplustert. *Journal of Plant Nutrition* **32** : 1065-1081.

Srivastava A K , Singh S and Albrigo L G (2008) Diagnosis and remediation of nutrient constraints in citrus. *Horticultural Reviews* **34** : 277-63.

Srivastava A K, Singh S, Das S N and Singh H (2010) Delineation of productivity zones in mandarin orchards using DRIS and GIS. *Better Crops – South Asia* **4**:13-15.

Srivastava A K, Singh S, Diwre V S and Singh H (2009) Site-specific nutrient management in 'Mosambi' sweet orange. *Better Crops – India* **3**: 10-11.

Srivastava AK, Singh S and Huchche AD (2000) An analysis on citrus flowering -a review. *Agricultural |Reviews* **21**(1): 2-25.

Srivastava A K, Singh S and Marathe,R A (2002) Organic citrus: soil fertility and plant nutrition. *Journal of Sustainable Agriculture* **19**(3) : 5-29.

Srivastava A K , Singh S and Tiwari K N (2006) Site specific nutrient management for Nagpur mandarin (*Citrus reticulata* Blanco). *Better Crops* **88** : 22-25.

Srivastava s A K, Singh S and Tiwari K N (2007) Diagnostic tools for citrus : Their use and implications in India. *Better Crops – India* **1**: 26-29.

Sultana U, Desai S, Reddy G and Prasad T N V KV (2020) Zinc solubilising and growth promoting microbes produce zinc nanoparticles. *Genes and Nutrition* **15** : 4-10.

Thaler D S , Floh E I S, Handro, W and Barbosa HR (2003) Plant growth regulators and amino acids released by *Azospirillium* sp. in chemically defined media. *Letters in Applied Microbiology.* **37** : 174-178.

Tiwari K N (2007a) Breaking yield barriers and stagnation through site-specific nutrient management. *Journal of the Indian Society of Soil Science* **55**: 444-454.

Tiwari K N (2007b) Reassessing the role of fertilizers in maintaining food, nutrition and environmental security. *Indian Journal of Fertilizers* **3**(1): 33-48 & 51-52.

Wang N, Jin T, Trivedi P , Setubal J C, Tang J, Machado M A, Triplet E, Coletta-Filho HD, Cubero J and Deng X et al (2015) Announcement of the international citrus microbiome phytobiome) consortium. *Journal of Citrus Pathology* **27940**:1-2.

Wang Z , Zhang H , Liu L , Li S , Xie J , Xue X and Jiang Y (2022) Screaming of phosphate solubilising bacteria and their abilities of phosphorous solubilisation and wheat growth promotion. *BMC Microbiology* **22**: 296-08.

Welch R S, Norvell W A , Schaefer S C, Shaff J E and Kochian L (1993) Induction of iron (III) and copper (II) reduction in pea (*Pisum sativum* L.) roots by Fe and Cu status: Does the root cell- plasmalemma Fe(III)-chelate reductase perform a general role in regulating cation uptake . *Planta* **190**: 555-61.

World Health Organization (2023) World health summit . https;//www.who.int/Newsroom/Events/Detail.

Wu Q-S, Li Y, Ying- Ning Z and He X- H (2015) Arbuscular mycorrhiza mediates glomalin related soil protein production and soil enzyme actuates in the rhizosphere of trifoliate arrange gowns under different planers. *Mycorrhiza* **25**: 121-30.

Wu Q-S ,Srivastava A K, Cao, M-Q and Wang J (2014) Mycorrhizal function on soil aggregate stability in root zone and root free hyphae zone of trifoliate orange. *Archives of Agronomy and Soil Science* .http://dx.doi.org/10.1080/03650340.2014.95226.

Wu Q-S , Srivastava A K and Zhou Y-N (2013) AMF-induced tolerance to drought stress in citrus: a review. *Scientia Horticulturae* **164** : 77-87.

Wu Q-S, Sun P and Srivastava A K (2017) AMF diversity and in citrus rhizosphere. *Indian journal of Agricultural Sciences* **87**(5): 653-56.

Wu T, Wang Y ,Yu C , Rawee C , Zhang X , Han Z and Wu L (2012) Carbon sequestration by fruit trees-Chinese apple orchards as an example. *PlosOne* 7: e38883.

Xi Q , Xu H, Wen R, Wang L, Yang Y, Zhang H and Su B (2024) Integrated management of of fruit trees and *Bletilla striata* implications on soil nutrient profiles and microbial community structures. *Frontiers in Microbiology*. 15: 1307677.doi.org./10.3389/fmicb2024.1307677.

Xuan Yu , Xu Liu, Tian Hui. Zhu. Guang, Hai. Liu and Cui, Mao (2011) Isolation and characterization of phosphate solubilising bacteria from walnut and their effect on growth and phosphorous mobilization. *Biology and Fertility of Soils* **47** : 437–46.

Zhang Q. Yang Z, Li Y, Chen D, Zhang J and Chen M (2010) Spatial variability of soil nutrients and GIS-based nutrient management in Yongji county, China. *International Journal of Geographical Information Science* **24**(7): 965-81.

Zhang Ze-Zhi , Srivastava A K , Wu Q-S and Li, G-H (2015) Growth performance and rhizosphere traits of peach (*Prunus persica*) in response to mycorrhization on replant versus non-replant soil. *Indian Journal of Agricultural Sciences* **85**(10) :125-13.

Zou Y N , Srivastava A K , Wu Q-S and Huang Y M (2014) Increased tolerance of trifoliate orange (*Poncirus trifoliata*) seedlings to waterlogging after inoculation with arbuscular mycorrhizal fungi. *Journal of Animal and Plant Science* **24**(5) : 415-20.

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Advances in medicinal plant cultivation techniques for enhancing yield and quality — a review

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Abstract

The cultivation of medicinal plants is undergoing a paradigm shift, driven by the dual demands of higher productivity. This review synthesizes recent advances in innovative cultivation systems, genetic improvement, and sustainable management practices aimed at enhancing yield, quality, and resource efficiency. Modern soilless systems such as hydroponics, aeroponics, and vertical farming are enabling precise control over growing environments, improving phytochemical content, nutrient uptake, and water-use efficiency. Tissue culture and bioreactor technologies are revolutionizing mass propagation, conservation, and targeted enhancement of bioactive compounds, while molecular breeding and CRISPR-based genome editing are unlocking new genetic potential. Concurrently, sustainable practices, including organic farming, integrated pest management, conservation tillage, cover cropping, and circular economy models, are reducing carbon footprints and safeguarding biodiversity. The review also examines future directions such as block chain-enabled traceability, life cycle assessment (LCA) for environmental benchmarking, and digital twin models for real-time cultivation optimization. These advancements collectively position medicinal plant cultivation to meet growing global demand for high-quality herbal products while aligning with ecological and regulatory imperatives.

Key words: Medicinal plant cultivation; Yield improvement; Phytochemical enhancement; hydroponics; Aeroponics; Tissue culture; Genome editing; Microbiome engineering; Sustainability; Precision agriculture

Medicinal plants have been an integral part of human healthcare for millennia, providing remedies that range from simple herbal preparations to highly refined pharmaceutical compounds. The World Health Organization (WHO) estimates that approximately 80% of the global population continues to rely on traditional plant-based medicines for primary healthcare (Beyene *et al.*, 2016), underscoring their enduring relevance to human health and cultural heritage. In recent decades, cultivation has expanded from small-scale gardens to large commercial operations, driven by rising global demand, advances in agricultural technology, and the urgent need to conserve threatened species. Successful medicinal plant production depends on an intricate interplay of factors, including the choice of species and genotypes, optimization of environmental conditions, integrated pest and disease management, and post-harvest handling. These parameters directly influence biomass accumulation, phytochemical content, and therapeutic efficacy. The last two decades have seen a notable shift towards science-based interventions that merge traditional knowledge with cutting-edge cultivation and processing technologies.

Modern propagation techniques such as tissue culture and bioreactor-based production ensure uniform, disease-free planting material and facilitate rapid multiplication of elite genotypes. Precision agriculture enhanced by IoT-enabled sensors, unmanned aerial vehicles (UAVs), and AI-based environmental control allows growers to monitor and adjust crop conditions in real time for optimal growth and metabolite synthesis. Sustainable production systems, including organic farming, agroforestry, and conservation tillage, are being adopted to meet environmental and regulatory requirements while enhancing market value.

This review synthesizes current advances in medicinal plant cultivation, focusing on strategies to enhance yield, improve phytochemical quality, and ensure environmental sustainability. It covers innovations in soilless cultivation (hydroponics, aeroponics, vertical farming), genetic improvement (conventional breeding, molecular tools, and CRISPR-mediated genome editing), microbiome engineering, and sustainable agronomic practices. The discussion also addresses market and policy drivers, such as traceability systems and compliance with Good Agricultural and Collection Practices (GACP), which are increasingly critical in global herbal trade. By examining both technological advances and sustainability imperatives, this review aims to provide a holistic framework for the next generation of medicinal plant production systems.

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Enhancing yield and quality for sustainability

Meeting the rising global demand for safe and effective herbal products requires cultivation systems that simultaneously enhance yield, ensure and standardize quality, and minimize environmental impacts. These objectives are interdependent: practices that optimize resource utilization and stabilize growing conditions tend to improve both biomass production and phytochemical composition, while sustainable frameworks help secure long-term supply chains and strengthen market confidence.

Yield: Global demand for medicinal and aromatic plants necessitates improving productivity without exhausting resources. Precision agriculture, supported by IoT-enabled sensors, AI-assisted decision tools, and geospatial analysis, has shown potential to optimize irrigation, nutrient delivery, and site-specific crop management (Mansoor *et al.*, 2025; Kumar *et al.*, 2025). Machine learning–based suitability mapping has also been applied to identify optimal growing zones for medicinal crops under rainfed and climate-stressed conditions (Roopashree *et al.*, 2024; Sadeghfam *et al.*, 2024). These approaches enhance both yield and resource-use efficiency, providing a climate-resilient pathway for medicinal plant production.

Quality: The concentration and stability of bioactive metabolites, which vary with genotype, cultivation conditions, and post-harvest processing (Ambali *et al.*, 2024; Hasmi *et al.*, 2025). Controlled environment agriculture and Good Agricultural and Collection Practices (GACP) help in standardizing quality (WHO, 2003; Chen *et al.*, 2016). More recently, metabolomics has emerged as a powerful tool to fingerprint chemical profiles, monitor environmental and processing effects, and support multi-marker quality control systems (Ji *et al.*, 2024; Wang *et al.*, 2023). Comparative studies, such as those on goose berries, highlight how harvest timing and environmental variation influence metabolite accumulation (Yao *et al.*, 2018). Together, these approaches ensure consistency, safety, and regulatory compliance in herbal products. Controlled environment agriculture and good agricultural practices have proven effective in optimizing active compound levels and improving medicinal plant quality (Saravanan and Das, 2024)

Sustainability: Unsustainable harvesting and habitat degradation threaten many medicinal species (Hamilton, 2004). Promoting sustainable cultivation through organic farming, agroforestry, and biodiversity conservation contributes not only to ecological health but also to improved yield and quality by maintaining soil fertility and ecosystem services (Marcelino *et al.*, 2023). Emerging approaches include circular economy models and life cycle assessments (LCAs), which help in identifying hotspots of energy and resource use in herbal value chains and propose pathways to reduce carbon footprints (Becerra *et al.*, 2022). Additionally, climate-focused strategies are needed to buffer medicinal plant resources against over-exploitation and environmental change (Mykhailenko *et al.*, 2024).

Traceability and market confidence: Sustainability and quality assurance are increasingly linked to digital traceability. Block chain-based systems are being piloted to integrate GACP records, laboratory test results, and lot identity across supply chains, thereby reducing adulteration risks and improving consumer confidence (Wang *et al.*, 2021).

Innovative cultivation practices

The innovative cultivation of medicinal plants (Fig 1) is undergoing a paradigm shift with the adoption of controlled-environment technologies, precision nutrient delivery, and advanced propagation systems. These approaches not only enhance yield and phytochemical quality but also improve production consistency and reduce environmental burdens. By integrating hydroponics, aeroponics, tissue culture, and vertical farming, medicinal plant production is being redefined to meet the dual challenges of global demand and sustainability.

Hydroponics: enhancing phytochemical content, nutrient uptake, and water efficiency

Hydroponics-soilless cultivation with nutrient-rich aqueous solutions-has emerged as a highly efficient system for medicinal plant production. Beyond its water-use efficiency, hydroponics allows precise manipulation of nutrient regimes to modulate secondary metabolite accumulation. Studies have demonstrated significant gains in both biomass and phytochemical content compared to soil-based systems (Atherton, 2023). A recent experiment on *Withania somnifera* (ashwagandha) showed remarkable improvements under hydroponic conditions, including a 72% increase in wet biomass along with enhanced plant height and leaf number (Agrahari, 2025). Similarly, optimizing nitrogen forms, such as tailoring NH_4^+:NO_3^- ratios, has been reported to elevate rosmarinic acid and other metabolites in *Melissa officinalis* (Safaei *et al.*, 2024). Such findings underscore hydroponics as a versatile tool for simultaneously enhancing productivity and therapeutic efficacy. Importantly, organ-targeted hydroponic designs-customized for roots, leaves, or flowers-are being developed to maximize yields of specific bioactive compounds (Atherton *et al.*, 2023).

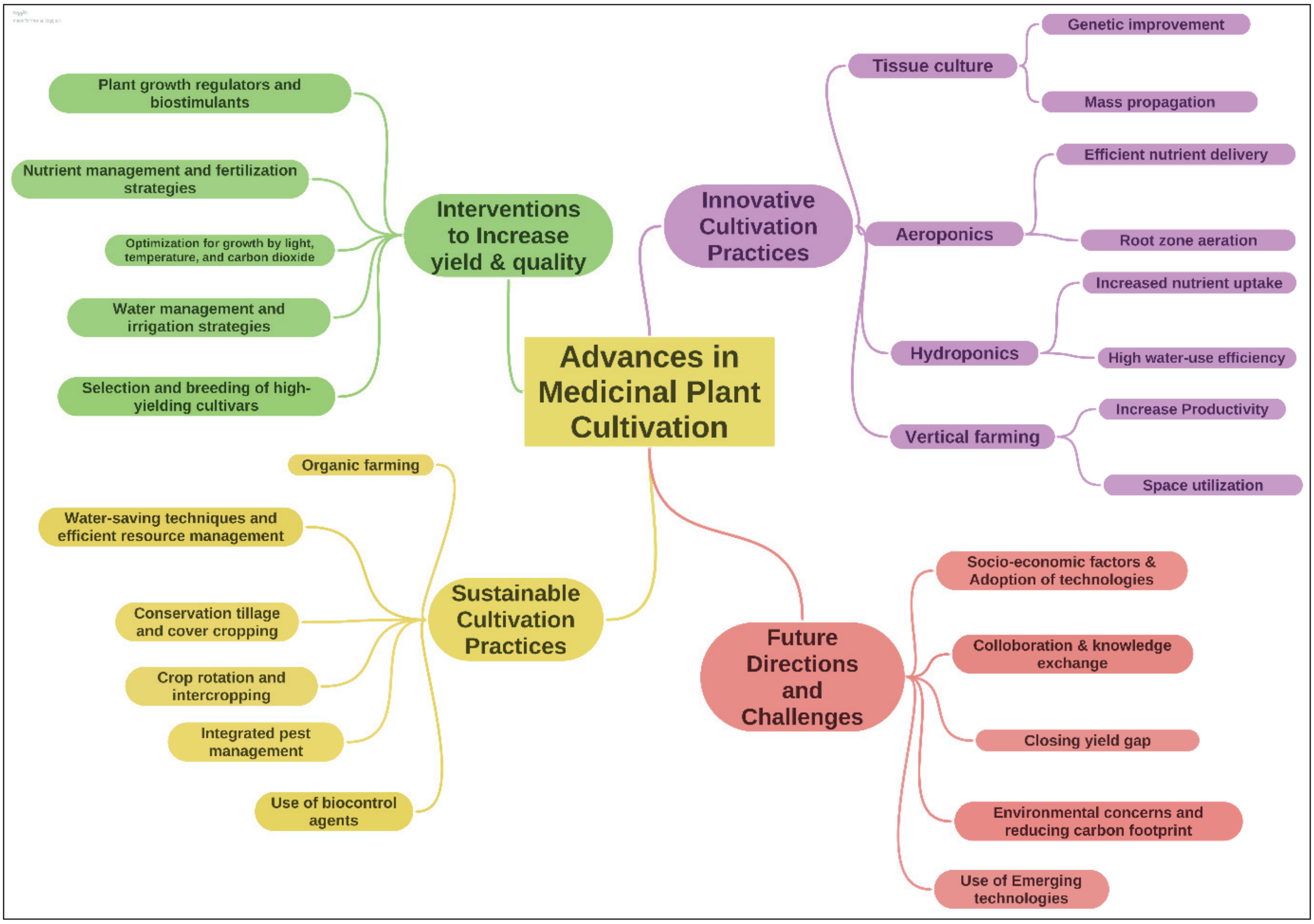

Fig. 1. Mind map of advances in medicinal plant cultivation

Aeroponics: optimizing root zone aeration and nutrient delivery

Aeroponic cultivation, where roots are suspended and intermittently misted with nutrient-enriched solutions, offers superior aeration and rapid nutrient uptake. This approach mitigates soil-borne pathogens while promoting root vigour and metabolite accumulation. With Industry 4.0 integration, aeroponic systems increasingly deploy sensors, automation, and AI-based controls to regulate mist frequency, nutrient concentration, and environmental parameters (Garzón *et al.*, 2023). Recent studies highlight innovative enhancements: electro stimulation treatments have improved root biomass and metabolite profiles in medicinal plants, while IoT–machine learning frameworks are being deployed for predictive irrigation scheduling and optimization of resource-use efficiency (Amjad *et al.*, 2025). These advances position aeroponics as an adaptable and high-precision system for medicinal species, especially those where root-derived compounds are commercially valuable.

Tissue culture: mass propagation, regeneration, and genetic improvement

Plant tissue culture remains a cornerstone of medicinal plant biotechnology. It enables mass propagation of genetically uniform, disease-free planting material while serving as a critical tool for conserving endangered species. Established protocols for somatic embryogenesis and de novo organogenesis have improved substantially in efficiency (Long *et al.*, 2022). Moreover, recent advances in nanoparticle-assisted culture media are being explored to mitigate contamination risks and enhance micropropagation success (Gunasena, 2024). Tissue culture platforms also provide avenues for targeted metabolite enhancement through precursor feeding, elicitor treatments, and even CRISPR-based metabolic engineering, linking propagation with biotechnological improvement of phytochemical profiles (Nazari *et al.*, 2023).

Vertical farming: maximizing space and controlled environments

Vertical farming offers a promising solution for high-density, year-round production of medicinal plants, particularly in urban or resource-limited settings. By stacking cultivation layers under controlled environments, vertical systems optimize space use while maintaining consistency in phytochemical quality (Dsouza *et al.*, 2025). Pharmaceutical crops such as *Digitalis purpurea* (foxglove) are now being cultivated indoors, ensuring uniform levels of cardiac glycosides (Bafort and Jijakli, 2024).

The integration of IoT sensors and AI platforms in vertical farms enables real-time disease monitoring, climate control, and predictive yield modelling (Rathor, 2024). Nonetheless, challenges remain-particularly in terms of high capital and energy demands (Reynolds, 2022). Recent research into renewable energy integration and closed-loop water and nutrient recycling is helping to mitigate these limitations, making vertical farming a viable long-term strategy for medicinal plant production in climate-uncertain futures.

Enhancing yield and quality

Selection and breeding

Breeding programs are foundation in enhancing both yield and phytochemical quality in medicinal plants. Traditional approaches-such as mass selection, hybridization, mutation breeding, and polyploidization-have led to cultivars rich in valuable metabolites like artemisinin from *Artemisia annua* (Delabays *et al.*, 2001) or oil in lemongrass from *Cymbopogon* spp. (Dutta *et al.*, 2017). For instance, mutation breeding has generated high-alkaloid cultivars through induced variability (Kolakar *et al.*, 2018), while cultivar selection in milk thistle (*Silybum marianum*) has achieved improved bioactive content (Alemardan*et al.*, 2013) and optimized herb and oil yield in chrysanthemum (Gajbhiye *et al.*, 2025).

While these methods remain essential, modern breeding integrates molecular and genomic tools to accelerate trait improvement with precision. Genomics-assisted breeding (GAB) and omics-assisted breeding (OAB) now allow rapid identification of quantitative trait loci (QTLs) and candidate genes tied to secondary metabolite pathways and stress resilience (Tyagi *et al.*, 2024). Advanced technologies like long-read sequencing have already produced over 400 medicinal plant genomes by early 2025, enabling robust gene annotation and identification of loci involved in secondary metabolism (Cheng *et al.*, 2025). Pre-sowing seed treatments have also been reported to boost germination vigour and expand flavonoid diversity in butterfly pea accessions (Makasana *et al.*, 2016).

In addition, synthetic polyploidization-applying colchicine or other agents-has emerged as a powerful tool to enhance agronomic traits and metabolite production. For example, tetraploid chamomile strains now dominate globally, showing heightened chemical activity (Gupta, 2024). Yet, variability in metabolite profiles post-polyploidization suggests complex genomic effects that must be carefully managed.

The most recent and transformative advance is the application of CRISPR/Cas9 gene editing in medicinal plant improvement. This technology enables precise upregulation or knockout of key genes in secondary metabolism, directly improving bioactive compound synthesis. Reviews and case studies published in 2024–2025 document successful CRISPR applications targeting pathways in *Ocimum sanctum*, *Withania somnifera*, and *Artemisia annua*, including modifications to flowering regulators and metabolic genes that enhance metabolite yield and plant fitness (Gao *et al.*, 2025; Das *et al.*, 2024). Early outcomes show improved artemisinin levels and stress tolerance without compromising plant viability (Afridi *et al.*, 2025). Collectively, by combining classical selection with GAB/OAB, synthetic polyploidy, and genome editing, breeders can now pursue multi-trait improvement: high yield, enhanced metabolite profiles, and adaptability-closing the gap between cultivation and applied phytopharmaceutical production.

Environmental optimization for growth, manipulating light, temperature and CO_2

Verma *et al.* (2023) observed the plant growth characteristics, yield, oil composition, and dry herb production in different cultivars of *Ocimum sanctum.* Optimizing environmental parameters is critical to maximizing both biomass and bioactive compound accumulation in medicinal plants. Fine-tuning light spectra, temperature, and carbon dioxide (CO_2) levels enables targeted modulation of plant metabolism, resulting in higher yield and enhanced phytochemical quality(Saravanan *et al.* 2013; Shah *et al.*, 2010; Nair *et al.* 2024).

Light quality and photoreceptor pathways: Light spectral quality-particularly the balance of red, blue, and UV wavelengths-regulates secondary metabolism through photoreceptor signaling. Recent research highlights how specific wavelengths, via receptors like cryptochrome and phytochrome, activate transcription factors (e.g., HY5, MYBs) that govern phenolic and terpenoid biosynthesis (Wu, 2025). For instance, blue–red LED treatment has been shown to elevate monoterpene and sesquiterpene production in aromatic medicinal species, enhancing fragrance and therapeutic profiles (Trivelliniet *al.*, 2023). Spectral optimization under controlled-environment systems offers a precise, non-invasive strategy to enhance metabolite yield without growing cycle extension.

Light-driven metabolic regulation: LED applications have demonstrated remarkable efficacy in enhancing phytochemical content. A study of Bungala *et al.* (2024) showed that red + blue LED light significantly increases anthocyanins, phenolics, and glucosinolates in baby leaf pakchoi-indicating substantial antioxidant potential. Broadly, manipulating light quality within growth chambers or plant factories offers a robust tool to standardize metabolite profiles across production batches.

Elevated CO_2 effects and climate interactions: Increasing atmospheric CO_2 consistently boosts photosynthetic rate, plant height, and biomass across medicinal taxa (Jangkangi, 2025). However, the impact on secondary metabolites is species-specific and complex. For example, elevated CO_2 increased flavonoid levels in ragweed pollen (Bernauer *et al.*, 2024), whereas in *Hypericum perforatum*, elevated CO_2 reduced hypericin concentrations by over 20%, alongside faster phenological development (Hounsou, 2024). These results underline that CO_2 enrichment must be approached with caution: while yield may rise, critical phytochemical targets might decline if not carefully managed.

Integrated environment-controlled systems: Modern controlled-environment agriculture (CEA), including plant factories and growth chambers, is increasingly adopting AI- or sensor-based regulation for simultaneous adjustment of light spectrum, temperature, and CO_2. These systems aim to maintain steady-state metabolite profiles while adapting to dynamic plant responses. Such integration holds promise for stabilizing both yield and quality in medicinal plant production.

Nutrient management

Nutrient management remains a cornerstone of sustainable medicinal plant production, as both macro- and micronutrients directly influence growth, biomass accumulation, and secondary metabolite biosynthesis. Strategic combinations of organic, inorganic, and biofertilizer inputs not only improve plant health but also enhance soil fertility and microbial activity-factors critical for consistent yield and quality in medicinal crops.

Role of macronutrients (N, P, K): Nitrogen availability and its form (NH_4^+ vs. NO_3^-) are pivotal for alkaloid and phenolic accumulation. For instance, NO_3^--based fertilization in *Melissa officinalis* significantly increased rosmarinic acid content, whereas NH_4 favoured leaf biomass (Fallah *et al.*, 2024). Potassium supplementation improves oil quality and enhances terpenoid production, as shown in rose-scented geranium where higher K doses elevated essential oil yield and citronellol–geraniol balance (Mazeed *et al.*, 2022). Phosphorus availability is also linked to root development and higher secondary metabolite flux, especially in root-harvested medicinal species like ashwagandha and ginseng.

Integrated nutrient management (INM): Combining organic manures, biofertilizers, and inorganic fertilizers has proven more effective than any single approach. Integrated practices improve soil microbial populations, nutrient mineralization, and enzymatic activities that support metabolite biosynthesis. For example, applying farmyard manure alongside NPK fertilizer increased both biomass and withanolide content in *Withania somnifera* (Basak *et al.*, 2020). Similarly, INM with organic amendments and beneficial microbes improved herb yield and essential oil content in French basil (Anwar *et al.*, 2005). Proper application of NPK fertilizers has been shown to enhance herb and oil yields while improving soil fertility (Mandal *et al.*, 2008)

Biofertilizers and plant–microbe interactions: Beneficial microbes such as Arbuscular Mycorrhizal Fungi (AMF), *Azotobacter*, and *Trichoderma* not only enhance nutrient uptake but also upregulate secondary metabolite pathways. AMF colonization has been shown to boost essential oil yield in *Ocimum basilicum* while simultaneously enhancing phosphorus acquisition efficiency (Khalediyan *et al.*, 2021). Microbial inoculants also promote stress resilience, making medicinal crops more tolerant to drought or salinity stress while sustaining phytochemical quality. The optimum use of nutrients and biofertilizer enhances Pisum sativum growth and quality metrics (Yadav *et al.*, 2025).

Organic sources and soil health: Organic amendments such as vermicompost, compost tea, and green manures improve soil structure, water retention, and nutrient cycling, creating favorable conditions for medicinal plant cultivation. Vermicompost extract application enhanced antioxidant capacity and phenolic content in *Drimiopsis maculata* (Dube *et al.*, 2018). Long-term use of organic inputs also supports soil microbial diversity, which correlates with higher consistency in metabolite production.

Precision fertigation and resource efficiency: Recent innovations in fertigation, including micro-sprinkler and drip systems, have optimized nutrient-water delivery in controlled cultivation. A study demonstrated that alternating fertigation with organic fertilizer inputs enhanced both biomass and bioactive compound yield in greenhouse-grown medicinal herbs (Yue *et al.*, 2023). Precision fertigation systems integrated with IoT sensors now allow real-time monitoring of nutrient solution composition, thereby minimizing nutrient losses and improving sustainability (Ahmad*et al.*, 2022).

Plant growth regulators and biostimulants for yield enhancement

The application of plant growth regulators (PGRs) and bio-stimulants has demonstrated significant potential in improving both yield and quality traits of medicinal and aromatic plants. Their effectiveness lies in stimulating plant growth, modulating secondary metabolite pathways, and enhancing resilience to abiotic stresses, thereby supporting sustainable production systems.

Organic and soil-based biostimulants: Organic manures and compost-derived biostimulants are widely reported to enhance growth and biomass accumulation. For example, organic amendments improved root yield in *Withania somnifera* (ashwagandha) while also boosting phytochemical concentrations (Jat *et al.*, 2021). Seaweed-based formulations are also gaining traction: in organically grown sage, foliar seaweed extracts increased biomass and essential-oil output by up to 25 % (Farruggia *et al.*, 2024). Similarly, vermicompost leachate has been shown to improve growth performance, phytochemical content, and antioxidant potential in *Drimiopsis maculata* (Dube *et al.*, 2018). These soil-based inputs contribute to improved soil microbial activity, nutrient cycling, and long-term fertility.

Stress-responsive biostimulants: Under challenging environments, stress-modifying bio stimulants improve plant resilience and maintain productivity. For instance, foliar application of biostimulants enhanced vegetative growth, nutrient uptake, and antioxidant activity in garden thyme (*Thymus vulgaris*) under water stress (Rahimi *et al.*, 2022). Such inputs help mitigate oxidative damage, regulate osmolyte accumulation, and maintain higher photosynthetic activity during stress events.

Novel biostimulant sources: Recent advances highlight the role of chitin- and chitosan-based formulations, which stimulate plant regeneration, cell division, and secondary metabolite biosynthesis in medicinal herb cultures (Sun *et al.*, 2023). Similarly, microbial inoculants (e.g., *Trichoderma*, *Bacillus*, Arbuscular Mycorrhizal Fungi) and botanical extracts act as natural elicitors, promoting biomass accumulation and enhancing bioactive compound levels (Gins *et al.*, 2017; Kocira *et al.*, 2021). Multi-species microbial consortia combining AMF, PGPR, and yeast enhanced both growth and phenolic content in greenhouse medicinal crops have been reported (Pérez-Moncada *et al.*, 2024).

Broad-spectrum benefits: Biostimulants and PGRs are now recognized as sustainable inputs for improving yield and the chemical composition of aromatic and medicinal plants (Shahrajabian *et al.*, 2022). They have proven effective not only under optimal conditions but also under abiotic stress scenarios, enhancing quality consistency across growing environments (Tadele and Zerssa, 2023). Recent reviews showed that vegetal protein hydrolysates stimulate root architecture and essential-oil yield in rosemary and sage through amino-acid signaling and improved nitrogen assimilation (Sun *et al.*, 2024). By maintaining balanced growth, nutrient assimilation, and phytochemical synthesis, these stimulants play a crucial role in ensuring marketable quality and therapeutic efficacy (Majkowska-Gadomska *et al.*, 2022).

Sustainable cultivation practices

Organic farming

Organic cultivation is increasingly recognized as a cornerstone of sustainable medicinal plant production. By eliminating the use of synthetic fertilizers, pesticides, and growth regulators, organic systems emphasize soil health, biodiversity, and the production of residue-free raw materials—thereby aligning with environmental objectives and the growing consumer demand for clean-label botanicals. ***Ecosystem and soil benefits*:** Long-term organic management enhances soil organic carbon, microbial biomass and enzymatic activities, all of which are critical for nutrient mineralisation and stable secondary-metabolite production (Raei and Alami-Milani, 2014). A recent synthesis of 140 field trials showed organic manures to increase essential-oil yield and antioxidant capacity across diverse medicinal crops by up to 28 % compared with mineral fertilisers (Rostaei and Fallah, 2024).

Phytochemical enhancement: Multiple studies confirm that organically managed plants often accumulate higher concentrations of phenolics, flavonoids or terpenoids, probably because mild nutrient stress and richer soil microbiomes up-regulate defence-related pathways (Tariyal *et al.*, 2021). Comparative work on sage, mint and chamomile grown under organic *versus* conventional regimes reported 10–35 % greater essential-oil content and elevated antioxidant activity in the organic plots (Todorova *et al.*, 2022).

***Substrate and nutrient optimisation**:* Organic substrates (compost, vermicompost, green manures) improve water-holding capacity and cation-exchange properties, leading to higher biomass in container or greenhouse culture of medicinal herbs (Herrera *et al.*, 1997). Recent guidelines recommend tailored compost blends that match crop-specific macro-/micronutrient needs while supporting beneficial microbes (Marcelino *et al.*, 2023).

Market and certification drivers: The premium price of certified-organic botanicals and the growing interest of phytopharmaceutical companies in traceable, low-residue raw material continue to expand organic acreage worldwide (Trisilawati *et al.*, 2020). For urban and peri-urban growers, organic practices dovetail with short supply chains and traditional-medicine markets, reinforcing local food–medicine systems (Madaleno, 2012).

Integrated pest-and-disease management and use of bio control agents

Integrated pest-and-disease management offers a holistic, low-residue strategy for medicinal-plant production. Cultural measures such as crop rotation, intercropping, sanitation and tolerant cultivars-lower initial pest pressure and pathogen inoculum enhances alkaloids (Marimuthu *et al.*, 2018).

Microbial biocontrol: Targeted antagonists such as *Trichoderma* spp. (soil-borne fungi) and *Bacillus thuringiensis* or *Beauveria bassiana* (insect pests) now form the backbone of many IPDM programmes, providing season-long suppression without compromising phytochemical profiles (Lahlali *et al.*, 2022).

Botanical products*:* Azadirachtin-rich neem oil, karanjin and pyrethrin extracts broaden protection while respecting organic and export residue standards (Sayed *et al.*, 2020; Isman, 2020).

Decision support: Economic-threshold–based spraying, pheromone trapping and routine residue testing restrict synthetic pesticides to a last-resort role, minimising environmental load and safeguarding herb quality (Kavitha *et al.*, 2011; Jat *et al.*, 2021).

Emerging tools: RNA-interference biopesticides and endophyte-mediated immunity are poised to strengthen IPDM over the next decade, offering species-specific control with minimal non-target effects (Ahmad*et al.*, 2025).

Together, these components preserve ecosystem health and ensure residue-safe raw material for high-quality phytopharmaceuticals.

Conservation tillage and cover cropping

Conservation tillage, mulching and cover-cropping are increasingly adopted to improve soil health, suppress weeds and stabilise yields in medicinal-plant systems. Non-tillage strips planted with aromatic herbs such as thyme or rosemary have proved effective living mulches, reduced erosion while allowing inter-row production of companion medicinals (Durán-Zuazo and Pleguezuelo, 2008). In *Panax notoginseng*, reduced-tillage beds combined with straw mulch moderated soil temperature and curtailed root-rot incidence by shifting edaphic microbial communities (Guan *et al.*, 2011). Similarly, conservation tillage lowered weed pressure in rain-fed peppermint without compromising oil yield (Farahani *et al.*, 2009). That said, responses can be crop-specific: for *Solanum khasianum*, conventional tillage still delivered higher fruit yield than no-till, likely because the crop's early growth benefits from a finely-tilled seedbed (Sanwal *et al.*, 2016). Agroforestry models-e.g., eucalyptus interplanted with citronella-illustrate how reduced tillage under tree shade can sustain soil organic carbon and essential-oil output.

Cover crops provide complementary ecosystem services. Leguminous or grass covers boosted biomass of *Serjania marginata* (Tabaldi *et al.*, 2012) and acted as permanent ground covers in orchards/vineyards, where medicinal perennials supply both habitat and secondary income (Petzer, 2023). In Crocus sativus, aligning planting dates with winter cover-crop termination plus deficit irrigation increased stigma yield (Koocheki *et al.*, 2016).

Crop rotation and intercropping for sustainable systems

Crop rotation and intercropping remain cornerstone practices for ecological intensification of medicinal-plant production. Rotating medicinal or aromatic crops with cereals, pulses or oilseeds breaks pest and pathogen cycles, diversifies soil microbial communities and balances nutrient extraction, thereby sustaining long-term productivity and soil health (Pandey *et al.*, 2019). In resource-poor drylands, intercrops such as lemongrass–pigeon-pea or coleus–groundnut provide land-equivalent-ratios (LER > 1.2) and steady cash flow, offering risk insurance for farmers (Pushpa *et al.*, 2018).

Multi-storey and alley systems-e.g., shade-tolerant turmeric beneath neem or moringa rows-maximise vertical light capture and organic-matter return, while living mulches suppress weeds and conserve moisture (Smitha, 2010). Integrating medicinal species into broader rotations has also been shown to restore soil organic carbon and microbial diversity depleted by continuous monocropping; combined with organic amendments, it mitigates microbiome vulnerability (Misra *et al.*, 2019).

Intercrops of rosemary or basil within orchards/ vineyards generate complementary income and enhance habitat for pollinators, exemplifying how medicinal plants can fit into diversified agro-ecosystem design (Kanene, 2016). Recent extension bulletins further highlight that pairing short-duration aromatics with staple crops improves labour use-efficiency and spreads input costs across seasons (Misra *et al.*, 2019).

Future Directions and Challenges

Emerging technologies and innovations

Cutting-edge technologies are rapidly reshaping medicinal-plant production. Plant-cell and hairy-root cultures have moved from benchtop flasks to continuous stainless-steel bioreactors equipped with on-line sensors, making it feasible to supply cosmetics and pharmaceutical industries with consistent, contaminant-free actives (Georgiev *et al.*, 2018). Parallel advances in nano-biotechnology now deliver phytochemicals in nanoscale carriers that increase solubility and bioavailability, while nano-encapsulated elicitors are boosting secondary-metabolite titres in vitro (Bernela *et al.*, 2023). At the cultivation scale, tissue culture and micropropagation provide uniform planting material for vertical plant factories where light, temperature and CO_2 are governed by sensor networks linked to AI-driven "digital twins," allowing growers to model and optimise metabolite trajectories before implementing changes in real time (Tripathi, 2025). Untargeted metabolomics integrated with next-generation sequencing is accelerating chemovar authentication and lead-compound discovery (Zhang *et al.*, 2023), while green extraction platforms-super-critical CO_2, deep-eutectic solvents and Quality-by-Design protocols-minimise solvent use yet meet stringent GMP standards (Tegtmeier *et al.*, 2023). Collectively, these converging innovations promise higher efficiency, tighter quality control and a markedly smaller environmental footprint.

Yield improvement and crop uniformity

Raising productivity without sacrificing chemotype consistency remains a central breeding and agronomic goal. CRISPR/Cas edits targeting rate-limiting genes in terpene, alkaloid and withanolide pathways have already delivered demonstrable jumps in active-compound yield in *Artemisia* and *Withania* species (Bhojiya*et al.*, 2024). Genomics-assisted selection is likewise fast-tracking heat- and drought-tolerant chemotypes of *Ocimum* and *Mentha*, helping stabilise yields under climate volatility (Tyagi*et al.*, 2024). On the management side, UAV-based multispectral imaging and IoT-linked fertigation allow centimetre-scale correction of nutrient or water deficits, improving uniformity within commercial blocks and lifting dry-matter yield by double-digit percentages (Sasmal*et al.*, 2024). High-density vertical hydroponics and modular aeroponic towers exploit stacked space and uniform LED spectra to narrow chemotype variability while increasing land-equivalent output (Dsouza *et al.*, 2025). As datasets balloon, machine-learning models are becoming indispensable for integratinggenotype, environment and management variables into real-time recommendations that bolster both yield and compositional uniformity.

Environmental concerns and carbon footprint reduction

Sustainability credentials are now as important as pharmacological efficacy. Updated WHO-GACP modules emphasise life-cycle assessments that capture water use, energy demand and greenhouse-gas emissions along the value chain (WHO, 2003). Recent LCAs of essential-oil production pinpoint steam distillation as the dominant CO_2 hotspot, prompting interest in solar-assisted distillers and waste-heat recovery (Becerra *et al.*, 2022). Circular bio-economy solutions, which convert spent herb biomass into biofertilizer or biochar, are gaining traction and can reduce net emissions and synthetic-fertilizer dependence (Marcelino *et al.*, 2023). Biodiversity concerns also remain pressing, as many source species are listed as threatened; therefore, on-farm refugia and sustainable wild-collection protocols are indispensable complements to ex-situ cultivation (Schippmann *et al.*, 2002; Alamgir, 2017). Soil-carbon-conserving practices such as reduced tillage and living mulches in aromatic alleys further shrink the production carbon footprint while preserving soil structure (Durán-Zuazo and Pleguezuelo, 2008). Embedding these low-impact strategies within digital monitoring and certification frameworks will be key to meeting both market expectations and planetary boundaries.

CONCLUSION

Recent advances in medicinal-plant science now span the entire value chain from genomics-enabled breeding and controlled-environment cultivation to green extraction and quality-by-design manufacturing. High-throughput propagation systems, precision farming, and sensor-driven climate control have significantly raised biomass and phytochemical yields while lowering water, nutrient, and energy footprints. Parallel progress in plant-cell culture, hairy-root bioreactors, and nano-biotechnology offers reliable, on-demand production of rare or highly valued compounds, easing pressure on wild populations. Equally important, life-cycle assessment, circular-bioeconomy strategies, and updated WHO-

GACP guidelines are embedding sustainability metrics and traceability into commercial practice, building consumer confidence in residue-safe, standardised herbal remedies. Continued integration of 'omics' platforms, artificial-intelligence decision tools, and eco-certification schemes will further align productivity with environmental stewardship. Realising the full potential of these innovations demands coordinated efforts: breeders and biotechnologists to deliver resilient, high-yielding chemotypes; growers to adopt precision, low-impact production systems; industry to invest in green processing technologies; and policymakers to create clear, science-based regulatory pathways. With sustained collaboration, medicinal-plant agriculture can supply consistent, high-quality botanicals-supporting public health and rural livelihoods while conserving the biodiversity on which this ancient resource ultimately depends.

REFERENCES

Afridi, M.S.K., Farhan, U., Mushtaq, A., Ahmad, A., Rana, H., Naseer, S., Mushtaq, S. and Ahmad, M. 2025. CRISPR Applications in Enhancing Medicinal Plant Yields. *Scholars Academic Journal of Biosciences* **8**: 1061-66. https://doi.org/10.36347/sajb.2025.v13i08.002

Agrahari, S., Singh, N., Bharti, B. and Kumar, S. 2025. Medicinal plant ashwagandha in hydroponics: Pioneering greywater remediation using response surface methodology along with plants' physiological and phytochemical attributes for sustainable resource recovery. *Chemosphere* **376**: 144260. https://doi.org/10.1016/j.chemosphere.2025.144260

Ahmad, S., Jamil, M., Lodhi, A.F., Barati, Z., Kakar, M.U., Gao, Y. and Zhang, W. 2025. RNAi revolution in agriculture: unlocking mechanisms, overcoming delivery challenges, and advancing sustainable Pest control. *Pest Management Science*. https://doi.org/10.1002/ps.70040

Ahmad, U., Alvino, A. and Marino, S. 2022. Solar fertigation: A sustainable and smart IoT-based irrigation and fertilization system for efficient water and nutrient management. *Agronomy* **12**(5): 1012. https://doi.org/10.3390/agronomy12051012

Alamgir, A.N.M.2017. Cultivation of herbal drugs, biotechnology, and in vitro production of secondary metabolites, high-value medicinal plants, herbal wealth, and herbal trade. *Therapeutic Use of Medicinal Plants and Their Extracts: Volume 1: Pharmacognosy*, Springer International Publishing, 379-452. https://doi.org/10.1007/978-3-319-63862-1_9

Alemardan, A., Karkanis, A. and Salehi, R. 2013. Breeding objectives and selection criteria for milk thistle [*Silybum marianum* (L.) Gaertn.] improvement. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **41**(2): 340-47. https://doi.org/10.15835/nbha4129298

Ambali, R., Saravanan, R., Safiya, S. and Makasana, J. 2024. Effect of processing methods on cyanogenic compounds, protein, and minerals of cassava leaves. *Current Horticulture* **12**(3): 54-60. https://currenthorticulture.com/index.php/CURHOR/article/view/205

Amjad, M., Arulmozhi, E., Shin, Y.H., Kang, M.K. and Cho, W.J. 2025. A Review of IoT and Machine Learning for Environmental Optimization in Aeroponics. *Agronomy* **15**(7): 1627. https://doi.org/10.3390/agronomy15071627

Anwar, M., Patra, D.D., Chand, S., Alpesh, K., Naqvi, A.A. and Khanuja, S.P.S. 2005. Effect of organic manures and inorganic fertilizer on growth, herb and oil yield, nutrient accumulation, and oil quality of French basil. *Communications in soil science and plant analysis* **36**(13-14): 1737-46. https://doi.org/10.1081/CSS-200062434

Atherton, H.R. and Li, P. 2023. Hydroponic Cultivation of Medicinal Plants-Plant Organs and Hydroponic Systems: Techniques and Trends. *Horticulturae* **9**(3): 349. https://doi.org/10.3390/horticulturae9030349

Bafort, F. and Jijakli, M.H. 2024. Vertical farming of medicinal plants. *Digital Agriculture: A Solution for Sustainable Food and Nutritional Security*, 129-177. https://doi.org/10.1007/978-3-031-43548-5_5

Basak, B.B., Saha, A., Gajbhiye, N.A. and Manivel, P. 2020. Potential of organic nutrient sources for improving yield and bioactive principle of ashwagandha (*Withania somnifera*) through enhanced soil fertility and biological functions. *Communications in Soil Science and Plant Analysis* **51**(6): 779-93. https://doi.org/10.1080/00103624.2020.1729368

Becerra, J.A., González, J.M. and Villa, A.L. 2022. Comparison by life-cycle assessment of alternative processes for carvone and verbenone production. *Molecules* **27**(17): 5479. https://doi.org/10.3390/molecules27175479

Bernauer, O.M., Jain, A., de Bivort, B., Holbrook, N.M., Myers, S.S., Ziska, L.H. and Crall, J.D. 2024. Elevated atmospheric CO_2 has small, species-specific effects on pollen chemistry and plant growth across flowering plant species. *Scientific reports* **14**(1): 13760. https://doi.org/10.1038/s41598-024-63967-z

Bernela, M., Seth, M., Kaur, N., Sharma, S. and Pati, P.K. 2023. Harnessing the potential of nanobiotechnology in medicinal plants. *Industrial Crops and Products* **194**: 116266. https://doi.org/10.1016/j.indcrop.2023.116266

Beyene, B., Beyene, B. and Deribe, H. 2016. Review on application and management of medicinal plants for the livelihood of the local community. *Journal of Resources Development and Management* **22**(1): 33-39.

Bhojiya, A.A. and Joshi, H. 2024. Crispr gene editing for secondary metabolite production: a review. *Gene editing in plants: CRISPR-Cas and its applications*, 437-475. Springer, Singapore. https://doi.org/10.1007/978-981-99-8529-6_17

Bungala, L.T.D.C., Park, S.U., Nguyen, B.V., Lim, J., Kim, K., Kim, J.K., Park, C.H., Le, A.T., Chung, Y.S. and Yeo, H.J. 2024. Effect of LED Lights on Secondary Metabolites and

Antioxidant Activities in Red Pakchoi Baby Leaves. *ACS Omega* **9**(22): 23420-23430. https://doi.org/10.1021/acsomega.3c10261

Chen, S.L., Yu, H., Luo, H.M., Wu, Q., Li, C.F. and Steinmetz, A. 2016. Conservation and sustainable use of medicinal plants: problems, progress, and prospects. *Chinese medicine* **11***:* 1-10. https://doi.org/10.1186/s13020-016-0108-7

Cheng, L.T., Wang, Z.L., Zhu, Q.H., Ye, M. and Ye, C.Y. 2025. A long road ahead to reliable and complete medicinal plant genomes. *Nature Communications* **16**(1): 2150. https://doi.org/10.1038/s41467-025-57448-8

Das, S., Kwon, M. and Kim, J.Y. 2024. Enhancement of specialized metabolites using CRISPR/Cas gene editing technology in medicinal plants. *Frontiers in plant science* **15***:* 1279738. https://doi.org/10.3389/fpls.2024.1279738

Delabays, N., Simonnet, X. and Gaudin, M.D.A.D. 2001. The genetics of artemisinin content in Artemisia annua L. and the breeding of high yielding cultivars. *Current medicinal chemistry* **8**(15): 1795-1801. https://doi.org/10.2174/0929867013371635

Dsouza, A., Dixon, M., Shukla, M. and Graham, T. 2025. Harnessing controlled-environment systems for enhanced production of medicinal plants. *Journal of Experimental Botany* **76**(1): 76-93.https://doi.org/10.1093/jxb/erae248

Dube, L., Naidoo, K.K., Arthur, G.D., Aremu, A.O., Gruz, J., Šubrtová, M., Jarošová, M., Tarkowski, P. and Doležal, K. 2018. Regulation of growth, nutritive, phytochemical and antioxidant potential of cultivated Drimiopsis maculata in response to biostimulant (vermicompost leachate, VCL) application. *Plant Growth Regulation* **86**: 433-44. https://doi.org/10.1007/s10725-018-0441-1

Durán Zuazo, V.H., Pleguezuelo, C.R.R., Francia Martínez, J.R., Martínez Raya, A., Arroyo Panadero, L., Càrceles Rodríguez, B. and Navarro Moll, M.C. 2008. Benefits of plant strips for sustainable mountain agriculture. *Agronomy for Sustainable Development* **28**: 497-505. https://doi.org/10.1051/agro:2008020

Dutta, S., Munda, S., Chikkaputtaiah, C. and Lal, M. 2017. Assessment of Selection Criteria for Development of High Yielding Genoptypes Using Variability Parameters in Lemongrass *Cymbopogon flexuosus* L. *Journal of Essential Oil Bearing Plants* **20**(6): 1450-60. https://doi.org/10.1080/0972060X.2017.1421104

Fallah, S., Maggi, F., Ghanbari-Odivi, A. and Rostaei, M. 2024. Optimizing lemon balm (*Melissa officinalis* L.) cultivation: Effects of different manures on plant growth and essential oil production during consecutive harvests. *Horticulturae* **10**(10): 1105. https://doi.org/10.3390/horticulturae10101105

Farahani, H.A., Valadabadi, S.A., Daneshian, J., Shiranirad, A.H. and Khalvati, M.A. 2009. Medicinal and aromatic plants farming under drought conditions. *Journal of Horticulture and Forestry* **1**(6): 86-92.

Farruggia, D., Di Miceli, G., Licata, M., Leto, C., Salamone, F. and Novak, J. 2024. Foliar application of various biostimulants produces contrasting response on yield, essential oil and chemical properties of organically grown sage (*Salvia officinalis* L.). *Frontiers in Plant Science* **15***:* 1397489. https://doi.org/10.3389/fpls.2024.1397489

Gajbhiye,N.A., Saha, T.N., Kadam, G.B., Raju, S., Shabeer, T.P.A., Karne, S., Prasad, K.V., Kumar, S.P.J. 2025. Chemoprofiling of essential oils from *Chrysanthemum morifolium* Ramat. flowers: Delineation of genotypic variations for industrial applications. *Industrial Crops and Products***230**: 121137. https://doi.org/10.1016/j.indcrop.2025.121137

Gao, H., Pei, X., Song, X., Wang, S., Yang, Z., Zhu, J., Lin, Q., Zhu, Q. and Yang, X. 2025. Application and development of CRISPRtechnologyinthesecondarymetabolicpathwayof the active ingredients of phytopharmaceuticals. *Frontiers in Plant Science* **15**: 1477894. https://doi.org/10.3389/fpls.2024.1477894

Garzón, J., Montes, L., Garzón, J. and Lampropoulos, G. 2023. Systematic review of technology in aeroponics: Introducing the technology adoption and integration in sustainable agriculture model. *Agronomy* **13**(10): 2517. https://doi.org/10.3390/agronomy13102517

Georgiev, V., Slavov, A., Vasileva, I. and Pavlov, A. 2018. Plant cell culture as emerging technology for production of active cosmetic ingredients. *Engineering in life sciences* **18**(11): 779-98. https://doi.org/10.1002/elsc.201800066

Gins, M.S., Gins, V.K., Baikov, A.A., Kononkov, P.F., Pivovarov, V.F., Sidelnikov, N.I., Rabinovich, A.M., Zagumennikova, T.N., Kotsubinskiy, A.V., Zlotnikov, A.K. and Goncharova, O.I. 2017. Antioxidant content and growth at the initial ontogenesis stages of *Passiflora incarnata* plants under the influence of biostimulant Albit. *Russian agricultural sciences* **43***:* 384-389. https://doi.org/10.3103/S1068367417050068

Guan, H., Zhang, Y., Chen, Y., Yang, J. and Sun, S. 2011. On the connections between sanchi root rot and edaphon dynamics in no-tillage sanchi-planted soil. In *2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring* (pp. 1598-1602). IEEE. https://doi.org/10.1109/CDCIEM.2011.447

Gunasena, M.D.K.M., Alahakoon, A.M.P.D., Polwaththa, K.P.G.D.M., Galpaya, G.D.C.P., Priyanjani, H.A.S.A., Koswattage, K.R. and Senarath, W.T.P.S.K. 2024. Transforming plant tissue culture with nanoparticles: a review of current applications. *Plant Nano Biology***10**: 100102. https://doi.org/10.1016/j.plana.2024.100102

Gupta, N., Bhattacharya, S., Dutta, A., Cusimamani, E.F., Milella, L. and Leuner, O. 2024. *In vitro* synthetic polyploidization in medicinal and aromatic plants for enhanced phytochemical efficacy-a mini-review. *Agronomy* **14**(8): 1830. https://hdl.handle.net/11563/186938

Hamilton, A.C. 2004. Medicinal plants, conservation and livelihoods. *Biodiversity & Conservation* **13**: 1477-1517. https://doi.org/10.1023/B:BIOC.0000021333.23413.42

Hasmi, K.K., Saravanan, R., Makasana, J., Thulasimani, K. and Safia, S. 2025. Comparative Study of Extraction Methods and Screening of Cassava Genotypes for High Stem Starch Yield: A Potential Industrial Source. *Starch-Stärke* **77**(3): e202400158. https://doi.org/10.1002/star.202400158

Herrera, E., Tremblay, N., Desroches, B. and Gosselin, A. 1997. Optimization of substrate and nutrient solution for organic cultivation of medicinal transplants in multicell flats. *Journal of herbs, spices & medicinal plants* **4**(4): 69-82. https://doi.org/10.1300/J044v04n04_08

Hounsou, E.K., Sonibare, M.A. and Elufioye, T.O. 2024. Climate change and the future of medicinal plants research. *Bioactive Compounds in Health and Disease-Online ISSN: 2574-0334,* **7**(3): 152-69. https://doi.org/10.31989/bchd.v7i3.1310

Isman, M.B. 2020. Botanical insecticides in the twenty-first century-fulfilling their promise?. *Annual Review of Entomology* **65**(1): 233-249. https://doi.org/10.1146/annurev-ento-011019-025010

Jat, R.S., Basak, B.B. and Gajbhiye, N.A. 2021. Organic manures and biostimulants fostered soil health and increased the harvest quality of the medicinal herb ashwagandha. *Agronomy Journal* **113**(1): 504-14. https://doi.org/10.1002/agj2.20457

Ji, P., Yang, X. and Zhao, X. 2024. Application of metabolomics in quality control of traditional Chinese medicines: A review. *Frontiers in Plant Science* **15**: 1463666. https://doi.org/10.3389/fpls.2024.1463666

Kanene, K.M. 2016. Indigenous practices of environmental sustainability in the Tonga community of southern Zambia. *Jàmbá: Journal of Disaster Risk Studies* **8**(1). https://doi.org/10.4102/jamba.v8i1.331

Kavitha, H.U. and Satish, S. 2011. Eco-friendly management of plant pathogens by some medicinal plant extracts. *Journal of Agricultural Technology* **7**(2): 449-61. http://www.ijat-aatsea.com/pdf/April_v7_n2_11/23%20IJAT2010_59FJ.pdf

Khalediyan, N., Weisany, W. and Schenk, P.M. 2021. Arbuscular mycorrhizae and rhizobacteria improve growth, nutritional status and essential oil production in *Ocimum basilicum* and *Satureja hortensis*. *Industrial Crops and Products* **160**: 113163. https://doi.org/10.1016/j.indcrop.2020.113163

Kocira, S., Szparaga, A., Krawczuk, A., Bartoš, P., Zaguła, G., Plawgo, M. and Černý, P. 2021. Plant material as a novel tool in designing and formulating modern biostimulants-Analysis of botanical extract from *Linum usitatissimum* L. *Materials* **14**(21): 6661. https://doi.org/10.3390/ma14216661

Kolakar, S.S., Nadukeri, S., Jakkeral, S.A., Lakshmana, D., Hanumanthappa, M. and Gangaprasad, S. 2018. Role of mutation breeding in improvement of medicinal and aromatic crops. *Journal of Pharmacognosy and Phytochemistry* **7**(3S): 425-29.

Koocheki, A., Rezvani Moghaddam, P. and Fallahi, H.R. 2016. Effects of planting dates, irrigation management and cover crops on growth and yield of saffron (*Crocussativus* L.). *Journal of Agroecology* **8**(3): 435-51. https://doi.org/10.22067/jag.v8i3.51323

Kumar, V., Zadokar, A., Kumar, P., Sharma, R., Siddiqui, M. W., Irfan, M. and Chandora, R. 2025. Advancing medicinal plant agriculture: Integrating technology and precision agriculture for sustainability. *PeerJ* **13**: e19058. https://doi.org/10.7717/peerj.19058

Lahlali, R., Ezrari, S., Radouane, N., Kenfaoui, J., Esmaeel, Q., El Hamss, H., Belabess, Z. and Barka, E.A. 2022. Biological control of plant pathogens: A global perspective. *Microorganisms* **10**(3): 596. https://doi.org/10.3390/microorganisms10030596

Long, Y., Yang, Y., Pan, G. and Shen, Y. 2022. New insights into tissue culture plant-regeneration mechanisms. *Frontiers in plant science* **13**: 926752. https://doi.org/10.3389/fpls.2022.926752

Madaleno, I.M. 2012. Organic cultivation and use of medicinal plants in Latin America. *Pharmacognosy Communications* **2**(4): 34-51.

Majkowska-Gadomska, J., Jadwisieńczak, K., Francke, A. and Kaliniewicz, Z. 2022. Effect of Biostimulants on the Yield and Quality of Selected Herbs. *Applied Sciences*, **12**(3): 1500. https://doi.org/10.3390/app12031500

Makasana, J., Pillai, V., Sharma, A., Dholakiya, B. Z., Gajbhiye, N. A. and Saravanan, R. 2016. Effect of seed treatment on germination and flavonoids diversity in accessions of butterfly pea (*Clitoria ternatea*). *Indian Journal of Agricultural Sciences* **86**(12): 1553-58. https://doi.org/10.56093/ijas.v86i12.65397

Mandal, K., Saravanan, R., Maiti, S. 2008. Effect of different levels of N, P and K on downy mildew (*Peronospora plantaginis*) and seed yield of isabgol (*Plantago ovata*). Crop protection **27**(6): 988-95. https://doi.org/10.1016/j.cropro.2007.12.002

Mansoor, S., Iqbal, S., Popescu, S.M., Kim, S.L., Chung, Y.S. and Baek, J.H. 2025. Integration of smart sensors and IoT in precision agriculture. *Frontiers in Plant Science* **16**: 1587869. https://doi.org/10.3389/fpls.2025.1587869

Marcelino, S., Hamdane, S., Gaspar, P.D. and Paço, A. 2023. Sustainable agricultural practices for the production of medicinal and aromatic plants: evidence and recommendations. *Sustainability* **15**(19): 14095. https://doi.org/10.3390/su151914095

Marimuthu, T., Suganthy, M. and Nakkeeran, S. 2018. Common pests and diseases of medicinal plants and strategies to manage them. *New Age Herbals: Resource, Quality and Pharmacognosy*, 289-312. https://doi.org/10.1007/978-981-10-8291-7_14

Mazeed, A., Maurya, P., Kumar, D., Yadav, S.S. and Suryavanshi, P. 2022. Efficient nutrient management for rose scented geranium (*Pelargonium graveolens* L' Herit ex Ait). *Journal of Applied Research on Medicinal and Aromatic Plants* **31**: 100409.https://doi.org/10.1016/j.jarmap.2022.100409

Misra, P., Maji, D., Awasthi, A., Pandey, S.S., Yadav, A., Pandey, A., Saikia, D., Babu, C.V. and Kalra, A. 2019. Vulnerability of soil microbiome to monocropping of medicinal and aromatic plants and its restoration through intercropping and organic amendments. *Frontiers in Microbiology* **10**: 2604. https://doi.org/10.3389/fmicb.2019.02604

Mykhailenko, O., Heinrich, M., Howes, M.-J.R., Salmerón-Manzano, E., Mollaei, S., Jamwal, R. and Batiha, G.E. 2024. Climate change and the sustainable use of medicinal plants: A call for "new" research strategies. *Frontiers in Pharmacology* **15**: 1496792. https://doi.org/10.3389/fphar.2024.1496792

Nair, R., Raju S., More S.J., Puthur J.T., Makasana J., Ravi V. 2024. Evaluating non-photochemical quenching (NPQ) kinetics and photosynthetic efficiency in cassava (*Manihot esculenta*) subjected to variable high light conditions. *Functional Plant Biology* **51**(10). https://doi.org/10.1071/FP24118

Nazari, M., Kordrostami, M. and Ghasemi-Soloklui, A.A. 2023. Conservation of medicinal plants by tissue culture techniques. In *Medicinal plants: Biodiversity, biotechnology and conservation* (pp. 801-8). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9936-9_27

Pandey, M., Nautiyal, B.P. and Kumar, N. 2019. Sustainability improvement of traditional cropping system in Uttarakhand, India, through intercropping with medicinal and aromatic plants. *Current Science* **117**(8), 1281-85. https://www.jstor.org/stable/27138442

Pérez-Moncada, U.A., Cruz-Sánchez, P., Hernández-Cruz, M.A. and García-Jiménez, J. 2024. *Design of microbial consortia based on arbuscular mycorrhizal fungi, PGPR and yeasts to improve medicinal-plant performance under greenhouse conditions. Plants* **13**(11): 1556. https://doi.org/10.3390/plants13111556

Petzer, H., Stone, W., & Lotze, E. 2023. Investigating the Potential of Medicinal Perennial Species as Permanent Cover Crops in Deciduous Orchards and Vineyards. https://agris.fao.org/search/en/providers/124740/records/67053f9eb1dfe472e14689e8

Pushpa, T.N., Umesha, K., Srikantaprasad, D., Chandregowda, M. and AP, M.G. 2018. Can medicinal plants provide sustainable economic security to dry land farmers? *Journal of Pharmacognosy and Phytochemistry* **7**(3S): 333-37.

Raei, Y. and Alami-Milani, M. 2014. Organic cultivation of medicinal plants: a review. *Journal of Biodiversity and Environmental Sciences* **4**: 6-18.

Rahimi, A., Mohammadi, M.M., Siavash Moghaddam, S., Heydarzadeh, S. and Gitari, H. 2022. Effects of stress modifier biostimulants on vegetative growth, nutrients, and antioxidants contents of garden thyme (*Thymus vulgaris* L.) under water deficit conditions. *Journal of Plant Growth Regulation* **41**(5): 2059-72. https://doi.org/10.1007/s00344-022-10604-6

Rathor, A.S., Choudhury, S., Sharma, A., Nautiyal, P. and Shah, G. 2024. Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review. *Heliyon* **10**(15). https://doi.org/10.1016/j.heliyon.2024.e34998

Reynolds, M. 2022. Vertical farming has found its fatal flaw. *Wired https://go. nature. com/3TJkcYT*.

Roopashree, S., Anitha, J., Challa, S., Mahesh, T.R., Venkatesan, V.K. and Guluwadi, S. 2024. Mapping of soil suitability for medicinal plants using machine learning methods. *Scientific Reports* **14**: 3741. https://doi.org/10.1038/s41598-024-54465-3

Rostaei, M., Fallah, S., Carrubba, A. and Lorigooini, Z. 2024. Organic manures enhance biomass and improve content, chemical compounds of essential oil and antioxidant capacity of medicinal plants: A review. *Heliyon* **10**(17). https://doi.org/10.1016/j.heliyon.2024.e36693

Sadeghfam, S., Rahmani, M.S., Moazamnia, M. and Morshedloo, M.R. 2024. Mapping climate suitability index for rainfed cultivation of medicinal plants by developing an AI-based probabilistic framework. *Scientific Reports* **14**: 20413. https://doi.org/10.1038/s41598-024-71208-6

Safaei, F., Alirezalu, A., Noruzi, P. and Alirezalu, K. 2024. Phytochemical and morpho-physiological response of Melissa officinalis L. to different NH^{4+} to NO^{3-} ratios under hydroponic cultivation. *BMC Plant Biology* **24**(1): 968. https://doi.org/10.1186/s12870-024-05693-2

Sanwal, C.S., Kumar, R., Anwar, R., Kakade, V., Kerketta, S. and Bhardwaj, S.D. 2016. Growth and yield of Solanum khasianum in Pinus roxburghii forest based silvi-medicinal system in mid hills of Indian Himalaya. *Forest Ecosystems* **3**(1): 1-9. https://doi.org/10.1186/s40663-016-0078-3

Saravanan, R. and Das, M. 2024. Medicinal plants industry in India: Challenges, opportunities and sustainability. *Medicinal Plants - International Journal of Phytomedicines and Related Industries*, **16**(1), 1-14.

Saravanan, R., Shah, S., Gajbhiye, N. 2013. Effect of light intensity on photosynthesis and accumulation of sennosides in plant parts of senna (*Cassia angustifolia* Vahl.). *Indian Journal of Plant Physiology* **18**(3): 285-89. https://doi.org/10.1007/s40502-013-0038-7

Sasmal, B., Das, G., Mallick, P., Dey, S., Ghorai, S., Jana, S. and Jana, C. 2024. Advancements and challenges in agriculture: a comprehensive review of machine learning and IoT applications in vertical farming and controlled environment agriculture. *Big Data and Computing Visions* **4**(2): 67-94. https://doi.org/10.22105/bdcv.2024.474315.1183

Sayed, S.M., Alotaibi, S.S., Gaber, N. and Elarrnaouty, S.A. 2020. Evaluation of five medicinal plant extracts on Aphis craccivora (Hemiptera: Aphididae) and its predator, Chrysoperla Carnea (Neuroptera: Chrysopidae) under laboratory conditions. *Insects* **11**(6): 398. https://doi.org/10.3390/insects11060398

Schippmann, U., Leaman, D.J. and Cunningham, A.B. 2002. Impact of cultivation and gathering of medicinal plants on biodiversity: global trends and issues. *Biodiversity and the ecosystem approach in agriculture, forestry and fisheries*.

Shah, S., Saravanan, R., Gajbhiye, N.A. 2010. Phytochemical and physiological changes in Ashwagandha (*Withania* *somnifera* Dunal) under soil moisture stress. *Brazilian Journal of Plant Physiology***22**: 255-61. https://doi.org/10.1590/S1677-04202010000400005

Shahrajabian, M.H. and Sun, W. 2022. Sustainable approaches to boost yield and chemical constituents of aromatic and medicinal plants by application of biostimulants. *Recent Advances in Food Nutrition & Agriculture* **13**(2): 72-92. https://doi.org/10.2174/2772574X13666221004151822

Smitha, G.R., Gowda, M.C., Sreeramu, B.S., Umesha, K. and Gowda, A.P. 2010. Influence of integrated nutrient management on growth, yield and quality of makoi. *Indian Journal of Horticulture* **67**(4): 395-398.

Sun, W., Di Tommaso, D., Rouphael, Y. and Colla, G. 2024. Amino-acid and protein-hydrolysate biostimulants: modes of action and applications in horticultural and medicinal crops. *Plants***13**(2): 210. https://doi.org/10.3390/plants13020210

Sun, W., Shahrajabian, M.H., Petropoulos, S.A. and Shahrajabian, N. 2023. Developing Sustainable Agriculture Systems in Medicinal and Aromatic Plant Production by Using Chitosan and Chitin-Based Biostimulants. *Plants* **12**(13): 2469. https://doi.org/10.3390/plants12132469

Tabaldi, L.A., Vieira, M.D.C., Zárate, N.A.H., Silva, L.R.D., Gonçalves, W.L.F., Pilecco, M., Formagio, A.S.N., Gassi, R.P. and Padovan, M.P. 2012. Cover crops and their effects on the biomass yield of Serjania marginata plants. *Ciência Rural* **42**: 614-20. https://doi.org/10.1590/S0103-84782012000400006

Tadele, K.T. and Zerssa, G.W. 2023. Biostimulants and Phytohormones Improve Productivity and Quality of Medicinal Plants Under Abiotic Stress. In *Medicinal Plants: Their Response to Abiotic Stress* (pp. 335-362). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5611-9_13

Tariyal, Y.S., Ansari, S. and Prasad, P. 2021. Organic Cultivation of Medicinal and Aromatic Plants: a Review. *Journal of Stress Physiology & Biochemistry* **17**(1): 129-33.

Tegtmeier, M., Knierim, L., Schmidt, A. and Strube, J. 2023. Green Manufacturing for Herbal Remedies with Advanced Pharmaceutical Technology. *Pharmaceutics* **15**(1): 188. https://doi.org/10.3390/pharmaceutics15010188

Todorova, M., Dobreva, A., Petkova, N., Grozeva, N., Gerdzhikova, M. and Veleva, P. 2022. Organic vs conventional farming of oil-bearing rose: Effect on essential oil and antioxidant activity. *BioRisk* **17**: 271-85. https://doi.org/10.3897/biorisk.17.77488

Tripathi, R.K.P. 2025. Smart Farming with "Blockchain": Revolutionizing Medicinal Plant Cultivation. In *Blockchain and Digital Twin Applications in Smart Agriculture* (pp. 251-274). Auerbach Publications.

Trisilawati, O., Rizal, M. and Pribadi, E. 2020. Organic cultivation of medicinal crops in the efforts to support the sustainable availability of Jamu raw materials. In *IOP Conference Series: Earth and Environmental Science* (Vol. 418, No. 1, p. 012077). IOP Publishing. https://doi.org/10.1088/1755-1315/418/1/012077

Trivellini, A., Toscano, S., Romano, D. and Ferrante, A. 2023. The role of blue and red light in the orchestration of secondary metabolites, nutrient transport and plant quality. *Plants* **12**(10): 2026. https://doi.org/10.3390/plants12102026

Tyagi, A., Mir, Z.A., Almalki, M.A., Deshmukh, R. and Ali, S. 2024. Genomics-assisted breeding: a powerful breeding approach for improving plant growth and stress resilience. *Agronomy* **14**(6): 1128. https://doi.org/10.3390/agronomy14061128

Verma, P.P., Agri, B., Kumar, D., Kumar, A. and Padalia, R.C. 2023. Fhenological development and production potential of different cultivars of holy basil (*Ocimum sanctum*) in lower hills of Uttarakhand. *Current Horticulture***11**(3). https://doi.org/10.48165/chr.2023.11.3.6

Wang, H., Zhou, Z., Liu, M., Liu, S., Dong, C. and Yang, Y. 2023. Advancing herbal medicine: Enhancing product quality and safety through robust quality control practices. *Frontiers in Pharmacology* **14**: 1267302. https://doi.org/10.3389/fphar.2023.1267302

Wang, Z., Wang, L., Xiao, F., Chen, Q., Lu, L. and Hong, J. 2021. A traditional Chinese medicine traceability system based on lightweight blockchain. *Journal of Medical Internet Research***23**(6): e25946. https://doi.org/10.2196/25946

World Health Organization. 2003. *WHO guidelines on good agricultural and collection practices (GACP) for medicinal plants*. World Health Organization.

Wu, W., Wu, H., Liang, R., Huang, S., Meng, L., Zhang, M., Xie, F. and Zhu, H. 2025. Light regulates the synthesis and accumulation of plant secondary metabolites. *Frontiers in Plant Science* **16**: 1644472. https://doi.org/10.3389/fpls.2025.1644472

Yadav, M., Meena, R.S., Pathan, A.R.K. and Garhwal, O.P. 2025. Effect of phosphorus, biofertilizers and zinc application on growth and quality-attributing characteristics of garden pea (*Pisum sativum*). *Current Horticulture***13**(1): 67-71. https://doi.org/10.5958/2455-7560.2025.00012.2

Yao, R., Heinrich, M., Zou, Y., Reich, E., Zhang, X., Chen, Y. and Weckerle, C.S. 2018. Quality variation of Goji (fruits of Lycium spp.) in China: a comparative morphological and metabolomic analysis. *Frontiers in Pharmacology* **9**: 151. https://doi.org/10.3389/fphar.2018.00151

Yue, X., Yang, Q., Liang, J., Tang, J. and Yang, Y. 2023. Alternate micro-sprinkler irrigation synergized with organic fertilizer: A sustainable water-fertilizer management technology of improving quality and increasing efficiency in Panax notoginseng production. *Industrial Crops and Products* **194**: 116335. https://doi.org/10.1016/j.indcrop.2023.116335

Zhang, W., Zeng, Y., Jiao, M., Ye, C., Li, Y., Liu, C. and Wang, J. 2023. Integration of high-throughput omics technologies in medicinal plant research: The new era of natural drug discovery. *Frontiers in Plant Science* **14**: 1073848. https://doi.org/10.3389/fpls.2023.1073848

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Status and strategic approaches of date palm (*Phoenix dactylifera*) production in India— a review

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Abstract

Date palm (*Phoenix dactylifera* L.) is emerging as an important fruit crop in the arid and semi-arid regions of India, particularly in Gujarat, Rajasthan, and to a lesser extent in Maharashtra and Tamil Nadu. Its cultivation offers considerable potential for agricultural diversification, driven by the adoption of tissue culture technology and introduction of high-yielding varieties. Prominent varieties include Barhee, Khunezi, Khalas, and Halawy for fresh fruit consumption; Zahidi, Shamran, Khadrawy, and Nagal for soft fruit purposes; and Medjool, which is primarily cultivated for dry dates (*Chuhhara*). Despite these advancements, India continues to depend heavily on imports to meet rising domestic demand, emphasizing the need to expand cultivation in other suitable agro climatic regions. Research progress in varietal improvement, disease management, and post-harvest processing has provided a strong foundation for sustainable growth. However, challenges such as limited technical expertise, inadequate irrigation, and somaclonal variation in tissue-cultured plants remain significant bottlenecks. Future strategies should focus on expanding cultivation in potential regions, strengthening post-harvest infrastructure, and enhancing both domestic and export markets. Through strategic innovation, farmer training, and supportive policy incentives, India can reduce import dependency, achieve self-sufficiency in date production, and establish itself as a competitive player in the global date market.

Key words: Date palm, Varieties, Tissue culture, Offshoot, Irrigation, Climate, Challenges

Date palm (*Phoenix dactylifera* L.; Family: Arecaceae), also known as khajoor or kharek, is an ancient fruit tree native to semi-arid and arid regions of the world. It thrives in poor, desert soils due to its hardy nature having deep root system. This fruit tree is particularly suited for cultivation under saline water irrigation. The date palm prefers its "feet" in water and its "head" in fire/sun, as it requires a dry, hot climate for proper growth and development of fruits. Its successful cultivation is possible in areas with adequate irrigation facilities and dry, hot climatic conditions.

Its fruit is highly nutritious and favoured worldwide. Varieties such as Halawy, Khalas, Khuneizi, Chipchap, Braim, Barhee, and Anand DP-1 are consumed fresh (doka stage) due to their sweet taste and flavour. Besides fresh consumption, several value-added products such as dry dates, pind, beverages, jams, paste, chutney, pickles, vegetables, and biscuits are made from dates. Fresh dates are often used in processed products, and date mouth fresheners are another product with diverse uses (Rathore, 2012). Fresh date fruit can be used to make ready-to-serve (RTS) drinks, although, temperature plays a role in its storage (Godara and Pareek, 1985). The RTS drinks or juices cannot be stored for long due to rapid fermentation. Medjool cultivar is highly suitable for making dry dates (*Chhuhara*) because of its late maturity, high yield, and large berry size, which contribute to a high recovery percentage (Rakesh *et al.*, 2023). Fruit yield varies among cultivars depending on location, tree age, and cultural practices employed (Chandra *et al.*, 1992; Singh *et al.*, 2006). Dates can supplement the dietary needs of desert communities where nutritious food options are scarce. Both dry dates (*Chhuhara)* and soft dates (*Pind Khajoor*) are in high demand and have significant market potential (Meena *et. al.,* 2025). Due to the presence of tannins, many date varieties are astringent at the green doka stage. However, some varieties, such as 'Halawy' and 'Barhee,' are not astringent even when light green or yellow and are palatable at the fresh doka stage (Singh, 2018). After a lengthy evaluation of date palm varieties under the hot, arid conditions of Bikaner, the following varieties are recommended for cultivation (Table 1) in Rajasthan.

Studies are ongoing to assess the germplasm value of seedling date palm and to establish tissue culture protocols for propagating improved varieties and ensuring the availability of quality planting material. Since India is the world's largest importer of dates, local production has significant potential to supply domestic markets and create job opportunities in the horticulture sector. The constraints faced by date growers in its cultivation, post-harvest management, and marketing have also been discussed.

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Origin and distribution

The exact geographic origin of the date palm has not

Table1: Suitable varieties of date palm and uses

Variety	Maturity period	Uses
Halawy, Khuneizi, Nagal, Muscat, Anand DP-1,	Early (Mid of June to Ist week of July)	Fresh eaten ,processed products,
Khalas, Zahidi, Shamran, Khadrawy, Braim, Chip-chap, Sayer,	Mid-season (July)	Fresh, eaten, processed products, pickle,
Barhee, Medjool, Sewi, Dayari,	Late (Last week of July to first week of August)	Fresh eaten, processed products dry dates beverages,bakery products, jam, chutney, fruit drinks,

yet been definitively established. It has been cultivated since at least 4,000 BC in Mesopotamia, but there are various theories about its origins. This discussion will examine these theories with a specific focus on India, considering observations that have not been adequately addressed. Sanskrit literature highlights the widespread presence of *P. sylvestris* in the Indian subcontinent and the absence of *P. dactylifera*.

Zaid and de Wet (2002) suggested that the date palm (*Phoenix dactylifera*) may have evolved from *P. reclinata* of tropical Africa, *P. sylvestris* of India, or as a hybrid between the two. Globally, twelve *Phoenix* species have been identified. Sanderson (2001) notes that the date palm appears in ancient records across a broad area from the Indus Valley (now Pakistan) to Mesopotamia (now Iraq), the Nile Valley, Southern Persia, the Eastern Mediterranean, and the Horn of Africa. He suggests that this wide distribution implies the palm originated in a more restricted area and was later spread by human activity to regions with favourable geographic, soil, and climatic conditions. Sanderson (2001) supports the theory that the date palm originated in the Indus Valley, where *P. dactylifera* may have existed as a natural hybrid with *P. sylvestris* from at least the 6th millennium BC. Barreveld (1993) reports that the earliest evidence of date palms has been found in Ancient Egypt, where cultivation seems to have coincided with the rise of the oldest civilization in Northeast Africa.

Jaikrishna Thakar served as a curator of forests and gardens in Porbandar State (now Gujarat) from 1886 to 1904. During his tenure, he studied the flora of the Baroda Hills and authored a comprehensive flora on the subject. In his work, he includes only *P. sylvestris*, describing it as a tree mostly without offshoots, with flower clusters measuring 2.54-3.76 cm and fruits that are yellow or orange. Thakar (1926) noted the cultivation of Egyptian date palms and mentioned that in the Kutch-Bhuj and Abadasa regions, date palms known as *kharakadi* or *khalela* (*P. sylvestris*) produced very sweet and tasty yellow and red fruits. In his 1926 book, Thakar states that *P. sylvestris* grows wild and is cultivated in Kutch-Bhuj, while *P. dactylifera* (referred to as *khajuriarabi*) was observed in the Bhuj King's Sarad garden. Fruits from *P. sylvestris* in the Bhuj and Abadasa regions were popular. Old date palm seedlings exist in the coastal belt of the Kachchh region (Pareek and Sodagar, 1985; Muralidharan *et al.*, 2008).

The introduction of Arabian date palms into India likely began with the first Mohammedan invasion of Sind (in undivided India) in the early eighth century when dates were believed to have been brought to Western India for cultivation (Blatter, 1926). The presence of *P. dactylifera* in the Indus Valley is attributed to either Alexander the Great's army (4th century BC), Arab conquerors (7th century), or pilgrims from Mecca (Newton *et al.*, 2013). Hooker (1894), in the *Flora of British India*, mentions *P. sylvestris* as wild and grown throughout the plains of India, Burma, and the Indus Basin, while *P. dactylifera* was introduced into Sindh and Northwest India. Cooke (1908), in the *Flora of Bombay Presidency*, mentions only *P. sylvestris*.

Wild *khajoor* trees are found naturally in the Aravali Hills in Udaipur and Mount Abu. The local *desi khajoor* tree is found throughout the country but produces inferior quality fruit with a large stone and less pulp. From its crown, a liquid called "neera" or *taddi* is extracted, used as a fresh drink and for making jaggery. It is also found in the Bundelkhand region and is a suitable component for agroforestry systems (Tewari *et al.*, 2001). Variations in seedling growth and development in *Phoenix* species under nursery conditions were recorded by Singh and Bhargava (2009). In addition to *Phoenix dactylifera*, another fruiting species at HAU farm, which produces small fruits (2-3g) with very small stones, may be *P. reclinata*. A small, bushy type of *Phoenix* species found in the coastal belt of Odisha, with large seed kernels and low pulp content, may be *P. canariensis*. Basu and Chakraverty (1994) reported that *P. dactylifera* was cultivated in the Indian Botanical Garden, Calcutta, in the early nineteenth century.

Newton *et al.* (2013) explored the complex relationship between *P. dactylifera* and *P. sylvestris* in India. They observed that *P. dactylifera* is characterized by an erect trunk, large stones, less pulp, but a sweet taste. Their travels in Kutch, Saurashtra (Kathiawad), and the Aravalli Hills revealed that *P. dactylifera* was exclusively cultivated in Kutch and not observed in the wild, whereas *P. sylvestris* was found both wild and cultivated in the Kathiawar

Region. Gros-Balthazard (2013), through phylogenetic analysis of *Phoenix* based on chloroplast sequences and genetic diversity, identified closely related populations of wild date palms for the first time.

The study of hybridization in *Phoenix* highlighted difficulties in identifying species within the genus. Experimental data suggested that *P. sylvestris* is not the progenitor of *P. dactylifera*. All commercial date cultivars have been developed through the selection of chance seedlings based on local needs. Many varieties have been introduced from date-growing countries to India, with over 1,000 varieties available globally. *Medjool* is recognized as the top variety in the world. In Pakistan, which ranks 6th in production, cultivars such as *Begam Jangi*, *Dhakki*, *Aseel*, *Kharbalion*, *Fasli*, and *Mozawati* are grown on a large scale for processing and export. In Gulf countries, famous cultivars include *Ajwa*, *Barhi*, *Deglet Noor*, *Medjool*, and *Sukkary*. In the 18th century, some crossbreeding work in *Phoenix* species was done in the USA to develop a promising male variety, resulting in the identification of the *Fard-4* male palm (Nixon and Carpenter, 1972)

Research and technologies development

Research and development on date palms in India commenced in 1955, when the Indian Council of Agricultural Research (ICAR) sanctioned the Coordinated Scheme for Date Palm Improvement. The main center was established in Abohar, located in the Ferozepur district of Punjab, an area deemed highly suitable for date palm cultivation due to its dry, arid climate and the availability of canal water for irrigation (Kalra, 1976). The primary objective of the scheme was to expand date palm cultivation in appropriate regions across the country. This ought to be achieved through the selection, propagation, and distribution of cultivars/varieties that could be grown successfully, as well as by identifying optimal cultural management practices, such as pruning, pollination, and methods for achieving optimum fruit bearing and proper ripening.

In 1956, JC Bhakshi, the scheme's in-charge, was sent to the USA to select and procure different date palm varieties. He successfully obtained a significant number of suckers from fifteen cultivated varieties. By 1964, 19 varieties were procured from Egypt, Aden, West Pakistan *etc.* within India. In 1959, an improvement initiative for the date palm scheme was launched in Khedoi-Kachchh, Gujarat, by the Bombay Presidency (now part of Gujarat and Maharashtra). This was to address the date palm resources in Kachchh. Later, the initiative was relocated to Mundra based on ICAR's recommendations. Suckers and planting material were distributed across various parts of the country and to ICAR and state government centers for further evaluation.

The major date palm growing areas in India include Kachchh (Gujarat), Rajasthan, parts of Punjab, and to a lesser extent, Tamil Nadu. In the Kachchh region, there are over 2 million date palms, mostly propagated from seeds and offshoots, which provide a rich biodiversity for experimentation and improvement. Recent efforts by the Indian government have led to an increase in date palm cultivation from 8,973 hectares to 16,000 ha, with notable advancements in Rajasthan through the introduction of tissue culture planting materials. Currently, date palms are cultivated in approximately 23,071 ha across the country (Table 3). Significant work remains to be done in improving cultivars, employing hybridization techniques, screening local varieties, training farmers, establishing regional cultivation norms, and enhancing grading, packaging, marketing, and fruit shelf life (Abbas, 2014a).

Date palm research in Gujarat began in 1959 when state government established the Date Palm Research Centre in Khedoi, Anjar taluka, Kachchh district. The Centre aimed to evaluate various date palm offshoots procured from around the world. Subsequently, in 1978, ICAR established another Date Palm Research Centre under Gujarat Agricultural University in Mundra, Kachchh district. The coastal belt of the Kachchh region harbors rich genetic diversity in date palms, which should be further exploited. Elsewhere in the country, date palm populations are less abundant. At ICAR-CIAH, Bikaner, 65 genotypes/cultivars have been conserved in the National Field Gene Bank, collected from various sources (Singh *et al.*, 2006; CIAH, Bikaner 2016-17) and evaluated for growth performance and fruiting characteristics, including three germplasm varieties introduced from ICARDA, Amman, Jordan in 2015. In 1998, offshoots of the varieties *Braim, Chipchap,* and *Sukkar* were introduced from Iraq. However, *Sukkar* did not survive due to the small sized of suckers and lack of roots. Conversely, *Braim* and *Chipchap* are performing well under hot, arid conditions and yielding good fruit (Singh *et al.*, 2005). In January 2009, offshoots of two germplasm varieties, *Siwi*and *Ahmat,* were introduced from Egypt through NBPGR, New Delhi and both are thriving under Bikaner conditions. A late-maturing, rain-tolerant, red berry-coloured genotype has been identified at CIAH, Bikaner (CIAH, Bikaner; 2016-17; Singh *et al.,* 2023).

The institutions such as SDAU, DRS, Mundra (Gujarat); CAZRI, Jodhpur; SKRAU, Bikaner; PAU, RFRS, Abohar (Punjab); Central State Farm, Jaitsar, Sri Ganganagar; Suratgarh Farm (Table 2); and COE Date Palm, Bhojka, Jaisalmer (Rajasthan) maintain tissue culture plants of nine varieties and evaluate their performance.

Table 2: Status of date palm germplasm in India

Centre/place	Nos.	Suitable varieties/genotypes
ICAR-CIAH, Bikaner	68	Halawy, Khalas, Zahidi, Khuneizi, Chip-chap
DRS,SKRAU, Bikaner	35	Halawy, Barhee, Khalas, Zahidi, Khuneizi, Medjool,
RFRS, PAU, Abohar, Punjab	34	Halawy, Barhee, Medjool, Zahidi,
DRS,SDAU, Mundra, (Gujarat)	18	Halawy, Barhee and Local red type
CAZRI, Jodhpur	19	Halawy and Anand DP -1(TC plant early maturity)
Centre of Excellence Date palm, Bhojka, Jaisalmer,	09	Barhee, Khadrawi, Khalas, Jamli, Saggai, Khuneizi, Medjool and 02 male cultivars.

A substantial number of date palm varieties and some promising selections, Sel.-9, Sel.-13, Yaqubi, Kotho, Trofo, Bhukso, Gulchati, Madhepura, Khedoi-7, Sopari, and Saidy, have been identified from natural populations in the Kachchh region. The farmers in Kachchh have made some selections themselves (Pareek and Sodagar, 1986). These yellow and red berry varieties are particularly suited for producing various processed products (Singh *et al.*, 2009). An elite green-coloured, sweet berry type at the doka stage has also been identified in Kachchh at farmer fields. M/s Kachchh Crop Service (KCS) has recognized several elite red and yellow fruit varieties at farmers' fields and is producing tissue culture plants from these elite materials for large-scale planting. Tissue culture-raised plants have shown a higher survival rate compared to traditional sucker or offshoot plantations due to better root development (Fig.1).

In Kachchh region of Gujarat, maximum date palms are natural and as grove in depressions, on riverbank, *nala* and boundary of the farms. In natural date grove populations maximum seedlings are male. In Gujarat major area of date palm cultivation is in the coastal area of Bhuj, Anjar, Khedoi, Mundra, Mandvi, Gandhidham, etc.

During 2020-21, area of date palm cultivation has increased to 19,980 ha with production of 18,5346 tonnes fresh fruits with productivity of 9.27 ton/ha (Table 3). The tissue culture plants of cultivar Barhee imported from UK through UAE have been planted at farmers' field in Kachchh district. They started fruiting 3-4 years after of planting. In these plantations, suckers productions are not allowed by growers for better growth and early fruiting. Mr. Rahul Gala Shah founded a Society in 2006 for date palm farming. The spell out an association of farmers, has become largest organization of Barhee date growers in India. A total of 25,000 offshoots/ tissue culture plants were procured from Israel, Jordan and United Arab Emirates (UAE). Now, date palm cv. Barhee plantation has spread over throughout Kachchh and is started production of fruits. Further, date palm planting material is also spread over Gujarat. The area and production of date palm is increasing in Gujarat (Fig.2).

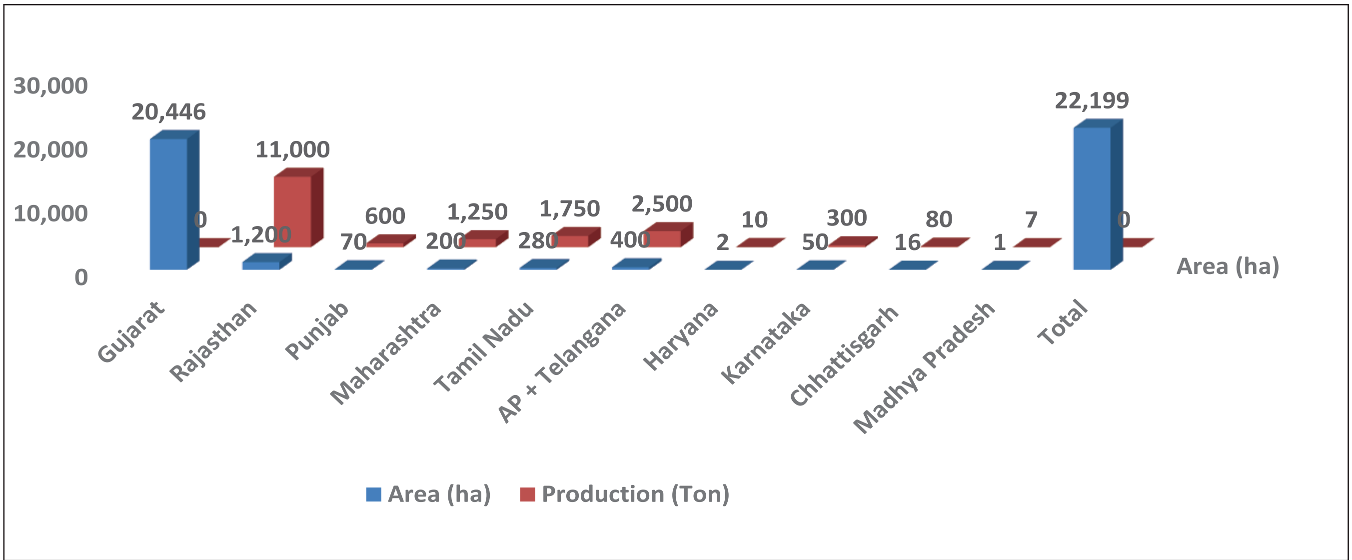

Fig. 1. Area and production of date palm in India
Source: Government's Department of Horticulture and through Personal Communication

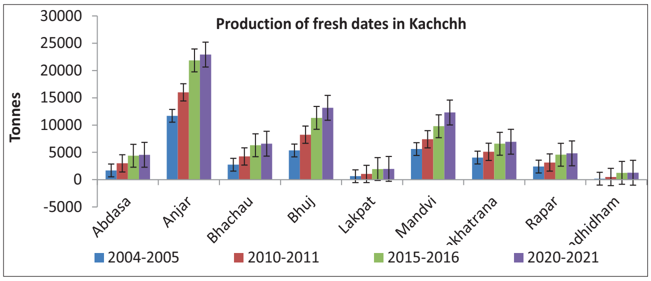

Fig.2. Area and production of date palm in Kuchh district of Gujarat

In India date palm production is not meeting our domestic demand and maximum dates are imported from date-growing countries of the world. During 2013, India imported 311575 tonnes date from UAE, Pakistan, Egypt, etc, of worth 183169,000 US $ and it was increasing pattern, during 2021 as 450356 tonnes. Egypt and Saudi Arab are largest dates producing countries in the world.

According to FAO stat, India is one of the largest importers (No1 position) of dates in the world. Under National scenario, import of dates can be reduced up to some extent by expansion in area and quality production by planting of date palm in Rajasthan, Gujarat, Punjab, Haryana and Tamil Nadu (Fig 3 and 4).

However, 2021, India's position as an exporting country for product dates, fresh/dried is37th in the world. The export quantity 766 tonnes for costing 1287 US$ and share per centage of 0.07 on the world.

Further, India also exports a small quantity of dates and processed products to neighbouring countries like Nepal, Myanmar, Bhutan, Singapore, Maldives and Sri Lanka, amounting 6,35,000 US $. This may increase in the future.

Date palm cultivation

The very best dates known can be grown at Montgomery, Multan, Khushab, Sirsa and Lahore (now in Pakistan) and Ludhiana (in India), but that Delhi and Ambala (India) fall somewhat short of the required climatic standards. Milne stated that minimum and maximum temperatures are suitable for the fruiting season at all stations, he observed that if first class dates ripen under 3,277 heat units then finest dates should ripen in Punjab. In the fruiting season, excess rainfall and normal high humidity cause the most damage during ripening period. For offshoot propagation, if the fruits are ripe on mother tree, at that time offshoot is cut, there can be no doubt of the type of fruits that offshoots will bear. Before being removed, offshoots should be pruned of mature leaves, preserving the tender young opened leaves in central bud.

To prevent excessive water loss from transpiration, offshoots should weigh at least 2.7 kg; those of lesser weight will likely die. Trimmed offshoots ready to be planted should weigh 5.4-6.8 kg and be 3-4 years old. Some 6-12 month before offshoot is to be removed; earth should be heaped around base of the mother palm and kept moist to stimulate root growth and thereafter planting is done in field at 5 to 6 m. distance. Raising of seedlings and selection work was initiated and improvement work on date palm was done by Jawanda and Kalra (1972) at Abohar, Punjab.

Water management is crucial for offshoot plantations, as date palms yield best under well-drained, aerated soils. Roots extend 2–3 m deep, so aeration must

Table. 3 Area and production of fresh dates in Gujarat during 2005-2021

Districts	2005-06		2010-11		2015-16		2020-21	
	Area ha	Production (Tonnes)	Area ha	Production (Tonnes)	Area ha	Production (Tonnes)	Area ha	Production (Tonnes)
Ahmadabad	6	51	2	10	2	17	8	56
Banaskantha	85	357	100	500	152	770	210	1,449
Bharuch	0	0	0	0	18	62	13	60
Dwarka	-	-	-	-	11	56	25	150
Gandhinagar	1	5	1	5	2	0	2	14
Jamnagar	0	0	8	31	85	425	148	651
Kachchh	13,171	92,197	16,693	1,23,995	17,658	1,65,632	18,920	1,79,362
Morbi	-	-	-	-	57	303	131	786
Patan	16	160	30	264	89	462	204	1,440
Porbandar	0	0	2	8	2	10	9	46
Rajkot	0	0	3	21	68	382	94	773
Surendranagar	11	110	13	130	59	354	130	410
Others	0	0	0	0	23	11	86	149
Total Area	**13,290**	**92,880**	**16,852**	**1,24,964**	**18,226**	**1,68,474**	**19,980**	**1,85,346**

Source: Director of Horticulture, Government of Gujarat

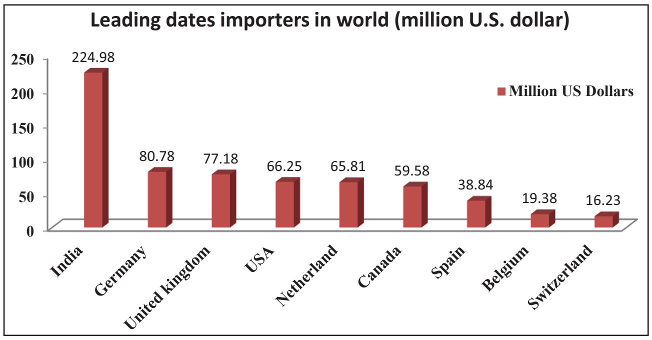

Fig.3. Imports of date palm worldwide
Source: Food and Agricultural Organisation (FAO), 2021

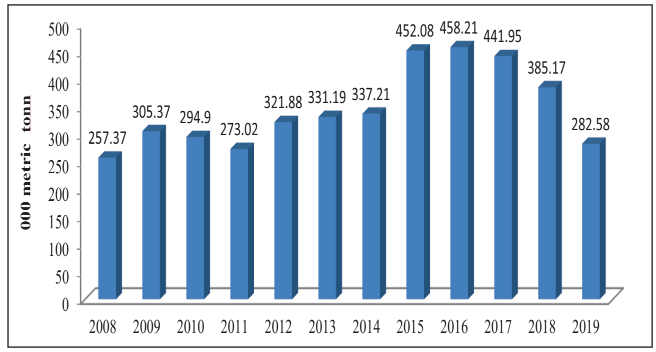

Fig.4. Export volume of date palm neighbouring countries
***Source*:** FAO Stat database

be maintained to this depth, with the water table kept between 2.7 and 4.9 m. Manure should be applied after growth begins. In Punjab, coal ash serves as an effective mulch, conserving moisture and preventing termite attack. Intercropping can be practiced during the early years; legumes or other fruits such as pomegranates or figs are recommended. The soil should be kept moist for the first month after date palm planting and until they are fully established. Offshoots in well-drained medium loamy soil in September require daily watering for the first 40 days, every-other-day watering for the next 40 day and thereafter watering every 6 day until growth begins. In spring, watering should be every 4 or 5 days until the rains commence. An annual application of 25 kg of well-seasoned manure per adult plant is needed. In arid region, oil seeds crop like *Brassica juncea*, and *Eruca sativa* can be grown in newly establishing orchards. As taramira is a rainfed crop grown during *rabi* season in arid region.

The timing of hand pollination varies; if weather is warmer, flowering is earlier. Pollination is appropriate when the female spathe bursts and the stigma is receptive. The low temperature in preceding year affects fruit setting in date palm (Shabana and Al-Sunbol, 2007). The receptivity time of stigma in date variety varied. It has been observed that pollination and fruit setting in cv. Medjool is highly receptive. The pollination and stigma receptivity in date palm cv. Shamran was studied by Gupta and Thatai (1980) at Abohar. The male flower cluster with its enclosing spathe is cut when it is about to open. Waxy scales cover the stamens. One or two small branches are cut from the male cluster and placed among the small branches of the female cluster. One male tree may sufficient to pollinate 100 female trees; however, it is safer to have 3-5 male palms per 100 female palms. Netting to protect the ripening fruits is necessary to protect against birds damage. In hot arid conditions, it is experienced that many bunches/berries are damaged due to high wind velocity, dust storm/ hot sand. Protection measures/ covering of bunches should be followed.

The research work on date palm was conducted on establishment of suckers, rooting, and to screen better varieties at Abohar, Punjab (Kalra, 1976, Katyal and Dutta, 1976). The performance of various cultivars was monitored in Abohar area to assess their performance (Vij *et al.*, 2005). Different hormonal treatments were applied in aerial suckers for root development. Mounding/earthing is also practised for rooting in high offshoots and results were encouraging (Vij *et al*, 1977). Under varietal evaluation, maximum number of fruits (15-21) per strand in cv. Deglet Noor; maximum fruit (23-68 g) and seed weight (2-3.5 g) in cv. Medjool were observed. Total soluble solids recorded were (27.6%) in cv. Halawy. Halawy and Barhee fruits were good for fresh eating at *doka* stage and cv. Medjool for *chuhhara* (dry date) making, whereas cv. Zahidifruits were good for processing as soft dates. The old seedling palms (50-60 year.) are growing well on farm road side and some of them producing good quality fruits. Some farmers of border areas in Punjab maintain seedling palms. There is a better scope for chance seedling selection and identification of elite material.

Table 4: Import of dates products in India

Units	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2021
Quantity (MT)	193467	256295	247300	311575							450356
Value 000US $	95043	141713	112649	183169							240350

Source: FAO Stat database

Gujarat

Along the western border of Gujarat, Kutch, Saurashtra and North Gujarat are considered the best regions for date palm cultivation. Thakor (1926) observed the Arabian date palm in the private garden of King of Kutch. Old records show that date palm groves on north-western border of India were developed from seeds discarded by army encampments and in part from seeds and offshoots planted by settlers, returning from the Haj pilgrimage. It is said that 400 years ago Mundra in Kutch was the only (Tables 3 and 4).

Sea route through which pilgrims went for Haj from India and on return brought the dates. In the course of time, date plantations increased. Previously Kutch, the largest district of Gujarat, was almost isolated from the mainland. Only after 1947 with the improvement of road and railroad connections were the trade channels opened and the marketing of dates improved. There was considerable increase in date palm plantations; in 2004-05 the total area increased from 8,973 ha to 16,000 ha during last decade (Abbas, 2014a). Under the National Horticulture Mission, Government of India, Gujarat has received grants to promote date palm cultivation and research. Date cultivation suffered heavy losses in 1998 from a major hurricane and hundreds of plants were destroyed and also during severe storm / earthquake in Kachchh region. In general, seedlings are growing on Farm boundary, roadside, and foothills. A rich diversity in date plants is available near Kera, Khedoi village and male palms spathes are used for collection of pollen grains.

Date palm seedling plantation has done at Research farm, SK Nagar, Gujarat for evaluation. A few plants are in fruiting stage. The growth in male palms is vigorous and fast than female and male plants ratio is 40-50%. Male palms are used for pollination purpose.

Date palm Research Station, SDAU, Mundra, is working on date palm research since 1978 and has made the following recommendations for Gujarat region:

- Cultivars Halawy and Barhee are recommended for commercial plantation. The Khalal stage of Halawy cultivar is the best quality for making chuhhara, which is prepared by immersing the fruits in boiling water for 20 minutes and then drying them on trays in an air circulation oven at 45°C for 60–65 hours.
- The Barhee cultivar is the best for making pind khajoor.
- Medium-quality fruits are useful for preparing good-quality beverages. The Local Red variety is well-suited for making jam.
- Cultivars Medjool, Hatemi, Ruziz, Selection-3, and Tayar are resistant to white scale, Parlatoria blanchardi.
- Using 600-gauge low-density polythene at the color break stage of the fruit (ICBR of 1.1.73) protects against rain damage in late-maturing cultivars.

Kachchh region

About 70-80% of date palm cultivation in coastal belt of Kutch, from Anjar to Mandvi, originated from seeds, and majority of fruits are of inferior quality (Ramdevputra *et al.*, 2009). During 2019 survey in the Kachchh area, rich genetic diversity was observed in fruits of date palms at doka stage, with variation in fruit colour, weight, size, taste, total soluble solids and acidity (Singh *et al.*, 2020). As a result, offshoots of date palm cultivars were obtained from different date-growing countries through the United Nations Development Program (UNDP) and their evaluation was undertaken at Date Palm Research Station (DRS), Mundra. Five introduced date palm cultivars—Zahidi, Halawy, Barhee, Khadrawy, and Sayar and one Local Red variety as the control were evaluated from 1999 to 2001 DPRS, Mundra, Kutch. During 2000-2001, the Barhee cultivar produced the maximum yield of 66.17 kg / palm over three years. The Sayer and Khadrawy cultivars recorded lowest yields.

The highest number of strands (62.08) and longest strand length (44.92 cm) were recorded in the Barhee cultivar, although Halawy was also statistically comparable to Barhee. The maximum fruit weight was recorded in Halawy in 1999, while during 2000-2001, the Barhee cultivar had highest average fruit weight of 15.40 g, 12.63 g, and 12.74 g, respectively. Fruits of Barhee, Zahidi, Khadrawy, and Sayar cultivars had poor taste quality and were astringent at khalal stage, whereas Halawy, Barhee and Local Red varieties were superior, with a market price of INR 15/kg. Barhee yielded highest return of INR 992.70 / palm / year due to its sweet taste and softness at khalal stage (Ramdevputra *et al.*, 2009).

The Kutch Date Palm Development Consortium, an association of farmers registered under the Society Act (1960) and based in Bhuj, Gujarat, is the largest organization of Barhee date palm growers in India. The organization addresses all the needs of its members, including the import of date palms, Post Entry Quarantine (PEQ) facilities, fertilizers, manure, pesticides, technical knowledge, and development of marketing channels and buyback guarantee. A total of 25,000 offshoots and tissue-cultured plants were procured from Israel, Jordan, and the United Arab Emirates for the development of date orchards (KDDC, 2009).

Rajasthan

The northern arid regions in India consist largely of the Rajasthan Desert, the Rann of Kutch and semiarid regions of Punjab and Gujarat. Rajasthan occupies almost 60% of the total of these regions. The region has sandy saline soil of 8-10 pH, with very low rainfall, cold winters and very hot summers. Furthermore, it has salty ground water, strong winds and low soil fertility. Maharaja Shri Ganga Singh ji brought date palm plants and was planted in the Garden, Sri Ganga nagar and other places in Rajasthan. The Rajasthan canal system represents the major irrigation scheme. With construction of the Indira Gandhi Canal, Jaiselmer District has an area of 677,000 ha and Barmer District 3,100 ha of irrigation facilities. This facility has led to making this region a garden of date palms as it grows well under extreme temperatures and saline soil, although requiring a proper water supply.

The commercial varieties of date palm were introduced from the USA, Pakistan and Middle East countries during 1955-1962. The performance of some of the cultivars was found more beneficial under arid irrigated conditions at Abohar, Punjab. The success opened up the possibilities of commercial date palm cultivation in India. Therefore, new thrust was given to date palm research since 1978 under the All India Coordinated Fruit Improvement Project of the ICAR at (now AICRP on Arid Zone Fruits), Bikaner and Jodhpur in Rajasthan, Abohar in Punjab, Hisar in Haryana and Mundra in Kachchh, Gujarat. The area under cultivated type date palm (*Phoenix. dactylifera*) is less in India and now it is being increase after introduction of tissue culture planting material especially in Gujarat, Rajasthan, Tamil Nadu and other place.

M/s. Atul Pvt. Ltd., a prominent industrial chemical company located in South Gujarat, has undertaken a massive effort to make the Rajasthan Desert green with date palms. The company and the Rajasthan Government have formed a joint venture company, M/s. Atul Date Palm Ltd., a publicprivate-cooperative venture. A memorandum of understanding (MOU) was signed between UAE University, Al-Ain and M/s. Atul Ltd., to transfer tissue culture technology of date palm. M/s Atul Pvt.Ltd., in 2011 acquired a majority holding in DPD Ltd., London, which produces tissue culture date palm plantlets for distribution worldwide.

The Atul date palm project is very ambitious and when fully implemented will represent an outstanding private/public program effort for date palm cultivation in Rajasthan. However; there are many scientific, social, climatic conditions to overcome. (Rajmohan *et al.,* 2010**,** report for date palm in Rajasthan) in two phases: first, import of secondary hardened plantlets and establishment of demonstration farms and second, the establishment of nurseries and import of primary hardened plants with secondary hardening in India. Activities included: (a) About 47,000 primary tissue culture palms of Barhee, Khalas, Khunezi and Medjool cvs. (female and male) were imported from Arab nations and secondary hardening is in process at a new nursery at Jodhpur, Rajasthan.

After one year plant showed satisfactory growth; (b) In an area of 104 ha at Jaisalmer, Rajasthan, tissue culture female palms of cvs. Barhee, Medjool, Saggai and Zamli have been planted along with male cv. Madsari and Ghanami for pollination. Growth of all cultivars after 10-12years of planting has been evaluated and it was found Barhee, Khuneizi, Medjool are suitable in respect of better yield and quality of fruits. However, stunted growth, morphological variation in plants were noticed during farmer's fields in tissue culture date palm orchards.

The Rajasthan Date Palm Project, supported by the state government, established 140 ha of plantations using tissue-cultured plants of several cultivars at Khara Farm, Bikaner, and Sagra–Bhojka Farm, Jaisalmer. This farm has developed as Centre of Excellence for date palm in Rajasthan. Date palm orchard development work in Thar desert is appreciable. Drip irrigation is practiced moreover; during visit of farm maintenance of the irrigation system through contract was inadequate. A large number of plants exhibit a phenotype that is not typical of the cultivar. Problems during production in the laboratory stage may be the cause for this presumed somaclonal variation (Table 5).

Table 5: Area of date palm cultivation in different districts of Rajasthan.

District	Area (ha)	Varieties planted
Sri Ganaganagar	170.00	Barhee, Khuneizi, Khalas, ,Medjool,
Hanumangarh	130.00	Barhee and Medjool,
Churu,	25.5	Barhee,
Bikaner	300.00	Barhee, Khadrawy, Khuneizi, Khalas, Medjool, Zamali, Saggai and male plants
Jaisalmer	500.00	Barhee, Khadrawy, Khuneizi, Khalas, Medjool, Zamali, Saggai and male plants
Barmer	205.00	Barhee, Khuneizi, ,Medjool,
Jhunjhunu	12.00	Barhee, Khuneizi, Khalas, ,
Nagaur	42.00	Barhee, Khuneizi, Khalas, ,
Jodhpur	37.00	Barhee, Khuneizi, Khalas, ,
Pali	22.00	Barhee, Khuneizi,
Sirohi	13.80	Barhee,
Jalore	40.00	Barhee, Khuneizi, Khalas,

The average fruit yield / palm at full *doka* stage was, in Barhee (66.0 kg), Halawy (59.7 kg), Khalas (43.7 kg) and Medjool (35.0 kg). The date palm are planted at 8mx8m spacing and common cultural practices were adopted. The cultivar Medjool is goodfor high yield and preparing dry dates (*chuhhara)*; Halawy, Barhee, Khalas, Khunezi, Sewi, Braim,Chip-chap, are best for fresh eating and processing (Singh *et al,* 2006). Spray of Ethephon 1000ppm at colour turning stage hasfound usefulfor earlyripening and improvement of berries in date palm (Meena *et al,* 2009). In a morphological characterization study of stone, variability in stone/seed characters in date palm was observedand accordingly, varieties may be groupedin small, medium and large/ big sized (Singh *et al*,2020).

One genotype (CIAH/DP/Sel.-1) late maturing, rain tolerant of red colour berry has identified by ICAR-CIAH, Bikaner. The fruits were harvested (45-50kg/tree) at *doka* stage at the end of August and first week of September. The length of bunch is bigger in size (90-105cm.), bunch weight 6-8kg.,number of bunch 9-12; number of berries/strand 25-29,fruit size 3.20 cm x 2.20 cm. Average fruit weight 10-12g, TSS 34-38^{0} brix, obtained IC number 0624544 for specific rain tolerant late maturity characters, Fruits are sweet in taste, edible at *doka* stage. Besides fresh consumption, it can alsobe used for making value added products (Singh*et al*,. 2023).

Tamil Nadu

Seed propagation is not useful due to dioecious nature. The common method of date palm propagation is sucker/offshoots of an appropriate size and weight (Mohammad, 1978). At present, tissue culture technique is more common for large scale plant multiplication. Saliah nursery (Dates India, 2011b) in Tamil nadu imports tissue culture plants of Meznaz, Chayar, Jaglool, Barhee, Jagidar, Khadravi and Khalas. According to Mr. S. Nizamudeen, these plants have grown to 1.5-3.0 m tall. They are all female trees and bear fruits from the second year of planting and recommended practices are as follows:

- *Planting and irrigation:* planting in a pit 60 cm x 60 cm x 60 cm. Biofertilizers like vermi-compost, sheep manure or farm yard manure (any one of them) can be used with plant spacing of 6 x 6 m. Irrigation of 30 litre per tree once a week up to 1 year. For the next 2 years, 50 litre per tree once a fortnight. For the subsequent 2 years, 100 litre/ tree once a month under drip irrigation, then the drip system should be converted into basins.

- *Intercropping:* during the early years intercropping can be done to generate additional income and to provide protection to young palm trees against heat. Plants like *Aonla* (Phyllanthus emblica), fig (Ficus carica) *badhal* (monkey fruit, lakoocha), *seetha phal* (custard apple), Cajanus cajan, Vigna radiata, Macrotyloma uniflorum, sesame, Helianthus annuus, Zea mays, Sorghum bicolor and finger millet can be grown. For such plantings additional irrigation must be provided.

- *Pollination:* Pollination is done by hand for better pollination honey bee rearing should be introduced.

Date-palm flowering take place during January to February. Fruit harvest is done in June or July. After 5 years of planting the fruit is harvested at three stages. The fruiting begins from the fifth year of planting. Under drip irrigation the yield in 5th years is 50 kg, year 6 is 60 kg, years 7 and 8 is 100 kg and in year 9 reaches150 kg. The average of 150 kg fruits/year for a tree assumes that it is healthy. The date palms yield well for up to 50 years but for following 50 year the yields decrease. For better pollination and fruit yield 10 males are necessary for 100 female plants (Dates India, 2011b).

Organic date palm

Mr. K. G. Murugavel is first southern India to successfully cultivate organic Barhee dates. About 30 km from Coimbatore, he has a 1 ha farm in Vanjipalayam where he has 3.1 m tall palms of Barhee. A total of 200 plants grow in neat rows; each boxed in by thin sprinkler pipes and 8 m apart. Each tree was laden with 50-80 kg of shiny yellow dates, nicknamed *honeyballs*. They are crunchy and sweet. In Feb. 2009 he imported 200 plantlets from the UAE and planted them on his farm. Holes were filled with organic manure, ash and sand, 148 plants / ha, watered every 3 day. Neem cake and organic manures are applied once every 3 month. He harvested fruit within 28 months very fast time period for Barhee.

In the first year the plant height was 2.4 m tall with 20 kg of fruit and in the second year 40 kg /plant. When in full maturity each tree will be 20 m tall and estimated to yield 200-300 kg of organic dates which are harvested annually in July and September. This year each kilogram of dates fetched @ 300- per kg. The dates do not require any processing and are plucked at three stages.

In Hanumangarh, Rajasthan, a progressive farmer (M/s Laxmi Farm) is cultivated fruit crop and medicinal plants by adopting organic practices.

Tissue culture in date palm

Tissue culture plants of date palm were introduced in Kachchh region. Many importing agencies are engaged for this work.With a survey of date palm cultivation in Punjab, Kachchh and Tamil Nadu and recent attempts of covering vast arid and semi-arid regions of Rajasthan and its adjacent regions with date palm presents great challenges to improve cultivating practices, find local elite cultivars and import cultivars for better uniform acceptability and improved better date products. Over decades of cultivation practices followed in different regions, regenerating dates either by seeds or offshoots and trying different imported cultivars, there are present date fruits of great variations in size, shape, colour, weight, taste and astringency.

One way was to import tissue culture plants from abroad where such technologies have been developed either it was necessary to develop such technologies in India using either local elite cultivars and/or develop select cultivars found suitable for the conditions of India's different regions. The attempt of tissue culture was done in India by Kutch Crop Services Ltd., Mundra after setting a tissue culture lab. The lab has developed tissue culture plants of Barhee and local elite type. (KCSL, 2014). At CIAH, Bikaner a few of tissue culture plants of date palm supplied by M/s AV Thomas &Co., Kerala were evaluated under hot arid condition. More number of sucker productions was observed in comparison to suckers raised plants under field condition (Bhargava *et al.*, 2014). Physiological variation in tissue cultured plants was noted. Somaclonal variation has been observed in tissue culture raised plants.

Kutch Crop Services Ltd (KCSL), Mundra, Gujarat

The KCS, Mundra has been involved in socio-economic development since more than three decades in the Kachchh region. The need for evaluating date palm as a source of income for farmers of Kutch was established at Vivekananda Research and Training Institute (VRTI), Mandvi in 1994; in 1995 a study was initiated in consultation with Israeli scientists to identify elite date palm cultivars. The activities of KCSL are (a) improve the socio-economic conditions of local farmers in Kutch and other regions; (b) provide knowledge about scientific cultivation practices in a cost effective manner; (c) provide quality planting material at an affordable cost and (d) conserve the natural heritage of elite date palm.

During 2000, a tissue culture laboratory for date palm was started it was sponsored by Rural Agricultural Research and Development Society (RARDS) to set up a date palm tissue culture lab in Mundra, Kutch. With the scientific team , KCSL has succeeded in motivating entire team to develop the protocol for elite cultivars of date palm and laboratory is producing about 5-10 thousands plants. Cv. Barhee and KCS-143 plants were procured from KCS Ltd, Gajod, Bhuj to see their performance under arid condition and the performance was good. The KCSL has also supplied tissue culture plants to farmers for orchard development in Kachchh region.

Anand Agricultural University, Anand

The AAU Plant Tissue Culture Laboratory claims to have developed, for the first time in India, a protocol of micropropagation of indigenous genotypes of date palm. Field evaluations of tissue culture grown plants at Anand and Dantiwada (university fields) have shown total field establishment (no mortality), early flowering and profuse suckering. On flowering they were true to type DNA based molecular markers (viz. Random Amplified Polymorphic DNA (RAPD), Intersimple Sequence Repeat (ISSR) and Simple Sequence Repeat (SSR) have been employed to verify variant plants and proved their superiority and clonal fidelity. According to Dr. Subash, responsible for developing this technology, around 1,500 plants are under hardening process in different stages. The fruits from local genotypes and elite varieties have huge potential to capture local and global markets. The technology involves raising shoot apices (apical and auxiliary buds) of selected offshoots of elite cultivars. The stages involved are callus initiation, somatic embryo induction, development, maturation, germination and finally in-vitro plantlet development. The tissue culture plants (Anand -1, red type) have supplied to different organizations and farmers for planting and are performing well with respect growth and fruits yield. The protocol developed by AAU have ready for large scale development of plants.

Tissue culture and protocol development

In our country, many tissue culture lab are working for production of tissue culture plants of different fruit crops, but only a few of them are producing date palm plants. At Jodhpur, tissue culture lab is also established and working on date palm crop. At CCSHAU, Hisar, date palm tissue culture work has also been started a long year back for protocol development. Tissue culture technique has been followed to develop plantlets in the lab.Tissue culture protocol development varied from variety to variety in case of date palm plants. This fruit crop is differed from others. Single or same protocol cannot be implemented to other variety. Protocol development research work in date palm has also been carried out at Biotechnology lab, ICAR-CIAH, Bikaner and some successful results have been found for mass multiplication of tissue culture plantlets. Auxiliary apical meristem tissues were taken for callus formation. The different hormones media were tried for rooting after callus formation. Hardening process has also been developed for tissue culture raised plants (Anon., 2017-18).Evaluation of tissue culture plants have been carried out at Institutes farm. ICAR-CIAH is recognised centre for the evaluation of imported plantlets/ quarantine for date palm crop.

Spathe emergence, flowering and pollination

It is a dioecious fruit tree and male and female spathes are borne on separate palms. In date palm, flowering entirely differs from other fruit trees as emergence of spathe, opening and then flowering, which takes about a month period. It also depends on genetic character and climatic conditions of the region. The atmospheric temperature plays an important role in spathe emergence, opening and flowering process. The spathe emergence, opening and flowering is governed by climatic data recorded in different year in Thar Desert, Jaisalmer (Singh and Uchoi, 2016). The good orchard management practices can improve spathe emergence, flowering and fruiting in date palm as it is continuous process and depends on growth and development of the plants (More *et al.,*2014). The age factor in date palm plants is also responsible for flowering. In case of date palm, number of leaves also important factor for spathe emergence, opening and number of bunches plant.

In general, hand pollination is done in dates at the time of spathes opening in female plants. About 5% male plants are necessary for pollination purpose. Earlier there was no known male in the world. There is no hybrids and hybridization work has not been done so far in date palm (Nixon and Carpentor, 1984). Now, several male varieties of date palm *viz.* Al-in-city, Madsari, Fard-4, Charmis and Local, are available for pollen grain production.

To see the effect, the hybridization work should be tried. The male date palm genotype (CIAH/DP/M-01) has been identified for more pollen grain production 600-700g pollen/tree (Singh *et al.*, 2018).

Fresh collected pollen grain has found more effective than stored pollen grain for fruit setting and yield in cv. Halawy (Singh *et al*, 2019). Pollens can be stored for long time at suitable temperature in freez. The opening of spathes depends upon environmental temperature. Effect of pollination and different type covering of bunches are found suitable for quality fruit production (Kumawat, 2020). Under Bikaner conditions, spathe emergence starts from last week of January and completed at the end of February and sometime up to first week of March. It has been observed that prolonged winter delays the spathe emergence. Spathe emergence continues physiological process along with growth of trees. It has been observed that occasionally, spathes are emerged out during winter months.

The spathe emergence/opening is started during February month. At Abohar, flowering takes place by the middle of March. Spathe opening starts by the fourth week of February and continues up to third week of April. Similar observations have also been reported by Jawanda and Kalra (1972) at Abohar. Mertia and Vashishatha (1985) have observed variation in spathe emergence in different years in cultivar Halawy under hot arid condition of Jaiselmer.

Harvesting, post-harvesting handling and marketing

Harvesting, post-harvest management and marketing of dates is an important set of neglected agricultural practices in Kachchh region (Muralidharan *et al,* 2008). Kutch produces only khalal dates; rutab and tamar stage of dates are not produced because of unfavourable climatic conditions during June-July which are the months for further ripening of the dates. Kutch produces the largest share of dates in India and different processed products have been developed (Ramdevputra, 2003).

Dates produced from these three major sources in Kutch also have sub cultivars (varieties) developed from many years of cultivations, long life of trees and possibility of random, natural or human (inter varietal) pollination resulting in a complex heterogeneous population of genetic diversity producing mostly poor-quality dates and a few elite ones. Problems associated with harvesting and grading of fruits are not scientifically resolved or taken care of with appropriate awareness of the farmers. Hence date cultivars undergo monetary loss and frustration.

In Kachchh there are local varieties, tissue cultured selected local varieties and imported Barhee cv. Pre-harvest practices that determine fruit quality and appropriate covering of fruit bunches and thinning fruit strands or bunches require standardization. Postharvest grading of fruits depends on size, colour, flavour, weight, shape, sweetness and astringency at khalal stage. Quality of date cv. Medjool was assessed after giving hot water treatment and drying efficiency and found cv. Medjool is good for dry date (Rakesh Reddy *et al.*,2023).

Marketing involves establishing prices based on grading by an organized independent agency, growers association to avoid middle man interference. In Anjar, Bhuj there is lack of an open market where farmers bring their dates to sell; but in the absence of a grading and price setting agency it is unorganized and date growers depend upon the middleman who decides the quality and price.

Plant protection

The problem of diseases, insects, in date palm crop is low due to hardy nature of plant. However, main disease and insects attack have observed in date palm orchards *viz.* suckers rot, Graphiola, palm weevil, termites, mites, etc The executive summary of the report of the committee which visited Gujarat and Rajasthan states stated that in Rajasthan symptoms resembling those of trunk rot (*Thielaviopsis paradoxa*) pathogen are present on a few trees. The presence of this pathogen is difficult to determine and laboratory tests should be repeated. Due to this reason, plant is broken and fall down in dust storm.In Gujarat presence of red palm weevil is the main problem, which is considered to be a major threat to production and should be given priority. Another problem is the high levels of infection with *Graphiola,* a leaf fungus. Protocols for monitoring the red palm weevil are also present (Muralidharan *et al.*, 2019). It may be desirable to treat *Graphiola* chemically; control measures consist of: (a) leaf pruning, coupled with treatment with any wide spectrum fungicide and (b) planting of resistant cultivars. Control measure for red palm weevil involve: (a) pheromone based RPW-IPM strategy; (b) set monitoring traps; (c) check palms around traps and (d) treat infested plants.

The damage of immature fruits by birds in Rajasthan is common, the management practices and use of different type covering material should be recommended. To control of termites, chemical insecticides as well as organic methods should be followed.

Future thrusts area of research

Kachchh region has a high genetic diversity in date palms; not only due to the complex relationship of natural hybridization with sugar date palm but the present populations of date palms consist of a majority grown from seed, offshoots and more recently from tissue culture. A few recent attempts (Srivastava *et al.*, 2013, 2014) at molecular characterization to find the best genotypes and identify sexual differentiation have been made for date palms in Kutch. But more systematic and concentrated investigations are required to identify genetic markers for the best cultivar identification and characterization of fruit qualities, such as shape, weight, colour, taste and sweetness.

The mapping the genomes of cultivars of date palms will be a great step towards improving the date palm cultivars and throwing light on the origin and domestication of the date palm. For the date palms in Kutch it is necessary to have morphometric and cellular markings for different cultivars and especially of elite cultivars with superior date qualities recognized for global market. India has main four regions of date palm cultivation, Punjab, Gujarat, Rajasthan and the south-eastern coastal region (mostly Andhra Pradesh and Tamil Nadu); with advancing climatic changes and preference for date palm cultivars, the best cultivation practices and disease preventive measures should be standardized. The pollination is a skilled practice apart from selecting appropriate varieties having metaxenia pollen effects. If a pollen bank is established on a cooperative basis having necessary storing facilities and appropriate grading of varieties, it would be a boon to farmers.

Looking to the frequency of earthquakes and hurricanes in Kachchh region, it is necessary that germplasm of elite cultivars of Kachchh should be conserved to other growing site for future use. The present tissue culture technology developed in India to produce date palm plantlets requires fine tuning and appropriate changes to produce true-to-type plants. At present tissue cultured palms pose some problems of somatic clonal variations. Moreover, it is necessary to have tissue culture plantlets of elite cultivars suitable to different regions and satisfying local tastes and demand as well as export requirements.

The development of various technologies and the requirement for date-palm research, conservation of germplasm and exploitation of genetic diversity, crop improvement, utilization of fruits in India, at least two-three suitable locations at Bikaner, Jaiselmer and Mundra should be strengthen. The date palm has its own unique place in agro-Horticulture system. Its usefulness in many ways and means and ability to endure unfavourable climate with long life satisfy the objectives of agri-horticulture development in arid and semiarid regions for the benefit of the farmer's community. The various processed products made from date fruits have an economic and social benefits for creating jobs. By reducing import of date palm, foreign exchange can be also saved. Date processing industries should be established in date palm growing areas. As well as development of orchards of date palm in arid and semi-arid regions would be an asset for ecological development, crop diversification and eco-tourism. There are vast potential of eco-tourism in Rajasthan and Gujarat, which can be helpful in many ways for social and economic development.

Conclusion

Date palm cultivation in India has made significant strides, particularly in the arid regions of Rajasthan and Gujarat. Research efforts, including varietal improvement, disease control, and post-harvest processing, have laid the foundation for sustainable growth. However, challenges such as limited local expertise, inconsistent irrigation, and somaclonal variations in tissue-cultured plants need to be addressed to enhance productivity and marketability. Looking forward, the focus should be on expanding cultivation into other suitable regions, improving post-harvest handling and processing, and developing domestic and export markets. By fostering innovation and farmer education, India can become self-sufficient in date palm production and even emerge as a key exporter in global market.

REFERENCES

Abbas, R. 2014a. Comparative analysis of date palm culture in India and Pakistan. Daily Times (Pakistan), Feb. 10.

Abbas, R. 2014b. Production trends of dates in India and Pakistan. Agrihunt (Pakistan) March 3.

Ahmad, A., S. Soni Dutta, S. Singh, K. Varun Singh and M. K. Santosh. 2013. *Phoenix dactylifera* Linn. (pinekharjura) a review. *Int. J. Res. Ayurved. Pharm.* **4**(3):447-51.

Anon. 2016-17. Annual Report, ICAR-CIAH, Bikaner p 5-6

Anon. 2018-19. Annual Report, ICAR- CIAH, Bikaner p. 31-33

Anon. 2021-22. Annual Report, ICAR - CIAH, Bikaner, p. 19-21

Barreveld, W. H. 1993. Date palm products: FAO Agricultural Services Bulletin No. 10. Rome, Italy.

Basu, S. K. and K. K. Chakarvaerty. 1994. A manual of cultivated palms in India. Botanical Survey of India, Calcutta.

Bhargava, R., Singh, R.S .and Vashishtha, B.B. 2014. Studies on physiological parameters in tissue culture and sucker plants of date palm (*Phoenix dactylifera* L.) cultivars. *Indian. J. Arid Hort.*, **9**: 91-95.

Blatter, E. 1926. The palms of British India and Ceylon. Oxford University Press, London.

Chandra, A., Chandra, Anju and Gupta, I.C. 1992.Date palm Research in Thar Desert. Scientific Publishers, Jodhpur. 116p.

Chandra, A., Swaminathan, R., Choudhary, M.L., Manohar, M.S., Pareek, O.P., Chandra, A. 1990. Performance of date palm cultivars in Thar desert. *Indian J. Hort.* **47**:1: 28-33.

Chao, C.T. and Krueger, R. 2007. The Date palm (*Phoenix dactylifera*): an overview of biology, varieties and genetics. *Hort Science*, **42**: 1077-82.

Cooke, T. 1908. The flora of the presidency of Bombay. Taylor & Francis, London.

Dates India and Saliah Date Nursery.2011. Tamilnadu.www.datesindia.com/about us http://www.indiamart.com/dates-indiasaliah

Dates India. 2011a. Date palm in Tamilnadu. http://www.datesindia.com/about.php Dates India. 2011b.

Godara, N.R and Pareek, O. P. 1985.Effect of temperature on storage life of ready to serve date juice beverage. *Indian Jour. Agri. Sci.* **55** :347-49.

Gros-Balthazard, M. 2013. Hybridization in the genus *Phoenix*: a review. *Emir. J. Food Agric.* **25**(11):831-42.

Gupta, M.R.and Thatai, S.K. 1980. Receptivity of pistillate flower in date palm cultivar Shamran. Jour. of Research,(P.A.U.) **17**(4): 366-68.

Hooker, J. D. 1894. The flora of British India, Vol. 6, London.

Jawanda, J.S. and Kalra, S.K. 1972. Date improvement work at Abohar. *Punjab Hort. Jour.* **12**: 33-38.

Kalra, S.K. 1976. Date palm research in India. *Indian Farming* **26**: 11-12.

Katyal, S.L. and Dutta, C.P. 1976. Scope and problems in date industry in India. *Indian Farming* **26**:3-5.

KCSL. 2014 Kutch Crop Services Ltd. Kutch, Bhuj, Gujarat. http://www.kcs-india.com/products.php

KDDC. 2009. Kutch Dates Development Corporation. India Today, April 20th.2009

Meena, Ramkesh; Yadav, P.K. and Singh, R.S. 2009. Effect of ethephon spray on fruit quality attributes in Date palm cultivars under hot arid region. *Haryana J. of Hort. Sci.* **38**(3&4): 180-82.

Meena, R. K., Choudhary, M. K., Gurjar, P. S., Rane, J.Singh, A, K., Yadav, L. P., Singh, D. Choudhary, D. R, Jatav, M. K., Singh, R.S., Siddiqui, M. H., Alamri, S. and Khan. S. (2025). Morphological diversity assessment in date palm (Phoenix dectylifera L.) germplasms grown under hot arid region of India.*BMC Plant Biology* (2025) 25:1159https://doi.org/10.1186/s12870-025-07194-2.

Mertia, R.S. and Vashishtha, B.B. 1985. A note on performance of date palm cultivar Halawy at Chadan, Jaiselmer. *Annals of Arid Zone*, 24: 263-64.

Milne, D. 1918. The date palm (*Phoenix dactylifera*) and its cultivation in Punjab. The Punjab Government. Tech doc.

Mohammed, S. 1978. Problems in date palm propagation. *Indian Hort.* **23**(3): 15-18

More. T. A.; Singh, R. S and Sharma, S. K. 2014. Date palm (*Phoenix dactylifera* L.) In: Palms (ed. Singh, *et al*,), Westville Publishing House, New Delhi, pp 168-194

Muralidhara, B.M, Singh, R.S., .Hare Krishna and Bhargava, R. and Veena G.L. 2017. Assessment of Biochemical and Nutraceutical compounds in date palm (*Phoenix dactylifera* L.) cultivars. *International Jour. for Pure &Applied Bioscinece* **5**(5):311-317.

Muralidharan, C.M., Baidiyavadra,D.A. and Sharma,Kapil Mohan 2019. Variability in date groves of Kachchh and conservation through field gene bank, Tech. Bull. 05/2019, DRS, SDAU, Mundra, Gujarat, 18p.

Muralidharan, C.M., Panchal, C.N., Baidiayavadra, Sharma, K.M. and Verma, P. (2020) Sugar Tech. https: //doi.org/10.1007/s12355-020-00859-2.

Muralidharan, C.M., Tikka, S.B.S. and Piyus Verma 2008, Date palm cultivation in Kachchh, Tech. Bull.No. 02/2008 S.D. A.U. Mundra, Kachchh, 36p

Muthana, K.D., Puri, D.N. and Singh, U. 1976. Date palm cultivation in Arid region. *Indian Hort.* **21**(1):10.

Newton, C., M. Gros-Balthazard, S. Ivorra, L. Parudis, J. Pintaud and J. Terral. 2013. Phoenix dactylifera and P. sylvestris in northwestern India: A glimpse of their complex relationships. *Palms* **57**(1):37-50

Nixon, R.W., Carpenter, J.B. 1978. Growing dates in the United States, Agr. Inf. Bull. No. 207, USDA, Washington, D.C., pp 63.

Pareek, O.P. 1984. Date palm growing potential of Indian arid zone. *Indian Horticulture* pp.2-5 & 8

Pareek, O.P. and Sodagar, N.N. 1986. Date palm grooves in Kachchh. *Indian Hort*. **31**:21-27.

Priyanka Kumawat, RS Rathore, Sandeep Kumar, Gayatri Kumawat and Sheetal Rawat. 2022. Effect of stored pollen grains on quality and yield of date palm in Western Rajasthan, *The Pharma Innovation Journal*; SP-**11**(4): 1128-1132

Rakesh Reddy, S.V., Singh,R.S.,Meena,Ramkesh,Berwal,MK,Sarolia,D.K.,and Palpandian,P. 2023. Impact of hot water Pre-treatment on the Drying Efficiency and Quality of date's cv. Medjool. *Horticulture* **9**:784-96.

Ramdevputra, M.V. 2003**.** Studies on Post-harvest management of date palm (*Phoenix dactylifera* L.) Fruits. Ph.D. thesis submitted to SDAU, SKNagar,

Ramdevputra, M.V., Butani, A.B.,Savaliya,J.J.Punsuriya,A. G. and Kanzaria, D.R. 2009. Performance of date palm cultivars in Kachchh region .*The Asian Jour. Hort.* **4**(!): 181-83.

Rathore, Surya 2012. Post-harvest utilization of date palm fruits, Ph.D. thesis, College of Home Science, submitted to SKRAU, Bikaner, pp

Sanderson, G. 2001. Natural history of date palm Phoenix dactylifera. Phoenix dactylifera. enhg.4t.com.

Shabana, H and Al-Sunbol, A. 2007`. Date palm flowering and fruit setting affected by low temperature preceding the flowering season. *Acta Hort.* 736:16.

Singh, R. S, and Julius Uchoi. 2016. Flowering and fruiting pattern in Date palm (*Phoenix dactylifera* L.) Cultivars under arid conditions. In: Book- Flowering and fruiting in Perennial plants (*ed.* by Singh VK., CISH, Lucknow).

Singh, R. S. and Bhargava, R. 2009. Effect of seed treatment on germination and growth behavior of date palm (*Phoenix* species) under hot arid conditions. *Jour. Trop. Forestry* **25**: (1) 42-48.

Singh, R. S.; Bhargava R.; Vashishtha B. B. and Ramdevputra M.V.2009. Genetic diversity in date palm (*Phoenix dactylifera* L.). *Current Agric* **33**: 67-72.

Singh, R.S .Bhargava, R. and Sharma, B.D. 2020. Diversity in seed characters for Morphological characterization of Date palm (*Phoenix dactylifera* L) varieties. *Indian Jour. of Plant Genetic Resources* **33**(1): 102-105

Singh, R.S. 2018. Date palm- an ideal fruit for health and wealth*, Indian Horticulture* **63**(5): 17-21.

Singh, R.S., Bhargava, R, Ramkesh Meena and Sharma, B. D. 2018. Evaluation of male date palms *Phoenix dactylifera* L) for pollen production under hot arid conditions. *Indian Journal of Arid Horticulture* **13**: 39-41.

Singh, R.S., Bhargava, R, Ramkesh Meena and Sharma, B. D. 2019. Effectof stored Pollen on fruit set, yield and quality of Date palm (*Phoenix dactylifera* L.) cv. Halawy under hot arid conditions. ISAH- *Indian Jour of Arid Horticulture* **1** ((1) :82-83

Singh, R.S., Bhargava, R. and Dhandar D.G. 2005.Performance of Date palm introductions under hot arid conditions**.** *Indian Jour. Plant Genetic Res*. **18** (1): 65-66

Singh, R.S., Bhargava, R. and Dhandar D.G. 2006. Evaluation of Date palm germplasm under hot arid eco-system. *Indian Jour. Plant Gene. Res.* **19** : 91-95.

Singh, R.S., Bhargava, R. and Dhandar, D.G. 2003. Status and prospects of Date palm propagation. *Current Agric*. **27**: 9-16.

Singh, R.S., Meena, R.K., Kamlesh Kumar and Singh, D. 2020. Variability in date palm fruits (*Phoenix dactylifera* L.) collected from Kachchh region of Gujarat. ISAH-*Indian Jour of Arid Horticulture* **1**(2) :84-86.

Singh, R.S., R.Bhargava and B.D. Sharma 2020. Effect of hot water treatment on dry date preparation from date palm (*Phoenixdactylifera*) cultivars in arid region.*Current Horticulture* **8**(2): 41-43.

Singh, R.S.,Bhargava, R, Ramkesh Meena, Sharma, B. D. and Saroj, P.L .2023. Late maturing and rain tolerant genotype of Date palm (*Phoenix dactylifera* L.)**,** *Ind.Jour. Plant. Gen. Res.* **36**:1; 28-30.

Sodagar, N.N.; Murlidharan, C.M. and Ramdeoputra, M.V. 1996.Date palm propagation problems and prospects with special reference to Kachchh*. Jour. Applied Hort.* **2**: 102-05.

Srivashtav, V. S., C. V. Kapadia, M. K. Mahatma, S. K. Jha, S. Jha and T. Ahmad. 2013. Genetic diversity analysis of date palm (Phoenix dactylifera) in the Kutch region of India using RAPD and ISSR markers. *Emir. J. Food Agric*. **25**(11):907-15.

Srivashtav, V. S., V. H. Solanki, H. K. Patel and R. V. Kansara. 2014. Molecular characterization of Date palm (Phoenix dactylifera) using combined marker analysis grown in Kutch region of India. J. Cell Tiss. Res. **14**(1):4083- 88.

Tewari, R.K. Solanki,K.R.and Bajpaie, C.K. 2001. Krishi vaniki ke liye upyukt desi khajoor, *Phal-Phool,* Jan.-March issue, pp. 37-38.

Thakar, J. I. 1910. Vanaspti Sastra-barda Dugnarani Jadibuti (Botany. A complete and compre hensive account of the flora of Bardamo untain (Kathiavad). Gujarat Printing Press, Bombay.

Thakar, J. I. 1926. Plants of Kutch and their utility, Gujarat Printing press and Nirmaya-Sagar Press, Bombay.

V.K.; Kalra, S.K. and Bajwa, M.S. 1977. Studies on rooting of high offshoots in date palm, *Punjab Hort. Jour*. **17** (3&4): 135-38.

V.K.; Kalra, S.K. and Bajwa, M.S. 2005. Performance of date palm in Punjab. ?

Vaidya, B. 1953. Sanskrit SahiytamaVanaspati (Plants in Sanskrit literature). Gujarat vidyasabha, Ahmedebad. A translation from Gujarati to English is in preparation by J.J. Shah.

Zaid, A. and P. F. de Wet. 2002. Date palm cultivation. Plant Production and Protection Paper 156 FAO. Rome, Italy.

Zaid. A. 1995. Date palm cultivation: FAO. No. 56, Rome, Italy, 238p.

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Natural food colorants from fruits: exetraction and application in food industry— a review

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Abstract

The food industry is traditionally dependent on synthetic colorants to enhance visual appeal and consumer's attraction. However, growing health concerns among consumers and regulatory restriction have possessed to identify safer natural alternatives from plants. Fruits serve a promising source of natural colorants with added health benefits due to presence of different bioactive pigments such as anthocyanins, carotenoids, betalains, and chlorophylls. These compounds not only enhance aesthetic value of food but also offer antioxidant, anti-inflammatory and other functional properties. However, challenges persist in their extraction, stability, and sustainability. Natural pigments are often sensitive to environmental factors such as light, temperature, and pH, limiting their commercial application. In response, recent research has focused on optimizing extraction and stabilization techniques to improve pigment yield and stability while maintaining their bioactivity. This review summarizes recent studies, highlighting advances in the identification, extraction and application of fruit-derived colorants in food systems. Emphasis is placed on their dual role as coloring agents and functional ingredients. Overall, fruit-based colorants signify a viable, health-conscious alternative to synthetic colours, though further innovation is needed to enhance their stability, bioavailibity and commercial feasibility.

Key words: Functional foods, Fruits, Industrial use, Green extraction techniques, Pigment stability

Color plays a pivotal role in shaping consumer perception and acceptance of food products. Attributes such as size, shape, and especially colour are commonly used by consumers to assess the quality of food (Spence, 2022). The colour of food is often associated with characteristics like freshness, ripeness, and safety. Consequently, food colouring has become widely used to enhance the visual appeal and marketability of various food items (Wange *et al.,* 2019). Since colour forms the initial impression of any food item, manufacturers have adopted food colouring as a key marketing strategy. Food colorants can be categorized into four main types: inorganic, synthetic, nature-identical, and natural colors (Okafor *et al.,* 2016). Moreover, the food industry mostly relied on synthetic colourants due to their consistent vibrancy, cost-effectiveness, and stability throughout processing and storage (Martins *et al.,* 2016).

The majority of synthetic dyes with aromatic rings and azo functional groups may be harmful to human health, including hyperactivity, allergic responses, and asthma attacks, intestinal cancer, respiratory problems (Li *et al.,* 2014; Ntrallou *et al.,* 2020). Yet, growing consumer concerns over the potential adverse health effects of synthetic colours have prompted regulatory scrutiny and a shift toward natural alternatives. However, rising health concerns and regulatory restrictions have accelerated the search for safer, natural alternatives (Albuquerque *et al.,* 2020). Therefore, natural-food colorants have found their niche for valuable food products.

Fruits, due to their vivid pigmentation and abundance of phytochemicals, are among the most viable sources for natural food colorants (Mazza, 2018; Martins *et al.,* 2016). These natural food colorants not only impart vibrant colour development, but also deliver functional benefits like antioxidant and anti-inflammatory properties being rich in bioactive compounds (Rodriguez-Amaya, 2016). These health-promoting qualities, along with rising consumer demand for clean-label and environmentally friendly products, have increased the popularity of natural colorants in the food industry. Moreover, the use of natural colourants can provide technological and bioactive functionalities to those foods in which they are applied, delivering additional value-added properties (Rodriguez-Amaya, 2016).

Nevertheless, natural pigments face many hurdles as they are often sensitive to environmental fluctuations including light, temperature, oxygen and pH resulting in colour fading, batch variability, and short shelf life (Fernandez-Lopez *et al.,* 2020). Per say, betalains extracted from vegetable peels degrade rapidly at ambient temperatures and are most stable under frozen conditions, restricting their application in processed foods. Moreover, the cost of natural pigments remains higher than synthetic dyes due to extraction complexity, variability in raw materials, and lower yield efficiency. To overcome these challenges, researchers are developing innovative extraction and stabilization methods. Encapsulation strategies, including micro-encapsulation

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or use of biopolymers, enhance pigment stability by protecting against degradation and thereby improving their bioavailability (Hidalgo *et al.,* 2018).

This review thus aims to synthesize recent advances in the use of fruit-derived colorants in food systems. It will examine major pigment classes viz. anthocyanins, carotenoids, betalains, and chlorophylls and their extraction and stabilization techniques, technological applications, and dual roles as colorants and functional ingredients. By bridging aesthetic appeal with health-conscious innovation, fruit-based colorants represent a viable alternative to synthetic dyes, though their successful adoption depends on overcoming stability, cost, and supply challenges.

Colorant compounds from fruits

Among the compounds present in fruits that show coloring properties are anthocyanins, betalains, carotenoids, chlorophylls and other non-anthocyanin flavonoids. Anthocyanins have the widest range of colors presenting shades from blue to red; betalains, for red-violet, yellow-orange color, and mainly pink; carotenoids, range from red to yellow and chlorophylls, are mostly green but also can present blue tones. All these compounds, in addition to their colourant capacity, exhibit different bioactive properties evidencing health benefits with their consumption (Sigurdson *et al.,* 2017).

Anthocyanins

Anthocyanins is one of the largest groups of water-soluble plant pigments with more than 700 compounds have been identified in nature (Zhang *et al.,* 2019). Chemically, anthocyanins belong to the flavonoids group, a sub-class of the polyphenol family, contributing to the attractive orange, red, purple, violet, and blue colors of fruits. These compounds are secondary metabolites within the phenolic class (Nieto, 2020) and are responsible for the red, pink, violet, blue and even yellow colors ((Vidana Gamage *et al.,* 2021; Mazza, 2007). Among the 27 anthocyanidins reported in nature, cyanidin, delphinidin, pelargonidin, peonidin, malvidin, and petunidin account for over 90% of those found in plants. Cyanidin-3-glucoside is the most abundant anthocyanin in the plant kingdom (Mattioli *et al.,* 2020; Zhang *et al.,* 2014; Li *et al.,* 2017). They absorb light around 500 nm and are commonly found in many fruitss such as blackberries, blueberries, cranberries, strawberries, grapes, figs, pomegranate, jamun, karonda, plum etc (Khoo *et al.,* 2017; Wallace and Giusti, 2015). Anthocyanins have attracted significant interest due to their dual roles as natural colorants and bioactive compounds.

Beyond their coloring ability, anthocyanins have demonstrated multiple health benefits. Studies have linked them to anti-inflammatory, anti-oxidant, anti-tumor, anti-mutagenic, and anti-obesity effects (Sun and Li, 2018; You *et al.,* 2018). They are also associated with improved cardiovascular health through regulation of cholesterol and triglyceride levels, and possess anticoagulant properties. Furthermore, anthocyanins may support cognitive function and help prevent neurological disorders (Li *et al.,* 2017). Emerging evidence also points to their role in managing diabetes and offering protection against oxidative stress (Leong *et al.,* 2018; You *et al.,* 2018; Li *et al.,* 2017).

Anthocyanin production in plants can be influenced by environmental stress and pathogen attack, serving as part of the plant's defense system (Zhang *et al.,* 2014). Their widespread distribution in commonly consumed foods and their bioactive potential make them valuable compounds for both nutritional and industrial applications. Their use as natural alternatives to synthetic colorants is highly promising; however, their application is challenged by low stability. Factors such as pH, temperature, light, oxygen, metal ions, enzymes, and co-pigments can affect their structural integrity and color expression (Enaru *et al.,* 2021; Khoo *et al.,* 2017; Fan et al. 2019). Among these, pH is particularly critical, as the hue of anthocyanins shifts significantly with changes in acidity (Rodriguez Amaya

Table 1. Natural food pigments from fruits and their characteristics, solubility,and functional applications

Pigment Class	Source fruits	Color range	Solubility	Functional benefits	Reference
Anthocyanins	Berries, mulberries, black current, strawberries, pomegranate, jamun, karonda, plum etc.	Red to blue (pH-dependent)	Water	Antioxidant, pH indicator, health-promoting	Tiwari *et al.* (2009)
Carotenoids	Mango, guava, banana, papaya, citrus, peach, apricot etc.	Yellow to orange	Lipid	Pro-vitamin A, eye health, stable	Khoo *et al.* (2008)
Betalains	Beetroot, dragon fruit, Cactus, pear (prickly pear)	Red violet to yellow	Water	Antioxidant, vivid, limited pH stability	Sadowska-Bartosz and Bartosz (2021)
Chlorophylls	Green fruits	Green, red blue	Lipid / water	Functional pigments, limited uses	Dagnino-Leone *et al.*(2022)

2018).

Carotenoids

Carotenoids are a class of naturally occurring pigments responsible for the bright yellow, orange, and red coloration found in many fruits and vegetables (Nagarajan et al.2017). These compounds are particularly abundant in tropical and subtropical fruits such as mango, papaya, peach, apricot, and citrus fruits, where they contribute not only to the fruit's visual appeal but also to its nutritional value (Maldonado-Celis et al. 2019; Zhou et al.2020). Carotenoids such as β-carotene, lutein, and lycopene are among the most prominent and biologically significant members of this group (Rodriguez Amaya, 2016). The intense coloration of these pigments arises from their conjugated double-bond structures, which absorb visible light in the 400–550 nm range, thus producing hues that range from yellow to deep red (Saini and Keum, 2018).

A notable characteristic of carotenoids is their lipid solubility, which facilitates their incorporation into the fatty components of plant cells and makes them suitable for lipid-based formulations in food and cosmetic applications (Martins *et al.,* 2016). In addition, carotenoids are relatively stable under thermal processing, a property that enhances their utility in processed food products. However, their stability can still be influenced by factors such as light, oxygen, and pH, making proper storage and formulation essential to maintain their colour and bioactivity (Tharuka and Baojun, 2024). Recent studies have focused on improving carotenoid stability through encapsulation techniques and green extraction methods, including the use of deep eutectic solvents and nano-emulsions, to better preserve their structure and extend their shelf life during food processing and storage (Molina *et al.,* 2023; Gutierrez-Uribe *et al.,* 2022). Beyond their use as natural colourants, carotenoids are widely recognized for their health-promoting properties.

β-Carotene, for instance, is a well-established precursor of vitamin A and plays a vital role in maintaining healthy vision, immune function, and skin integrity (*Rodriguez-Amaya et al., 2021)*. Lutein, predominantly found in citrus peels, accumulates in the retina and macula of the eye, where it helps to filter harmful blue light and reduce the risk of age-related macular degeneration. Lycopene, a carotenoid pigment responsible for the red color in pink-fleshed fruits, is a potent anti-oxidant with demonstrated protective effects against oxidative stress, inflammation, and UV-induced skin damage (Crupi *et al.,* 2023). Exploring the use of carotenoid-rich by-products from fruit processing industries, such as mango and citrus peels, as sustainable sources of natural pigments for use in foods, supplements, and intelligent packaging systems is new area for researchers (Rodriguez-Amaya *et al.,* 2023).

Betalains

Betalains are naturally occurring pigments found prominently in red dragon fruit, prickly pear, (Sadowska-Bartosz and Bartosz, 2021). These pigments fall into two chemical classes—betacyanins, which impart red violet colour, and betaxanthins, responsible for yellow orange coloration (Khan, 2016; Rodriguez Amaya, 2016). Betalains are notably stable across a pH range of roughly 3 to 7, which makes them suitable for low to mildly acidic food matrices (Martinez *et al.,* 2024). However, they are highly sensitive to heat and light: both betacyanins and betaxanthins degraded at elevated temperatures typically above 60°C for betacyanins and above 40°C for betaxanthins—leading to breakdown products such as betalamic acid, neobetalins, and colorless or yellow derivatives ((Martinez *et al.,* 2024)).

Kinetic analyses of betalains from pitaya (red dragon fruit) peel reveal first order degradation with temperature; stability is acceptable at or below 60°C, but degradation accelerates significantly at temperatures above 80°C, especially for betacyanins (Chew *et al.,* 2019). To mitigate these limitations, recent studies have explored encapsulation and co-pigmentation strategies: for instance, ionic gelation with calcium alginate or liposomal encapsulation greatly enhance heat and light tolerance, while co-pigmentation with black carrot anthocyanins significantly increases half life and reduces degradation under thermal and light stress (Martinez *et al.,* 2024). Different bioactivities have been related to betalains such as antioxidant, antibacterial, antifungal, antiprotozoal, and anticancer properties (Sadowska-Bartosz and Bartosz, 2021).

Chlorophylls

Among all pigments present in nature, chlorophylls are most abundant in the plant kingdom, responsible for the green color; however, they have been the least studied as natural colorants (Rodriguez-Amaya, 2016). Among different Chlorophylls, a, b, c, d and e; chlorophyll a and b are the most found in several plant tissues and in green fruits. Their vibrant green color and antioxidant properties have prompted their use in clean-label food products, cosmetics, and nutraceuticals (Yang *et al.,* 2025). However, chlorophylls exhibit significant sensitivity to environmental conditions. They degrade rapidly under acidic pH, elevated temperatures, light exposure, and enzymatic activity—environments that commonly arise during food processing and storage. Acidic conditions and heat can displace the central magnesium, forming olive-brown pheophytin, while enzymatic action by chlorophyllase promotes breakdown into chlorophyllides (Pandiselvam *et al.,* 2023). Light and oxidative stress further exacerbate degradation, leading to fading and color loss (Tharuka and Baojun, 2024). Chlorophylls continue to be highly valued as natural green colorants, not only for their vibrant aesthetic contribution to food and cosmetic products but also for their functional and bioactive properties (Ebrahimi *et al.,* 2023). These include antioxidant activity, potential anti-inflammatory effects, and the ability to support detoxification processes**,** **anti-cancer**, and **anti-obesity,** all of which contribute to their growing appeal in health-conscious formulations (Masyita *et al.,* 2025).

Extraction and Stabilization process

The extraction and stabilization of natural pigments such as chlorophylls, anthocyanins, carotenoids, and betalains are essential for their effective application in food, pharmaceutical, and nutraceutical products (Nabi *et al.,* 2023). Conventional methods rely mainly on solvent extraction using ethanol, methanol, acetone, hexane, or water, depending on pigment solubility (Mungwari *et al.,* 2025). Chlorophylls and carotenoids, being lipid-soluble, are typically extracted with organic solvents such as acetone or hexane, while anthocyanins and betalains, which are water-soluble, are efficiently extracted with aqueous or hydroalcoholic solvents (Jiang et al. 2024). However, these methods often pose challenges such as solvent residues, low selectivity, and susceptibility of pigments to degradation.

To overcome these limitations, advanced extraction techniques have been developed, including ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction with CO_2 (Bhadange *et al.,* 2024). These approaches improve efficiency, reduce solvent use, and minimize thermal damage, thereby preserving pigment integrity and bioactivity. Once extracted, stabilization becomes critical since all natural pigments are sensitive to environmental stressors such as heat, light, oxygen, and pH. A variety of stabilization strategies are employed across pigment classes. Copigmentation with organic acids or polyphenols enhances anthocyanin stability by strengthening pigment–cofactor complexes, thereby improving color intensity and resistance to degradation. Microencapsulation using carriers such as maltodextrin, gums, or biopolymers protects chlorophylls, carotenoids, and betalains from oxidation and environmental stress, ensuring longer shelf-life (Laureanti *et al.,* 2023). The addition of natural antioxidants, such as ascorbic acid or tocopherols, further prevents oxidative degradation and enhances pigment stability during storage.

Specific modifications are also applied for certain pigments, such as conversion of chlorophyll into more stable chlorophyllins, or emulsification of carotenoids to improve dispersibility and protect against oxidative loss. Together, the integration of conventional and advanced extraction techniques with tailored stabilization strategies enables the recovery and preservation of these bioactive pigments (Mungwari *et al.,* 2025). Such approaches not only retain their vivid natural colors but also maintain their functional properties, including antioxidant, anti-inflammatory, and health-promoting effects. These advancements significantly expand the industrial potential of chlorophylls, anthocyanins, carotenoids, and betalains as sustainable and safe alternatives to synthetic colorants in modern food and nutraceutical systems.

Conventional methods

Conventional methods for pigment extraction largely rely on solvent-based techniques using ethanol, methanol, acetone, hexane, or water, depending on the solubility of the target compound (Lee *et al.,* 2024). For instance, anthocyanins and betalains, being water-soluble, are commonly extracted with aqueous or hydroalcoholic solutions, while lipid-soluble pigments such as chlorophylls and carotenoids are typically extracted using organic solvents like ethanol, acetone, or hexane (Taghavi *et al.,* 2023). These methods are simple, cost-effective, and widely applied in both research and industrial settings, making them the most established approach for natural pigment recovery. However, solvent extraction has limitations, including potential solvent residues, pigment degradation under heat or light, and relatively low selectivity, which can lead to co-extraction of unwanted compounds (Shawky *et al.,* 2025). Despite these drawbacks, conventional solvent extraction remains a baseline technique due to its accessibility, ease of operation, and suitability for initial screening or large-scale pigment isolation when carefully optimized.

Advanced extraction techniques for natural pigments

Advanced extraction techniques have been developed to overcome the limitations of conventional solvent-based methods and to ensure higher efficiency, selectivity, and preservation of pigment quality. Ultrasound-assisted extraction (UAE) employs acoustic cavitation to disrupt plant cell walls, enhancing solvent penetration and facilitating the release of pigments such as anthocyanins, chlorophylls, and carotenoids, while reducing extraction time and solvent use (Das *et al.,* 2022). Supercritical fluid extraction (SFE), particularly with supercritical carbon dioxide (CO_2), is highly effective for lipid-soluble pigments like carotenoids and chlorophylls, offering the advantage of being solvent-free, environmentally friendly, and capable of producing high-purity extracts (Morcelli et al. 2021). Microwave-assisted extraction (MAE) utilizes microwave energy to rapidly heat plant tissues and solvents, causing cell rupture and accelerating pigment release with minimal thermal degradation when carefully controlled (Lozano Pérez *et al.,* 2024).

Collectively, these advanced techniques not only improve yield and stability but also align with sustainable and green chemistry practices, making them increasingly attractive for industrial applications in food, nutraceutical, and pharmaceutical sectors. Advanced extraction techniques represent a significant shift toward greener, more sustainable practices in natural pigment recovery (Putra *et al.,* 2023). Compared to conventional solvent-based methods, they offer enhanced selectivity, shorter processing times, and reduced solvent consumption, which are particularly important for preserving the integrity of heat and light-sensitive pigments such as anthocyanins and betalains (Irianto *et al.,* 2025). Despite their benefits, advanced techniques also present certain limitations that must be addressed before large-scale industrial adoption.

Ultrasound and microwave-assisted extractions may involve high equipment costs and require careful optimization to prevent thermal degradation of sensitive compounds (Niari et al. 2025). Supercritical CO_2 extraction, although highly efficient for non-polar pigments, often requires co-solvents such as ethanol for effective recovery of polar compounds, which can increase complexity and cost (Niari et al. 2025). Furthermore, scalability remains a challenge, as the energy requirements and equipment design for continuous large-scale processing are still under development. Nevertheless, the integration of advanced extraction techniques with emerging technologies holds great promise for improving both the efficiency and sustainability of pigment recovery.

Stabilization approaches for natural pigments

Natural pigments, including anthocyanins, carotenoids, betalains, and chlorophylls, are widely valued in food, pharmaceutical, and cosmetic applications for their vibrant colors and health-promoting properties (Nabi et al. 2023). One widely studied method is co-pigmentation, in which pigments form reversible complexes with organic acids (e.g., citric, tartaric, or caffeic acid) or polyphenols such as flavonoids, tannins, or phenolic acids (Enaru *et al.,* 2021). This molecular interaction stabilizes the chromophore by preventing hydration and structural breakdown, thereby enhancing both the intensity and

Table 2. Extraction strategies for plant-derived pigments: Principles, applications, and limitations

Extraction Method	Principle	Pigments Targeted	Advantages	Limitations	References
Conventional Solvent Extraction	Dissolution of pigments in solvents (ethanol, methanol, acetone, hexane, or water) based on solubility	Water-soluble: Anthocyanins, Betalains; Lipid-soluble: Chlorophylls, Carotenoids	Simple, low-cost, widely available, suitable for lab-scale and large-scale processes	Low selectivity, potential solvent residues, thermal/light degradation, co-extraction of unwanted compounds	Mungwari *et al.*. (2025)
Ultrasound-Assisted Extraction (UAE)	Acoustic cavitation disrupts plant cells, enhancing solvent penetration and pigment release	Anthocyanins, Chlorophylls, Carotenoids	Higher yield, shorter time, lower solvent use, operates at low temperatures (protects heat-sensitive pigments)	Equipment cost, requires optimization to prevent pigment degradation	Das et al. (2022); Bhadange *et al.* (2024)
Microwave-Assisted Extraction (MAE)	Microwave energy rapidly heats solvent and plant matrix, causing cell rupture and pigment release	Anthocyanins, Carotenoids, Chlorophylls	Fast extraction, high efficiency, reduced solvent usage, good for heat-stable pigments	Risk of thermal degradation if not controlled, scalability challenges	Shawky *et al.* (2025)
Supercritical Fluid Extraction (SFE, CO_2)	Supercritical CO_2 acts as a solvent; often combined with co-solvents like ethanol for polar pigments	Carotenoids, Chlorophylls (lipid-soluble pigments)	Solvent-free, eco-friendly, high purity, good for sensitive bioactives	High equipment cost, less effective for polar pigments without co-solvent, complex operation.	Morcelli *et al.*(2021)
Hybrid Approaches (e.g., UAE + MAE, Enzyme + SFE)	Combination of physical/biochemical processes for enhanced pigment release and preservation	Applicable to all pigment classes (tailored methods)	Maximizes yield and stability, reduces processing time/energy use, more sustainable	Still in research stage, limited industrial-scale application, high setup cost.	Bhadange *et al.* (2024)

persistence of color (Yang *et al.,* 2025). Co-pigmentation is particularly effective for anthocyanins, which otherwise exhibit rapid fading in food systems (Yang *et al.,* 2025). For example, the addition of phenolic compounds has been shown to improve anthocyanin stability in berry-based beverages, extending both color retention and antioxidant activity (Estupiñan *et al.,* 2011). Another important technique is micro-encapsulation, where pigments are entrapped within a protective matrix, typically using wall materials such as maltodextrin, gum arabic, cyclodextrins, or biopolymers (Laureanti *et al.,* 2023). Encapsulation provides a physical barrier against oxygen, heat, and UV light, thereby preventing oxidation and pigment breakdown (Xu *et al.,* 2024). For instance, carotenoids encapsulated in maltodextrin-based carriers demonstrate enhanced stability and shelf-life in fortified food products (Sereti *et al.,* 2025). Spray-drying and freeze-drying are common encapsulation methods that convert liquid pigment extracts into stable powders with improved handling, dispersibility, and resistance to environmental stressors (Júnior *et al.,* 2023). More advanced encapsulation systems, including nanoemulsions and liposome-based carriers, are being developed to further improve pigment bioavailability and controlled release in functional foods and nutraceuticals (Zhu *et al.,* 2025). A complementary stabilization strategy involves the addition of antioxidants, which act as protective agents against oxidative damage. Natural antioxidants such as ascorbic acid, tocopherols (vitamin E), rosemary extract, and polyphenolic compounds are commonly incorporated into pigment formulations to reduce the formation of reactive oxygen species and free radicals that cause degradation (Gulcin, 2025). For example, the co-application of ascorbic acid with carotenoids or betalains has been shown to significantly reduce color fading during storage. Thus, stabilization strategies remain a cornerstone in advancing the use of natural pigments as safe, sustainable, and effective alternatives to synthetic colorants.

Applications in Food Industry

The use of natural colorant by food industry has been increasing due to their multifaceted beneficial effects on food preservation, sensory characterization, health association (Albuquerque et al.2020).

Bakery products

Natural colorants derived from fruits are increasingly being incorporated into bakery products to enhance visual appeal, improve nutritional value, and meet clean-label demands. These colorants not only provide attractive crust and crumb coloration but also impart potential health benefits, particularly due to their antioxidant properties.

Table 3. Application of natural colorants in common food products

Natural pigments	Food products
Anthocyanins	Bakery, frozen desserts, dairy products, beverages, smoothies, juices, and carbonated drinks
Carotenoids	Meat products, butter and vegetable oils, pasta, cheese,
Betalains	Yoghurt, cake mix, gummies, candies, jellies, ice cream, beverages, health drinks
Chlorophylls	Mix beverages, puddings, ice cream, cakes, muffins, bread

Applications span a range of bakery items, including bread, cakes, cookies, and biscuits. Common examples include turmeric for yellow hues in bread and cakes, and beet juice for imparting red tones to cookies, with minimal sensory disruption. Purified pigments and plant extracts have been shown to enhance the nutritional profile of bakery products without significantly affecting taste or texture. For instance, tomato waste, rich in lycopene, was successfully incorporated into cakes and cookies, contributing to increased product volume, enhanced DPPH radical scavenging activity, and brighter crumb color.

However, only formulations with 5% lycopene content showed a significant volume increase compared to controls (Eletr *et al.,* 2017). Further innovations include the use of jabuticaba (*Myrciaria jaboticaba*) peel extract, rich in anthocyanins, as a natural colorant for French macarons. Heat- and ultrasound-assisted extraction optimized pigment yield and stability, resulting in vibrant coloration without adverse sensory effects (Albuquerque *et al.,* 2020). Additionally, flours made from purple-fleshed sweet potatoes have been utilized to color biscuits, offering both appealing coloration and added health benefits due to their high anthocyanin content (Aziz *et al.,* 2018). Beyond aesthetics, many of these pigments (e.g., betalains, lycopene) confer antioxidant and even antimicrobial benefits, adding functional value to bakery products (Novais *et al.,* 2020)

Beverages

Colour is a critical sensory attribute in beverages, significantly influencing consumer perception, product appeal, and overall acceptability. During food processing, particularly thermal treatments, pH adjustments, and exposure to light significant colour degradation can occur. Therefore, colorants are often added to restore or enhance visual appeal. While synthetic dyes have been used for long for this purpose, increasing consumer awareness and regulatory pressure which have shifted the beverage industry toward natural, plant-derived colourants that offer both functionality and cleaner labels (FDA, 2025).

Natural colourants are now applied across a wide range of beverages, including fruit juices, flavoured waters, sports drinks, dairy-based beverages, and carbonated drinks. Among the most widely used natural sources are beetroot, turmeric, spirulina, sweet potato, marigold, jabuticaba skins, and gardenia, each offering pigments with distinct hues and stability profiles.

For example, beet juice, rich in betalains, is frequently used to impart red tones in fruit-based beverages due to its water solubility and relatively broad pH stability. Similarly, spirulina extract, containing phycocyanin, is a popular natural blue pigment used in sports and energy drinks (Petruzzi et al. 2017). The yellow colour in beverages is represented by carotenoids (bixin, lutein, and crocin), flavonoids (carthamin), and curcuminoids (curcumin). Riboflavin also imparts a yellow colour and serves as a vitamin, adding nutritional value. A comprehensive study by Cerreti et al. (2020) evaluated several natural yellow pigments including annatto (*Bixa orellana*), gardenia yellow (*Gardenia jasminoides*), lutein (*Tagetes erecta*), curcumin (*Curcuma longa*), and carthamin (*Carthamus tinctorius*) in beverage model systems, highlighting their varied stability under different storage and pH conditions.

Anthocyanins, abundant in many fruits, are also widely used, though they present challenges due to their pH sensitivity. Gomes Rocha et al. (2019) formulated whey-based protein beverages incorporating anthocyanin-rich extracts from jabuticaba skins. The study identified delphinidin-3-O-glucoside and cyanidin-3-glucoside (C3G) in the extract. Higher whey concentrations (4.0–6.0% w/v) yielded beverages with a stable and visually dominant red hue, though differences in chroma and redness (a*) were minimal, suggesting good pigment integration in the matrix. In another case, Tensiska et al. (2017) developed jelly beverages using encapsulated anthocyanins from purple sweet potato cv. Ayamurasaki. The encapsulated pigments retained high anthocyanin content and redness for up to 30 days of storage, emphasizing the benefits of encapsulation techniques for maintaining colour stability in beverage applications. Importantly, beverages have become a strategic platform to enhance fruit and vegetable intake, which remains below recommended levels in many populations. Fortification with natural colourants often co-delivering phytonutrients serves both functional and aesthetic purposes (Petruzzi et al. 2017). Additionally, natural colourants help in preventing colour loss during pasteurization and other thermal processes, preserving both appearance and perceived freshness. Recent innovations, such as microencapsulation, copigmentation, and protein-pigment hybrid systems, are being applied to improve the heat, light, and pH stability of natural pigments in beverages (Magalhaes et al.2024).

Dairy Products

Natural colorants play a pivotal role in enhancing the visual appeal and consistency of dairy products including yogurt, ice cream, and cheese. They can compensate for colour loss during processing or storage, intensify subtle hues, standardize batch appearance, and improve consumer acceptability (Martins et al. 2016). The complexity of dairy matrices, however, can introduce challenges such as color–texture interactions that must be carefully managed during formulation. Recent studies have advanced the use of natural pigments in the dairy sector. In yogurt-like soy models, betalain extracts from red beetroot and Opuntia, as well as anthocyanin extracts from hibiscus and red radish, were stabilized using nano-encapsulation in soy-lecithin systems.

Both encapsulated and non-encapsulated forms showed satisfactory colour retention over 21 days at 4°C, with the red radish extract imparting the most appealing pink hue, and encapsulated Opuntia delivering health benefits without compromising color quality (Dias et al. 2020). Emerging "blue" colourants from microalgae offer exciting opportunities for neutral-pH dairy products like ice cream. Phycocyanin from Spirulina demonstrated impressive color stability, with ΔE^* values significantly lower than controls after 182 days of storage, making it a promising natural blue shade (Hernández et al.2022). Ice creams are popular dairy or dairy-like frozen desserts at neutral pH, sometimes formulated with milk fat, milk proteins, fruits, and flavours. The most common colourants used in ice cream are curcumin (intense lemon shade), Carthamus (bright yellow with slight greenish shade),-carotenes (orange-yellow hues, preferred for vanilla-flavored products), annatto (yellow shades), beetroot (pink-red color), lycopene (red color), and chlorophylls or copper-chlorophylls (yellowish-green and bright green colors, respectively) (Krahl et al. 2016).

Aqueous and ethanolic/methanolic betacyanin extracts from red pitahaya (Hylocereus polyrhizus) were applied as a colourant in ice creams and found that betacyanin-supplemented ice creams exhibited the highest free radical scavenging activities (DPPH: 50–57%) (Gengatharan et al. 2020). Using colourants in cheese is also a common practice. Natural colourants are preferred mainly for their health benefits, providing additional properties such as antioxidant, an timicrobial, and surface-active activity to coloured cheese products (Rodriguez-Amaya, 2016). The main colourant used in cheese and butter is annatto, but for the cheese industry, the colorant is mainly composed of norbixin, responsible for imparting yellow/orange colour to cheddar cheese (Carter et al. 2017). Other usual colourants used in cheese are carminic acid and anthocyanin, paprika oleoresin, chlorophylls and chlorophyllin, and curcumin (Sharma et al. 2020).

Other products

Natural colourants are widely used in pasta products to produce new ways of coloured pasta, especially the popular "vegetable-added pasta". Dalla Costa et al. (2016) used 20% carrot flour as a substitute for-carotene for commercial dry wheat pasta and found 307% higher levels of carotenoids, 132% increased antioxidant capacity, and 608% higher total fiber compared to no carrot-added pasta. Saffron enrichment (0.2–0.4% w/w) of wheat flour pasta (Armellini et al. 2018) decreased L* but increased a* and b* values, higher antioxidant capacity compared to commercial pasta, and no textural parameters were affected. Cerezal Mezquita et al. (2019). Saffron and beetroot aqueous extracts were encapsulated in maltodextrin, gum arabic, modified starch, and chitosan and incorporated in a chewing gum system (Chranioti et al. 2015). Fruit-based extracts like Clitoria ternatea and freeze-dried blueberry juice have been shown to enhance both visual appeal and antioxidant content in gummy

Table 4: Challenges in using fruit-derived colorants in the food industry

Challenge	Details	Possible Solutions	Impact on Industry	Examples	References
Stability issues	Natural pigments (e.g. anthocyanins, carotenoids, betalains) are sensitive to pH, heat, light, and oxygen, leading to colour degradation during processing and storage	Encapsulation (spray-drying, liposomes, nanoencapsulation) - use of antioxidants like ascorbic acid - pH control through buffering agents	Inconsistent or fading color can lead to reduced shelf appeal, consumer distrust, and product reformulations	Purple grape anthocyanins fading in yogurt; encapsulated beet extract used in gummy candies to enhance stability	Novais *et al.* (2022)
Low yield and high cost	Fruit pigments are often present in low concentrations, and extraction is energy- and solvent-intensive, increasing cost	Valorization of fruit waste (e.g., peels, pomace) - Efficient extraction technologies like ultrasound-assisted extraction - cultivar selection for high pigment yield	Higher costs may limit use to premium products, reducing competitiveness with synthetic colorants	Pomegranate peel used for anthocyanin extraction in beverages; use of carrot pomace for natural orange coloring	Rodríguez-Mena *et al.* (2023)
Sensory interference	Some pigments impart undesirable flavors, odors, or astringency, especially in mildly flavored or dairy products	Use of purified concentrates - flavor masking agents - Formulation with complementary flavors	Alters taste perception and may require costly reformulation, affecting product development timelines	Elderberry anthocyanins adding bitterness to soft drinks; purified blueberry extract used in yogurt to avoid off-flavors	Reshna *et al.* (2023)
Regulatory hurdles	Approval and use of natural colorants vary by country. Limited safety data and lack of harmonized global regulations can restrict market access	Conduct toxicological evaluations - standardized documentation for food-grade certifications - Proactive engagement with food safety authorities	Can delay product launch, create trade barriers, and require multiple regional formulations	Anthocyanin use restricted in some Asian countries; companies like GNT Group navigating EU/US regulations for EXBERRY® colors	Varghese and Ramamoorthy (2023)
batch Variability	Natural pigments can show variability in color intensity due to differences in harvest time, growing conditions, or storage	Implement standardized sourcing and processing protocols - use of blending to achieve colour consistency	Inconsistent product color leads to branding issues and customer dissatisfaction	Seasonal variation in hibiscus extract leading to color shift in iced teas; blend standardization used by beverage companies	Ghosh *et al.* (2022)
Limited shelf life	Natural colorants often have a shorter shelf life compared to synthetic dyes due to oxidation or microbial degradation	Use of natural preservatives - vacuum-sealed or inert gas packaging - cold chain logistics	Limits distribution range and increases logistics and storage costs	Beet extract needing cold storage; microencapsulated fruit pigments with improved shelf life used in snack coatings	Dey and Nagababu (2022)

candies compared to conventional versions (Tarahi et al. 2024).

Recent work on "functional gummies" shows green-extracted berry anthocyanins withstand gelatin/pectin matrices and typical shelf conditions while elevating antioxidant capacity, supporting clean-label claims (Nima et al. 2024). In jelly candies, grape-juice anthocyanins survive cooking and storage with ~41% retention, and products remain sensorially accepted—evidence that real fruit pigments can deliver stable hue and consumer appeal (Yara et al. 2022). Betalains, though vivid, are heat- and pH-sensitive; encapsulating pitaya/dragon-fruit or prickly-pear pigments in maltodextrin/gum arabic or nanoliposomes markedly improves resistance to degradation in confectionery systems and enables brighter, longer-lasting reds/purples in gummies (Nurhadi et al. 2024)

Challenges and Limitations

While fruit-derived colourants offer a natural and health-conscious alternative to synthetic dyes, their adoption in large-scale food production presents several challenges and limitations (Novais et al. 2022). These obstacles span technical, economic, sensory, and regulatory domains and must be addressed for broader and more reliable use in the food industry.

CONCLUSION

Fruits remain one of the most underexploited yet powerful reservoirs of natural pigments. The pigments they contain are anthocyanins, carotenoids, betalains, and chlorophylls, serve as antioxidants, anti-inflammatory and disease-preventive compounds that can be transformed into healthy foods. Fruits represent a rich, renewable source of natural colorants with immense potential to replace synthetic dyes in food applications. Despite certain limitations, advancements in extraction technology and formulation strategies are making fruit-based colourants increasingly viable. Future research should focus on improving stability, reducing production costs, and ensuring regulatory compliance to fully harness the benefits of fruit-derived pigments in the global food industry.

REFERENCES

Albuquerque B R, Pinela J, Barros L, Oliveira M B P P, Ferreira I C F R 2020. Anthocyanin-rich extract of jabuticabaepicarp as a natural colorant: Optimization of heat- and ultrasound-assisted extractions and application in a bakery product. *Food Chemistry* **316:** 126364

Armellini R, Peinado I, Pittia P, Scampicchio M, Heredia A, Andres A 2018. Effect of saffron (*Crocus sativus* L.) enrichment on antioxidant and sensorial properties of wheat flour pasta. *Food Chemistry* **254**: 55–63.

Aziz A A, Padzil A M, Muhamad I I 2018. Effect of incorporating purple-fleshed sweet potato in biscuit on antioxidant content antioxidant capacity and colour characteristics. *Malaysian Journal of Analytical Sciences* **22(4):** 667-75.

Bhadange Y A, Carpenter J, Saharan V K 2024. A comprehensive review on advanced extraction techniques for retrieving bioactive components from natural sources. *ACS omega* **9(29)**:31274-31297.https://doi.org/10.1021/acsomega.4c02718

Carter B G, Park C W, Drake M A 2017. Sensitive detection of norbixin in dried dairy ingredients at concentrations of less than 1 part per billion. *Journal of Dairy Science* **100(11):** 8754-58.

Cazon P, Silva A S 2024. Natural pigments from food wastes: New approaches for the extraction and encapsulation. *Current Opinion in Green and Sustainable Chemistry* **47**:100929.https://doi.org/10.1016/j.cogsc.2024.100929

CerezalMezquita P, Morales J, Palma J, Ruiz M D C, Jáuregui M 2019. Stability of Lutein Obtained from Muriellopsissp biomass and used as a natural colorant and antioxidant in a mayonnaise-like dressing sauce. *CyTA-Journal of Food* **17(1):** 517-26.

Cerreti M, Liburdi K, Del Franco F, Esti M 2020. Heat and light stability of natural yellow colourants in model beverage systems. *Food Additives & Contaminants: Part A* **37(6):** 905-15.

Chew Y M, Hung C H, King V A E 2019. Accelerated storage test of betalains extracted from the peel of pitaya (*Hylocereus cacti*) fruit. *Journal of food science and technology56*(3): 1595-1600.

Chranioti C, Nikoloudaki A, Tzia C 2015. Saffron and beetroot extracts encapsulated in maltodextrin, gum Arabic, modified starch and chitosan: Incorporation in a chewing gum system. *Carbohydrate polymers***127**: 252-63.

Crupi P, Faienza M F, Naeem M Y, Corbo F, Clodoveo M L, Muraglia, M 2023. Overview of the potential beneficial effects of carotenoids on consumer health and well-being. *Antioxidants***12(5)**:1069.

Dagnino-Leone J, Figueroa C P, Castañeda M L, Youlton A D, Vallejos-Almirall A, Agurto-Muñoz A, Agurto-Muñoz C 2022.Phycobiliproteins: Structural aspects, functional characteristics, and biotechnological perspectives. *Computational and Structural Biotechnology Journal* **20**:1506-1527.https://doi.org/10.1016/j.csbj.2022.02.016

Dalla Costa Porto A, Cruz SilveiraThys R, De Oliveira Rios A, HickmannFlôres S 2016. Carrot flour from minimally processed residue as substitute of β-carotene commercial in dry pasta prepared with common wheat (*Triticumaestivum*). *Journal of food quality* ***39*****(6)**:590-98.

Das P, Nayak P K, krishnanKesavan R 2022. Ultrasound assisted extraction of food colorants: Principle, mechanism, extraction technique and applications: A review on recent progress. *Food Chemistry Advances* **1:**100144.

DeyS, Nagababu B H 2022. Applications of food color and bio-preservatives in the food and its effect on the human health. *Food Chemistry Advances* **1**:100019. https://doi.org/10.1016/j.focha.2022.100019

Dias S, Castanheira E M, Fortes A G, Pereira D M, Gonçalves M S T 2020. Natural pigments of anthocyanin and betalain for coloring soy-based yogurt alternative. *Foods* **9(6):** 771.

Ebrahimi, P, Shokramraji Z, Tavakkoli S, Mihaylova D, Lante A 2023. Chlorophylls as natural bioactive compounds existing in food by-products: a critical review. *Plants* **12(7):**1533.doi: 10.3390/plants12071533

Eletr A A, Siliha H A E, Elshorbagy G A, Galal G A 2017. Evaluation of lycopene extracted from tomato processing waste as a natural antioxidant in some bakery products. *Zagazig Journal of Agricultural Research* **44(4)**:1389-1401.

Enaru B, Drețcanu G, Pop T D, Stănilă A, Diaconeasa Z 2021. Anthocyanins: Factors affecting their stability and degradation. *Antioxidants* **10(12)**:1967.

Estupiñan D C, Schwartz S J, Garzón G A 2011. Antioxidant activity, total phenolics content, anthocyanin, and color stability of isotonic model beverages colored with Andes berry (RubusglaucusBenth) anthocyanin powder. *Journal of food science* **76(1):**S26-S34.https://doi.org/10.1111/j.1750-3841.2010.01935.x

FDA (2024–2025). *New approvals for natural colorants in foods and beverages*. www.fda.gov

Fernández-López J A, Fernández-Lledó V, Angosto J M 2020. New insights into red plant pigments: More than just natural colorants. RSC Adv **10:**24669–24682. https://doi.org/10.1039/d0ra03514a

Gengatharan A, Dykes G, Choo W S 2021. Betacyanins from Hylocereuspolyrhizus: pectinase-assisted extraction and application as a natural food colourant in ice cream. *Journal of Food Science and Technology* **58(4):**1401-10.

Ghosh S, Sarkar T, Das A, Chakraborty R 2022. Natural colorants from plant pigments and their encapsulation: An emerging window for the food industry. *Lwt* **153:**112527. https://doi.org/10.1016/j.lwt.2021.112527

Gulcin İ 2025. Antioxidants: a comprehensive review. *Archives of Toxicology* 1-105.

Hernández H, Nunes M C, Prista C, Raymundo A 2022. Innovative and healthier dairy products through the addition of microalgae: a review. *Foods* **11(5)**:755. https://doi.org/10.3390/foods11050755

Hidalgo A, Brandolini A, Čanadanović-Brunet J, Ćetković G, Šaponjac V T 2018. Microencapsulates and extracts from red beetroot pomace modify antioxidant capacity, heat damage and colour of pseudocereals-enriched einkorn water biscuits. *Food chemistry* **268:**40-48.

Irianto I, Putra N R, Yustisia Y, Abdullah S, Syafruddin S, Paesal P, Airlangga B 2025. Green technologies in food colorant extraction: a comprehensive review. *South African Journal of Chemical Engineering* **51(1)**: 22-34. https://doi.org/10.1016/j.sajce.2024.10.013

Jiang Y Ye J Hu Y, Zhang J Li W, Zhou X Hu Y 2024. Extraction and synthesis of typical carotenoids: lycopene, β-carotene, and astaxanthin. *Molecules* **29(19):**4549. https://doi.org/10.3390/molecules29194549

Júnior da S, Edson M, Araújo, et al (2023) Microencapsulation by spray-drying and freeze-drying of extract of phenolic compounds obtained from ciriguela peel. Sci Rep **13**:1–16. https://doi.org/10.1038/s41598-023-40390-4

Khoo H E, Azlan A, Tang S T, Lim S M 2017. Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. *Food & nutrition research* **61(1)**: 1361779.

Krahl T, Fuhrmann H, Dimassi S 2016. Ice Cream. In Handbook on Natural Pigments in Food and Beverages; Carle, R., Schweiggert, R.M., Eds.; Elsevier: Amsterdam, The Netherland, pp: 197–207.

Laureanti E J G, Paiva T S, de Matos Jorge L M, Jorge R M M 2023. Microencapsulation of bioactive compound extracts using maltodextrin and gum arabic by spray and freeze-drying techniques. *International journal of biological macromolecules* **253:**126969.https://doi.org/10.1016/j.ijbiomac.2023.126969

Lee J E, Jayakody J T M, Kim J I, Jeong J W, Choi K M, Kim T S, Ryu B 2024. The influence of solvent choice on the extraction of bioactive compounds from Asteraceae: A comparative review. *Foods* **13(19)**:3151.https://doi.org/10.3390/foods13193151

Li J. Ding, X Zheng, J Liu D Guo, F Liu H, Zhang Y 2014. Determination of synthetic dyes in bean and meat products by liquid chromatography with tandem mass spectrometry. *Journal of separation science* **37(17):**2439-2445.https://doi.org/10.1002/ jssc.201400349

Lozano Pérez A S, Lozada Castro J J, Guerrero Fajardo C A 2024. Application of microwave energy to biomass: a comprehensive review of microwave-assisted technologies, optimization parameters, and the strengths and weaknesses. *Journal of Manufacturing and Materials Processing* **8(3):** 121.https://doi.org/10.3390/jmmp8030121

Magalhães D, Gonçalves R, Rodrigues C V, Rocha H R, Pintado M, Coelho M C 2024. Natural pigments recovery from food by-products: Health benefits towards the food industry. *Foods* **13(14)**: 2276.https://doi.org/10.3390/foods13142276

Martinez, R. M., Melo, C. P., Pinto, I. C., Mendes-Pierotti, S., Vignoli, J. A., Verri, W. A., &Casagrande, R. (2024). Betalains: A narrative review on pharmacological mechanisms supporting the nutraceutical potential towards health benefits. *Foods*, **13(23)**, 3909. https://doi.org/10.3390/foods1323390

Martins N, Roriz C L, Morales P, Barros L, Ferreira I C 2016. Food colorants: Challenges, opportunities and current desires of agro-industries to ensure consumer expectations and regulatory practices. *Trends in food science & technology* **52:**1-15.

Masyita A, Hardinasint G, Astuti A D , Firdayani F, Mayasar D, Hori A, Kuraishi T 2025. Natural pigments: innovative extraction technologies and their potential application in health and food industries. *Frontiers in Pharmacology* **15:**1507108. doi: 10.3389/fphar.2024.1507108.

Mattioli R, Francioso A, Mosca L, Silva P 2020. Anthocyanins: A comprehensive review of their chemical properties and health effects on cardiovascular and neurodegenerative diseases. *Molecules* ***25*(17)**: 3809. https://doi.org/10.3390/molecules25173809

. Mazza G 2018. Anthocyanins in Fruits, Vegetables, and Grains; Routledge: Boca Raton, FL, USA.

Morcelli A, Cassel E, Vargas R, Rech R, Marcílio N 2021. Supercritical fluid (CO2+ ethanol) extraction of chlorophylls and carotenoids from Chlorella sorokiniana: COSMO-SAC assisted prediction of properties and experimental approach. *Journal of CO2 Utilization* **51:**101649. https://doi.org/10.1016/j.jcou.2021.101649

Mungwari C P, King'ondu C K, Sigauke P, Obadele B A 2025. Conventional and modern techniques for bioactive compounds recovery from plants. *Scientific African* **27:** e02509. https://doi.org/10.1016/j.sciaf.2024.e02509

Nagarajan J, Ramanan R N, Raghunandan M E, Galanakis C M, Krishnamurthy N P 2017. Carotenoids. In: Galanakis CM, editor. Nutraceutical and Functional Food Components: Effects of Innovative Processing Techniques. Cambridge, Massachusetts: *Academic Press;*. pp. **259-296**: ISBN 9780128052570

Niari S, Hamdami N, Dalvi-Isfahan M, Le-Bail A 2025. Ultrasound and microwave assisted extraction of acorn oil (Quercusbrantii): Optimization and characterization. *Appl Food Res* **5**:100706. https://doi.org/10.1016/j.afres.2025.100706

Nieto G 2020. Anthocyanins: Health benefits and potential use as functional ingredient: A Review. *Anthocyanins. Antioxidant properties, sources and health benefits* 1-27.

NimaMohammadi, Franchin M, Pressete C G, Antunes L M G, Granato D 2024. Green recovery and application of berry anthocyanins in functional gummies: Stability study, plasma and cellular antioxidant and anti-inflammatory activity. *Food Research International* **196**:115128 ttps://doi.org/10.1016/j.foodres.2024.115128.

Novais C, Molina A K, Abreu R M, Santo-Buelga C, Ferreira I C, Pereira C, Barros L 2022. Natural food colorants and preservatives: A review, a demand, and a challenge. *Journal of agricultural and food chemistry* **70(9)**:2789-2805. https://doi.org/10.1021/acs.jafc.1c07533

. Ntrallou K, Gika H, Tsochatzis E 2020. Analytical and sample preparation techniques for the determination of food colorants in food matrices. *Foods* **9(1)**:58. https://doi.org/10.3390/foods9010058.

Nurhadi B, Qonit M A H, Mubarok S, Saputra R A 2024. Enhancing betacyanin stability: Comparison of dragon fruit *(Hylocereus polyrhizus*) pulp and peel powders through encapsulation technology during storage. *Food Science & Nutrition,* **12(5):**3251-3264. doi: 10.1002/fsn3.3992. PMID: 38726450; PMCID: PMC11077181.

Okafor S N, Obonga W, Ezeokonkwo M A, Nurudeen J, Orovwigho U, Ahiabuike J2016. Assessment of the health implications of synthetic and natural food Colourants–A critical review. *Pharmaceutical and Biosciences Journal* **1-11**

Pandiselvam R, Mitharwal S, Rani P, Shanker M A, Kumar A, Aslam R, Khaneghah A M 2023. The influence of non-thermal technologies on color pigments of food materials: An updated review. *Current Research in Food Science* **6**:100529. doi: 10.1016/j.crfs.2023.100529. PMID: 37377494

Petruzzi L, Campaniello D, Speranza B, Corbo M R, Sinigaglia M, Bevilacqua A 2017. Thermal treatments for fruit and vegetable juices and beverages: A literature overview. *Comprehensive reviews in food science and food safety* **16(4):**668-691.

Putra N R, Yustisia Y, Heryanto R B, Asmaliyah A, Miswarti M, Rizkiyah D N, Rohman G A N 2023. Advancements and challenges in green extraction techniques for Indonesian natural products: A review. *South African journal of chemical engineering* **46(1):**88-98.

Rodriguez-Amaya, D B 2019.Natural food pigments and colorants. In *Bioactive molecules in food* pp. 867-901. Springer, Cham.

R Gopi S, Balakrishnan P 2022. Introduction to flavor and fragrance in food processing. In *Flavors and fragrances in food processing: Preparation and characterization methods* (pp. 1-19). American Chemical Society.

Reshna K R, Gopi S, Balakrishnan P 2023. Introduction tonce in Food Processing. ACS SympS Flavor and Fragraer **1433**:1–19. https://doi.org/10.1021/bk-2022-1433.ch001

Rodriguez-Amaya DB. Natural food pigments and colorants. *Curr. Opin. FoodSci.* **2016**(7): 20–26.

Rodriguez-Amaya D B, Esquivel P, Meléndez-Martínez, A J 2023. Comprehensive update on carotenoid colorants from plants and microalgae: Challenges and advances from research laboratories to industry. *Foods* **12(22):** 4080. https://doi.org/10.3390/foods12224080

Sadowska-Bartosz I, Bartosz G 2021. Biological properties and applications of betalains. *Molecules* ***26*(9):** 2520.

Saini R K, Y Keum 2018. Carotenoid extraction methods: A review of recent developments. Food Chemistry 240:90–103. doi: 10. 1016/j.foodchem.2017.07.099

Seret F, Alexandri M, Papapostolou H, Papadaki A, Kopsahelis N 2025. Recent progress in carotenoid encapsulation: Effects on storage stability, bioaccessibility and bioavailability for advanced innovative food applications. *Food Research International* 115861. https://doi.org/10.1016/j.foodres.2025.115861

Sharma P, Segat A, Kelly A L, Sheehan J J 2020. Colorants in cheese manufacture: Production, chemistry, interactions, and regulation. *Comprehensive Reviews in Food Science and Food Safety* **19(4)**: 1220-1242.

Shawky E, Nahar L, Nassief S M, Sarker S D, Ibrahim R S 2025. A comprehensive review of large-scale extraction and purification of food-derived bioactive phenolic components. *Process Biochemistr* **154**:196–219. https://doi.org/10.1016/j.procbio.2025.04.027*y*.

SidiqueBahar Q, Shahi N C, Richa R, Showkat S, Gupta A K, Naik B, Kumar V 2025. Insights into Extraction methods of pigments from Celosia cristata L. flower: A review. *Journal of Agriculture and Food Research* ***19***:101599. https://doi.org/10.1016/j.jafr.2024.101599

Sigurdson G T, Tang P, Giusti M M 2017. Natural colorants: Food colorants from natural sources. *Annual review of food science and technology* **8(1):** 261-280.

Spence C 2023. On the manipulation, and meaning (s), of color in food: A historical perspective. *Journal of Food Science* **88(S1):** A5-A20.

Sun T, Rao S, Zhou X Li L 2022. Plant carotenoids: recent advances and future perspectives. *Molecular Horticulture* **2(1):**3. https://doi.org/10.1186/s43897-022-00023-2

Taghavi T, Patel H, Rafie R 2023. Extraction solvents affect anthocyanin yield, color, and profile of strawberries. *Plants* **12(9):**1833. https://doi.org/10.3390/plants12091833

Tarahi M, Tahmouzi S, Kianiani M R, Ezzati S, Hedayati S, Niakousari M 2023. Current innovations in the development of functional gummy candies. *Foods* ***13*****(1):** 76. https://doi.org/10.3390/foods13010076

Tensiska T, Marta H, Cahyana Y, Amirah N S 2017. Application of encapsulated anthocyanin pigments from purple sweet potato (*Ipomoea batatas L.)* in jelly drink. *KnE Life Sciences* 482:493.

TharukaWijesekara, BaojunXu 2024. A critical review on the stability of natural food pigments and stabilization techniques. *Food Research International* ***179***:114011.

.Tiwari B K, O'Donnell C P, Cullen P J 2009. Effect of non thermal processing technologies on the anthocyanin content of fruit juices.*Trends in Food Science & Technology* ***20:*****(3-4)**: 137-145. https://doi.org/10.1016/j.tifs.2009.01.058

Varghese R, Ramamoorthy S 2023.Status of food colorants in India: conflicts and prospects. J fur Verbraucherschutz und Leb **18**:107–118. https://doi.org/10.1007/s00003-023-01427-y

Vidana Gamage G C, Lim Y Y, Choo W S 2021. Anthocyanins from Clitoria ternatea flower: Biosynthesis, extraction, stability, antioxidant activity, and applications. *Frontiers in Plant Science* ***12*****,:** 792303. 10.3389/fpls.2021.792303

Vinha A F, Rodrigues F, Nunes M A, Oliveira M B P 2018. Natural pigments and colorants in foods and beverages. In *Polyphenols: Properties, recovery, and applications* (pp. 363-391). Woodhead Publishing. ISBN 978-0-12-813572-3.

Wang Q J, Mielby L A, Junge J Y, Bertelsen A S, Kidmose U, Spence C, Byrne D V 2019. The role of intrinsic and extrinsic sensory factors in sweetness perception of food and beverages: a review, *Foods* **8 (6):** 211, https://doi.org/10.3390/ foods8060211.

Xu Y, Yan X, Zheng H, Li J, Wu X, Xu J, Du, C 2024. The application of encapsulation technology in the food Industry: Classifications, recent Advances, and perspectives. *Food Chemistry* X, **21:**101240. Xu, Y., Yan, X., Zheng, H., Li, J., Wu, X., Xu, J., ... & Du, C. (2024). The application of encapsulation technology in the food Industry: Classifications, recent Advances, and perspectives. *Food Chemistry: X*, *21*, 101240.

Yang Z Li F, Shen S, Wang X, Nihmot Ibrahim A, Zheng H, Zhang, Y 2025. Natural chlorophyll: a review of analysis methods, health benefits, and stabilization strategies. *Critical Reviews in Food Science and Nutrition* **65(16):**3069-3083. doi: 10.1080/10408398.2024.2356259

Yara Paula de Oliveira Nishiyama-Hortense, Maria Júlia de Paula Rossi, Victoria Diniz Shimizu-Marin, NatáliaSoaresJanzantti, Sergio Gómez-Alonso, Roberto Da-Silva, Ellen Silva Lago-Vanzela, 2022. Jelly candy enriched with BRS Violeta grape juice: Anthocyanin retention and sensory evaluation,FutureFoods,Volume 6:100179, https://doi.org/10.1016/j.fufo.2022.100179.

You Y, Han X, Guo J, Guo Y, Yin M, Liu G, Zhan J 2018. Cyanidin-3-glucoside attenuates high-fat and high-fructose diet-induced obesity by promoting the thermogenic capacity of brown adipose tissue. *Journal of Functional Foods* **41:** 62-71.

Zhang, J., Celli, G. B., & Brooks, M. S. (2019). Natural sources of anthocyanins. Exploiting Targeted Delivery for Improved Health; Su-Ling M, Celli G B, Eds; The Royal Society of Chemistry: London, UK , pp. 1–33.

Zhao B, Sun M, Li J, et al (2022a) Carotenoid Profiling of Yellow-Flesh Peach Fruit. Foods 11:. https://doi.org/10.3390/foods11121669

Zhao L, Liu Y, Zhao L, Wang Y 2022 Anthocyanin-based pH-sensitive smart packaging films for monitoring food freshness. *Journal of Agriculture and Food Research* 9:100340. https://doi.org/10.1016/j.jafr.2022.100340

Zhou W, Niu Y, Ding X, Zhao S, Li Y, Fan G, Liao K 2020. Analysis of carotenoid content and diversity in apricots (*Prunus armeniaca L.)* grown in China. *Food chemistry* **330:** 127223.

Zhu Y, He L, Xu M, et al 2025. A review on emerging carriers to improve bioaccessibility and bioavailability of astaxanthin. *J Futur Foods*. https://doi.org/10.1016/j.jfutfo.2025.05.005

Research Article

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Genetic variability and divergence studies to identify superior germplasm for wine grape (*Vitis* sp.) under semi-arid condition

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Abstract

The study was carried out to assess genetic variability of wine grape germplasm at ICAR- National Research Centre for Grapes, Pune during 2020–21, 2021-2022 and 2022- 2023. A total of 75 germplasm were evaluated for various yield-contributing traits. The combined data from three years revealed significant difference among all genotypes. The germplasm, Arka Hans, Arka Shyam, Clairette, Sauvignon Blanc, Muscat White, and Petit Syrah, performed well during all year. The pruning biomass demonstrated the highest phenotypic and genotypic of variability (68.39% and 68.28%, respectively). The bunch weight, berry weight, number of berries/bunch, seed weight, bunch width, berry length, compactness and peduncle length exhibited high heritability. Based on Mahalanobis D2 statistics, three cluster were identified with a majority of germplasm falling into cluster I group while cluster II showed highest intra-cluster similarity (3.86 %) that demonstrated maximum genetic diversity.

Key words: Wine grape, Genotypic, Heritability, Phenotypic, Genetic diversity.

The grapevine is the most important fruit crop in the world. Grape belongs to Vitaceae family which includes around 60 inter-fertile wild species of *Vitis* found across Asia, North America, and Europe under subtropical, mediterranean, and continental temperate climates. Among them, the most commonly cultivated and widely distributed species is the European grapevine (*Vitis vinifera* L.). Grape possesses diverse medicinal properties encompassing antioxidant, antidiabetic, cardioprotective, neuroprotective, anticarcinogenic, immunomodulatory, antiatherogenic, anti-obesity, antiaging, anti-infection, and antipyretic effect (Somkuwar *et al.*, 2023).

This extensive variation is largely a result of long history of grapevine cultivation and vegetative propagation which has allowed for the preservation of cultivars over the centuries (Laucou *et al.,* 2011). In the characterization of fruit trees, fruit traits have been primarily utilized as key morphological characteristics (Cunha *et al.,* 2007). India is most suitable region for diversity and cultivation of grape in the world. Keeping in view, studies were planned to assess the genetic diversity in wine genotypes for fruit yield and quality traits under semi-arid conditions.

MATERIALS AND METHODS

The study was carried out during 2020–21, 2021-2022 and 2022- 2023 at ICAR- National Research Centre for Grapes, Pune (18°32N and 73°51E). Pune has sub tropical and semi-arid climatic conditions with a temperature range of 7.2^{0}C minimum and 37.90^{0}C maximum during trial period. The annual average rainfall was between 600-700mm, with the majority of rains occurring during south-east monsoon period from June to August. The soil is heavy black with pH 7.75 and EC 0.46 dS m^{-1}. The seventy-five wine grape genotypes (*Vitis vinifera* L.) grafted on Dogridge rootstock planted in National Active Germplasm Site (NAGS) were selected. In this region, double pruning and single cropping pattern are being practiced.

The crop is harvested during March - April and foundation pruning is done leaving single bud on a last season matured cane after harvesting while second pruning is done during October. The level of forward pruning was normally kept to short canes or spurs leaving behind 4-7 buds depending upon the cane thickness in all varieties. All recommended cultural practices were followed. The observation were recorded on including pruning biomass (g), time of veraison (DAP), time of full bloom, time of verasion, bunch weight (g), berry weight (g), berry diameter and length (mm), bunch length and width (cm), number of berries/bunch, total soluble solid (°Brix), acidity (%), peduncle length (mm), bunch compactness, berry firmness (%), seed number/berry and seed weight. Qualitative traits of berry and bunch were recorded based on grape DUS guideline.

Five vines per replication were selected in each genotype and fifty samples were used for traits measurements. Quantitative characters were measured using suitable equipment such as digital caliper and precision weighing balance, while qualitative traits were measured based on rating, scoring, and coding according

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to the grape descriptor. Data on various growth, quality and yield parameters were recorded. The INDOSTAT software was utilized to conduct statistical analyses, including ANOVA, genotypic and phenotypic correlation, to explore the connections between yield and its contributing factors.

RESULTS AND DISCUSSION

All the genotypes differed significantly with in different attributes. The pooled average performance of wine genotypes for growth and yield related traits is given Table 1. The variety Champion recorded higher pruning biomass (2.64 kg) compared to Cayuga White (0.05kg). The difference in pruning weight among varieties may be attributed to difference in vigour of vine resulting from assimilation of carbohydrates due to more number of canes, number of leaves produced and other growth parameters results in more dry matter production. As highly vigorous varieties produce more pruning weight than less and medium vigorous varieties. The results aligns with these of Benz *et al.* (2006) and Jayalakshmi *et al.* (2019). Bud burst is a varietal character as it marks the beginning of seasonal growth and it is strongly influenced by temperature.

The variety Rosaria Bianca took 8.00 days, while Marquise took 14.33 days for 50% bud break. Days required for bud burst differ among grape varieties and depends on climatic conditions prevailing in that area. The time taken for bud burst is used as a criterion to classify grape varieties into early, mid, and late categories. This was in accordance with the findings of Gris *et al.* (2010). The variety Ribier and E29/3 (BC X TS) took more days (40.67) to 50 % flowering than Candaigua (30.67). Flowering is a unique characteristic that is influenced by multiple genes and environmental conditions play a crucial role. Warm, sunny weather encourages earlier flowering compared to rainy and cool conditions. Similar findings were reported by Anjanawe *et al.* (2020) for bud burst and flowering in wine grapes under Malwa Plateau conditions.

The maximum bunch weight was observed in Symphony (558.93 g), while minimum in Rose of Peru (35.66 g). The heavier the bunch, more will be the grape yield. Variations in bunch weight among different varieties can be attributed to inherent genetic traits of each variety. Greaca variety recorded highest 50 berry weight (254.25 g), while lowest was noted in VP × Beauty Seedless (41.28 g). Higher number of berries per bunch was observed in Clairette (186.80), while lower in Champion (26.27) followed by Amber Sweet (26.97). The maximum berry diameter and length were recorded in Aledo (21.33mm and 23.67 mm respectively). The maximum bunch length was observed in Muscat Petit (19.70 cm), while Leon Mellot (6.20) had minimum bunch length. The genotype, E29/3 (BC X TS), had maximum bunch width (13.40 cm), whereas Goethe had minimum (2.53 cm). Similar results were also reported by Anupama *et al.,* (2016) for different wine varieties.

Differences between phenotypic (PCV) and genotypic coefficients (GCV) of variation for all morphological traits under study are given in Table 2. Data revealed that magnitude of PCV was higher than GCV for all the characters studied. The estimate of PCV and GCV were high for pruning biomass (68.39 and 68.28), bunch weight (51.10 and 51.03), 50 berry weight (42.99 and 42.91), number of berries/bunch (42.18 and 41.97), compactness (39.54 and 39.34) and seed weight (42.68 and 42.38) indicating the presence of adequate genetic variation among the germplasm and suitability of these attributes for further improvement. Gupta *et al.,* (2015) also found that the phenotypic and genotypic coefficients of variance were high for bunch weight, berry weight and yield.

Low PCV and GCV were recorded for time of verasion (5.39 and 5.09), time of full bloom (8.12 and 7.64), total soluble solid (11.34 and 10.72) and physiological maturity (5.78 and 5.69). The estimates of PCV and GCV for time of verasion, time of full bloom, total soluble solid and physiological maturity were small in magnitude, but their values were similar suggesting that environmental factors had influence on the inheritance of these traits. A higher percentage of additive variability can result in large genetic gain, high heritability and significant genetic advancement. The genetic variability is heritable from one generation to the next. Therefore, heritability and genetic gain serve as valuable tools for breeders in assessing the direction and magnitude of selection. Yield and yield attributes are polygenic in nature and are subjected to different degree of non-heritable variation (Sivcev *et al.,* 2000).

Heritability estimate gives a measure of transmission of characters from one generation to next and the consistency in the performance of progeny in succeeding generations that depends mainly on the magnitude of heritable portion of variation. Average bunch weight (99.72), berry weight (99.64), number of berries per bunch (99.01), compactness (98.98) and bunch length (94.69) are key traits in grapes that show high heritability, indicating significant potential for improving grapes through selection. Heritability is more valuable and informative when evaluated together with genetic gain and genetic gain as a percentage of the mean (Saniya *et al.,* 2018). The genetic advance was reported as high for average bunch weight (276.15), berry weight (104.73) and number of berries per bunch (62.19).

Table 1: Pooled mean performance of wine grape germplasm for fruit traits

Genotype	PB	TOB	ToFB	ToV	ABW	BW	NOB	BD	BL	TSS	AD	CP	SF	BuL	BuW	PL	PM	SW	NOS
Aledo	0.91	10.67	39.67	109.00	124.34	176.87	57.94	21.33	23.67	18.09	0.67	5.56	51.20	15.78	12.66	22.07	141.67	5.39	2.33
Amber Sweet	0.53	10.00	36.33	99.33	85.63	137.36	26.91	15.17	17.60	18.01	0.55	3.82	38.23	9.27	5.70	10.95	121.33	4.03	1.33
Arka Hans	0.47	9.33	33.33	114.00	398.04	122.17	62.60	15.10	16.87	21.25	0.44	4.36	48.33	13.70	3.70	20.77	143.67	5.22	2.33
Armas	0.22	11.67	35.00	114.67	177.30	104.13	62.20	13.77	15.17	17.31	0.67	5.45	47.27	12.60	6.40	17.23	148.67	4.20	1.67
Bangalore Purple	0.45	8.67	38.00	109.33	383.97	180.57	86.23	18.47	19.57	18.32	0.61	5.36	66.43	13.83	2.00	24.00	139.33	6.24	2.67
E-8-25	0.52	12.33	34.67	116.67	57.09	62.43	36.37	12.03	12.30	18.68	0.58	2.49	43.30	15.50	8.47	20.33	143.33	3.30	1.67
Goethe	0.95	10.00	30.00	109.33	201.48	115.48	50.51	15.57	17.27	19.67	0.53	4.41	54.47	9.27	2.53	13.33	138.00	6.60	2.33
Gulabi	0.34	9.67	34.00	101.00	226.27	125.44	103.56	15.50	17.00	16.36	0.50	3.43	46.63	15.13	7.44	14.67	140.00	4.52	1.33
Gold	2.09	11.00	35.33	104.33	362.26	149.30	85.46	16.00	19.66	18.19	0.65	2.65	67.70	19.62	11.99	30.50	144.33	5.25	1.67
H-27	0.56	9.33	34.33	110.33	268.79	92.78	122.83	12.61	12.67	17.52	0.75	5.43	56.70	16.40	8.33	31.07	138.33	6.46	1.33
Khalili	2.51	12.67	31.00	101.33	248.57	206.54	61.02	15.50	17.90	17.57	0.76	2.69	48.17	8.40	3.63	16.13	132.00	5.44	2.33
Muscat of Alexandria	0.42	9.67	34.33	104.00	264.95	207.30	46.79	16.83	17.47	17.54	0.77	3.65	61.87	17.60	9.16	30.87	133.00	5.39	1.67
Muscat White	0.82	8.67	37.00	103.00	122.13	68.07	64.79	13.56	15.04	23.12	0.72	8.45	59.33	15.37	11.53	25.20	125.67	4.49	2.00
Pearl of Csaba	0.84	10.00	36.67	99.00	269.34	102.03	77.71	14.90	18.00	24.15	0.61	5.39	55.50	17.50	6.70	31.47	127.33	0.00	0.00
Petit Syrah	0.51	9.00	38.00	103.00	510.94	62.79	115.10	12.60	13.77	20.13	0.65	8.48	42.47	12.17	8.47	21.90	132.33	5.23	1.67
Ribier	0.70	12.33	40.67	109.33	330.45	66.92	72.43	18.40	19.50	16.62	0.72	2.65	50.47	15.73	8.40	13.47	134.67	3.84	1.67
Riesling	0.44	10.67	37.00	110.67	274.20	176.90	41.80	16.93	18.73	18.47	0.81	2.52	45.40	18.07	9.20	17.80	137.33	5.14	1.00
Rubi red	0.76	11.67	35.00	105.33	389.39	72.39	41.93	13.67	14.67	18.87	0.66	2.49	47.40	12.70	6.43	21.80	137.67	7.58	1.67
Sauvignon Blanc	1.01	9.67	34.00	100.33	322.48	71.97	71.07	12.40	12.67	22.63	0.57	5.49	52.53	9.40	5.33	12.00	141.33	4.89	1.33
Seibel 9308	0.72	9.67	34.00	104.00	255.03	84.25	70.47	13.83	16.20	18.75	0.60	3.50	31.77	11.40	5.20	13.27	136.00	6.79	2.67
Semillon	0.70	9.33	38.00	109.00	194.30	77.59	113.19	13.17	14.17	18.57	0.71	4.33	43.40	14.43	4.33	15.70	138.33	6.43	1.67
SV-12309	0.25	12.00	36.00	103.00	367.86	54.16	90.29	12.73	13.40	18.20	0.71	6.80	59.73	13.17	3.63	12.77	140.67	7.43	1.67
SV-23501	0.79	9.00	31.33	108.00	477.77	88.76	111.02	12.27	13.27	17.10	0.67	8.45	52.00	12.67	3.57	8.00	134.67	6.99	1.67
Symphony	0.68	8.67	40.00	103.67	558.93	106.53	70.43	15.70	16.77	20.70	0.64	2.53	50.50	13.77	7.30	20.43	131.00	4.35	1.67
Tannat(B2-6-1)	0.77	12.00	34.33	103.33	112.01	104.43	63.30	16.07	16.93	19.23	0.82	5.31	54.57	10.40	5.53	17.20	136.00	7.54	1.67
Tigrosa	0.45	11.00	34.00	97.00	410.04	67.03	77.37	12.40	13.83	18.33	0.73	7.38	56.03	9.27	6.83	15.27	123.67	5.37	1.67
Tslimlyanski Chernyi	0.62	12.00	35.33	100.33	297.49	113.88	65.30	18.40	19.07	17.99	0.99	2.36	41.40	19.33	8.20	16.37	126.67	3.43	1.67
VP X Beauty Seedless	1.07	10.00	31.33	105.33	55.57	41.28	55.22	13.77	17.93	20.48	0.61	4.48	46.50	9.33	3.60	11.70	137.00	3.58	1.00
VP X Centennial Seedless	0.30	11.67	35.00	97.67	164.44	87.12	28.22	15.43	18.37	16.67	0.64	4.53	51.13	12.53	6.63	21.13	130.00	5.53	1.67
Golden Queen	0.74	11.00	37.00	97.67	224.86	175.97	46.63	16.43	17.60	23.68	0.59	4.46	71.67	14.27	9.52	20.30	121.67	5.06	1.33
Alden	2.14	10.00	35.33	102.67	262.87	182.78	54.77	15.52	17.67	18.66	0.72	8.45	40.70	14.16	9.59	25.23	116.67	11.84	2.00
Barbarossa	0.82	9.00	37.00	102.67	146.70	58.77	43.03	12.27	14.03	22.92	0.51	4.50	58.00	9.27	5.43	17.63	128.00	4.59	1.67
Black Champa	0.72	9.67	31.00	113.00	165.87	196.52	30.66	18.10	18.43	17.30	0.66	4.50	51.93	7.33	11.50	16.73	131.00	6.30	1.67
Labrusca (FV)	1.07	9.33	31.33	99.33	323.40	92.84	57.50	16.77	18.43	18.28	0.65	8.52	40.40	13.47	7.47	21.30	124.00	7.50	1.67
Bianca	0.94	10.33	34.00	94.00	159.64	124.40	38.77	13.27	13.87	17.97	0.56	6.43	41.10	15.84	9.91	18.83	118.00	7.29	2.00
Champion	2.64	13.33	35.67	105.67	54.39	105.49	26.27	16.37	18.20	18.62	0.76	4.38	45.70	9.30	5.53	11.77	128.67	6.00	1.67
Doradillo	1.12	10.33	38.00	102.67	235.01	176.93	86.50	17.94	18.97	18.06	0.71	4.47	61.61	18.50	10.41	13.03	121.00	5.11	1.33
(Gulabi X Bangalore Purple)	0.33	9.00	38.33	105.00	558.68	104.80	76.95	16.90	18.23	18.53	0.57	5.55	60.97	10.43	6.83	32.93	127.00	4.20	2.00
Arka Kanchan	0.62	10.00	36.33	107.33	247.67	189.76	72.39	15.56	16.63	15.89	0.56	2.30	59.39	17.16	10.22	20.97	121.33	9.34	1.67
Vermentino	0.09	10.33	36.00	99.00	136.83	100.17	65.99	14.60	15.53	21.82	0.65	5.30	51.73	14.37	8.20	19.57	116.33	5.27	1.33
Viognier	0.65	9.33	32.00	94.00	137.20	103.27	90.80	14.23	12.57	17.67	0.74	9.55	48.77	12.17	5.73	12.63	117.33	6.48	2.00
Arka Chitra	1.08	10.00	35.00	102.67	317.27	237.71	91.45	18.77	21.27	16.94	0.75	2.79	52.64	17.63	9.27	26.37	127.33	3.46	1.67
Peru white	0.95	9.33	35.33	104.67	338.27	179.38	74.97	17.50	19.33	24.80	0.55	4.22	48.33	17.60	4.53	24.90	128.67	5.38	1.67
Waltham Cross	1.82	11.00	37.67	99.33	273.93	200.76	66.28	16.17	20.16	18.44	0.94	5.29	59.46	15.66	9.58	28.97	123.67	5.38	2.00
E12/2	1.47	10.67	30.00	110.00	69.71	157.74	51.27	13.50	14.50	21.69	0.65	2.62	40.48	11.03	5.47	22.23	130.67	6.47	1.33
Red prince	1.95	13.00	35.00	106.00	132.59	113.21	62.02	14.10	17.57	21.03	0.67	3.43	62.17	12.83	6.57	29.10	126.67	5.88	1.67
Maroo Seedless	0.13	10.00	38.33	106.00	257.96	148.04	123.92	13.33	14.63	19.37	0.71	6.43	45.30	12.53	6.33	10.23	127.33	0.00	1.67
E29/3 (BC XTS)	0.89	8.33	40.67	100.00	355.70	110.90	140.80	12.97	14.53	21.68	0.61	6.63	57.11	17.40	13.40	27.13	116.33	0.00	1.33
E4/15 IIHR Hybrid	1.34	9.00	33.33	106.00	358.30	170.50	74.22	21.07	20.13	17.53	0.75	4.49	66.03	7.90	12.20	26.57	121.33	4.55	2.00
Medica	0.54	11.00	29.00	104.67	356.03	112.84	110.90	15.20	16.53	18.93	0.51	6.61	61.97	16.53	11.23	21.93	120.00	0.00	1.33
Beauty Seedless	0.50	8.33	37.33	91.00	399.80	49.67	79.00	12.27	14.37	20.35	0.55	7.47	67.41	15.90	8.53	28.73	119.67	0.00	1.33

Genotype	PB	TOB	ToFB	ToV	ABW	BW	NOB	BD	BL	TSS	AD	CP	SF	BuL	BuW	PL	PM	SW	NOS
Arka Soma	0.42	8.67	35.00	105.33	526.66	173.23	60.60	17.93	19.27	20.01	0.61	3.44	53.97	13.97	4.40	25.27	131.33	5.27	2.00
Arka Shyam	1.04	10.00	29.33	100.67	226.63	86.38	73.83	14.03	15.03	20.93	0.55	4.68	67.78	17.03	6.40	26.30	123.33	6.29	1.67
Athens	0.74	12.33	36.00	103.00	356.00	134.89	54.53	15.57	20.57	21.07	0.63	5.54	36.33	11.50	8.20	23.30	122.00	5.61	1.67
Trebbiano	0.41	13.33	38.67	97.67	386.33	71.03	162.27	12.73	14.17	18.38	0.52	3.58	46.67	15.73	7.50	16.10	124.67	6.55	1.67
Gaeganega	0.51	13.33	35.00	103.00	461.97	79.37	91.76	14.50	15.50	17.28	0.67	7.30	54.20	14.50	5.23	21.73	128.00	4.78	2.00
Catawba	0.94	10.33	35.67	104.00	81.90	105.57	57.84	13.67	14.60	22.83	0.71	5.38	53.17	9.51	5.79	19.23	125.00	6.35	2.33
Charark-2	0.78	8.33	34.33	101.33	243.13	83.78	96.03	13.83	15.10	22.23	0.77	4.80	37.60	16.40	8.33	17.03	126.67	6.68	2.67
Charark-3	0.20	10.00	33.33	100.67	289.00	77.42	111.27	13.93	14.51	20.42	0.48	5.49	51.07	13.60	8.40	21.23	127.00	6.32	2.00
Rose of Penn	0.82	12.33	34.67	103.00	189.78	97.94	30.67	13.67	16.33	21.13	0.51	8.42	50.53	8.23	5.57	12.57	125.67	5.15	2.33
Rose Ciotat	0.85	12.67	34.67	101.33	121.00	100.82	57.33	17.43	18.63	18.03	0.57	3.44	46.47	10.77	6.43	3.77	127.33	8.22	3.00
Cabernet Franc	0.27	9.33	37.33	110.00	133.86	63.25	75.28	14.10	12.20	18.57	0.55	4.40	42.57	11.07	6.63	15.83	135.67	6.40	2.33
Marquise	0.52	14.33	31.67	100.67	159.23	115.48	68.17	13.33	15.27	18.62	0.59	5.59	49.00	17.57	9.47	29.40	125.67	0.00	0.00
Cayuga White	0.05	11.67	32.33	102.33	66.20	128.25	46.50	15.93	16.30	17.19	0.85	4.44	36.83	9.10	4.43	13.13	125.33	4.02	1.33
Rosaria Bianca	0.44	8.00	37.33	105.67	245.69	123.02	70.82	18.00	21.93	16.52	0.70	3.49	54.90	14.66	10.28	29.77	125.00	5.41	2.33
Clairette	0.32	12.33	40.33	110.33	374.97	81.18	186.80	14.00	14.43	19.00	0.63	8.43	43.77	18.43	7.63	14.10	129.67	7.77	3.00
SV-12364	0.51	13.33	32.67	103.33	380.90	61.41	52.86	12.17	12.60	22.48	0.59	2.59	54.43	14.73	5.83	16.20	136.33	6.85	2.00
Candaigua	0.22	9.33	28.67	104.33	117.48	241.89	33.63	18.17	19.80	16.51	0.65	3.67	55.63	8.63	7.50	11.43	125.00	6.01	2.33
SV-18402	0.67	11.00	31.00	105.67	533.66	93.67	65.87	12.77	14.93	18.53	0.62	3.56	58.57	11.63	4.63	6.67	126.33	5.85	2.00
Leon Mellot	0.60	13.00	32.33	105.67	43.83	41.42	55.18	10.80	12.03	17.98	0.75	9.31	54.50	6.20	3.57	4.90	124.67	2.91	1.67
Muscat Petit	1.03	11.67	34.67	106.33	225.01	66.62	116.38	12.00	13.06	17.79	0.78	8.45	63.43	19.70	10.36	26.20	126.33	0.00	0.00
Rose of Peru	0.52	12.00	35.33	101.33	35.66	75.34	93.91	13.57	15.40	18.32	0.79	3.56	55.03	11.97	3.83	12.20	125.67	7.16	2.33
Greaca	0.26	10.00	34.67	96.67	291.71	254.25	63.23	18.60	21.90	15.92	0.66	6.23	47.83	16.87	9.23	14.43	121.67	5.22	2.33
Concord	0.72	12.00	31.33	105.00	391.64	157.12	43.63	13.60	18.80	18.17	0.62	3.72	52.66	10.93	6.80	18.27	133.00	7.35	2.00
Choltu White	0.24	13.00	30.67	104.00	421.39	167.96	56.09	16.67	18.07	25.40	0.61	4.60	37.87	10.70	6.40	15.23	124.33	2.83	1.67
Mean	0.76	10.63	34.86	104.11	263.03	118.67	72.29	15.04	16.57	19.23	0.65	5.09	51.57	13.45	7.24	19.18	129.23	5.20	1.76
C.V.	6.55	11.89	4.76	3.08	4.65	4.47	7.28	9.56	8.65	6.43	14.75	6.90	8.67	9.90	9.97	7.55	1.74	8.64	27.90
S.E.	0.03	0.73	0.96	1.85	7.07	3.06	3.04	0.83	0.83	0.71	0.06	0.20	2.58	0.77	0.42	0.84	1.30	0.26	0.28
C.D. 5%	0.08	2.04	2.68	5.17	19.75	8.55	8.49	2.32	2.31	1.99	0.16	0.57	7.22	2.15	1.17	2.34	3.62	0.72	0.79

Table 2: Coefficient of variability, heritability, and genetic advance for different parameters of wine grape during 2020–21, 2021–22 and 2022-23

Character	Range	Mean	SD	PCV (%)	GCV (%)	Heritability (%)	Genetic advance
Pruning biomass (kg)	0.05- 2.64	0.7606	0.52	68.39	68.28	99.69	1.06
Time of budburst (DAP)	8.00-14.33	10.62	1.53	14.36	12.61	77.15	2.42
Time of full bloom (DAP)	28.67-40.67	34.85	2.83	8.12	7.64	88.56	5.16
Time of veraison (DAP)	91.00-116.6	104.1	5.62	5.397	5.096	89.16	10.32
Average bunch weight (g)	35.66-558.93	263.03	134.42	51.1	51.035	99.72	276.15
50 berry weight (g)	41.28-254.25	118.66	51.02	42.99	42.91	99.64	104.73
No. of berries/bunch	26.27-186.80	72.28	30.49	42.18	41.97	99.01	62.19
Berry diameter (mm)	10.80-21.33	15.03	2.24	14.9	13.84	86.3	3.98
Berry length (mm)	12.03-23.67	16.57	2.66	16.04	15.25	90.32	4.94
Total Soluable Solid (°B)	15.89-25.40	19.22	2.18	11.34	10.72	89.3	4.01
Acidity (%)	0.44-0.99	0.65	0.10	15.62	13.1	70.3	0.14
Compactness	2.30-9.55	5.09	2.01	39.54	39.34	98.98	4.1
Skin firmness (%)	31.77-71.67	51.57	8.58	16.63	15.85	90.94	16.06
Bunch length (cm)	6.20-19.70	13.45	3.34	24.8	24.13	94.69	6.5
Bunch width (cm)	2.00-13.40	7.24	2.55	35.23	34.76	97.33	5.11
Peduncle length (mm)	3.77-32.93	19.18	6.78	35.31	35.04	98.47	13.74
Physiological maturity(DAP)	116.33-148.67	129.23	7.48	5.78	5.69	97	14.93
Seed weight (g)	0.00-11.84	5.19	2.22	42.68	42.38	98.63	4.5
Number of seed/berry	0.00-3.00	1.76	0.55	31.53	27.1	73.91	0.84

The data on genotypic and phenotypic correlation coefficient among different characters is presented in Table 3. The correlation analysis indicated that average bunch weight was significantly correlated between pruning biomass (r=0.334), berry weight (r= 0.412), berry diameter (r=0.786) and berry length (r=0.348). Days taken to physiological maturity was positively correlated with time of veraison (r=0.489). Peduncle length was significantly correlated with pruning biomass (r=0.169), time of full bloom (r=0.178), beery weight (r=0.184), berry diameter (r=0.157), berry length (r=0.212) and bunch length (r=0.451).

Table 3: Phenotypic and genotypic correlation coefficient of yield parameters of wine grape

Traits		PB	TBB	TFB	TOV	BW	BD	BL	TSS	AD	CP	SF	BuL	PL	PM	ABW
PB	P	1**														
	G	1**														
TBB	P	0.109^{NS}	1**													
	G	0.152^{NS}	1**													
TFB	P	-0.076^{NS}	-0.123^{NS}	1**												
	G	-0.089^{NS}	-0.157^{NS}	1**												
TOV	P	-0.015^{NS}	0.005^{NS}	-0.042^{NS}	1**											
	G	-0.027^{NS}	-0.011^{NS}	0.082^{NS}	1**											
BW	P	0.193^{NS}	-0.117^{NS}	-0.090^{NS}	0.088^{NS}	1**										
	G	0.195^{NS}	-0.166^{NS}	-0.109^{NS}	0.103^{NS}	1**										
BD	P	0.094^{NS}	-0.140*	0.073^{NS}	0.091^{NS}	0.611**	1**									
	G	0.115NS	-0.166^{NS}	0.123^{NS}	0.161^{NS}	0.749**	1**									
BL	P	0.204*	-0.050^{NS}	0.092^{NS}	0.016^{NS}	0.625**	0.811**	1**								
	G	0.229*	-0.085^{NS}	0.094^{NS}	0.055^{NS}	0.725**	0.936**	1**								
TSS	P	0.056^{NS}	-0.045^{NS}	0.035^{NS}	-0.123^{NS}	-0.182**	-0.221**	-0.180**	1**							
	G	0.061^{NS}	-0.114^{NS}	0.041^{NS}	-0.147^{NS}	-0.213^{NS}	-0.265*	-0.196^{NS}	1**							
AD	P	0.175**	0.104^{NS}	0.089^{NS}	0.046^{NS}	0.133*	0.137*	0.112^{NS}	-0.232**	1**						
	G	0.274*	0.176^{NS}	0.099^{NS}	-0.060^{NS}	0.204^{NS}	0.264*	0.191^{NS}	-0.356**	1**						
CP	P	-0.081^{NS}	-0.054^{NS}	0.002^{NS}	-0.195**	-0.278**	-0.264**	-0.292**	0.050^{NS}	0.063^{NS}	1**					
	G	-0.082^{NS}	-0.081^{NS}	0.013^{NS}	0.2311*	-0.283*	-0.319**	-0.336**	0.047^{NS}	0.081^{NS}	1**					
SF	P	0.096^{NS}	-0.110^{NS}	0.045^{NS}	-0.047^{NS}	0.063^{NS}	0.075^{NS}	0.061^{NS}	0.002^{NS}	-0.009^{NS}	0.054^{NS}	1**				
	G	0.112^{NS}	-0.160^{NS}	0.054^{NS}	-0.084^{NS}	0.078^{NS}	0.060^{NS}	0.052^{NS}	0.019^{NS}	-0.055^{NS}	0.062^{NS}	1**				
BuL	P	-0.043^{NS}	-0.051^{NS}	0.292**	-0.132*	0.104^{NS}	0.084^{NS}	0.094^{NS}	-0.022^{NS}	0.037^{NS}	-0.079^{NS}	0.168*	1**			
	G	-0.051^{NS}	-0.085^{NS}	0.393**	-0.152^{NS}	0.120^{NS}	0.104^{NS}	0.102^{NS}	-0.034^{NS}	0.114^{NS}	-0.094^{NS}	0.192^{NS}	1**			
PL	P	0.169*	-0.224**	0.178**	-0.043^{NS}	0.184**	0.157*	0.212**	0.134*	0.017^{NS}	-0.040^{NS}	0.354**	0.451**	1**		
	G	0.174^{NS}	-0.284*	0.220^{NS}	-0.047^{NS}	0.192^{NS}	0.173^{NS}	0.231*	0.162^{NS}	-0.001^{NS}	-0.039^{NS}	0.411**	0.498**	1**		
PM	P	-0.048^{NS}	0.045^{NS}	0.020^{NS}	0.489**	-0.151*	-0.042^{NS}	-0.060^{NS}	-0.092^{NS}	-0.071^{NS}	-0.262**	-0.073^{NS}	-0.025^{NS}	-0.076^{NS}	1**	
	G	-0.054^{NS}	0.060^{NS}	0.007^{NS}	0.580**	-0.159^{NS}	-0.051^{NS}	-0.052^{NS}	-0.100^{NS}	-0.086^{NS}	-0.276*	-0.080^{NS}	-0.029^{NS}	-0.079^{NS}	1**	
ABW	P	0.334*	-0.189^{NS}	-0.256^{NS}	0.292^{NS}	0.412**	0.786**	0.348*	-0.289^{NS}	0.246^{NS}	-0.196*	0.061^{NS}	0.138^{NS}	0.008^{NS}	-0.156^{NS}	1**
	G	0.367*	-0.238^{NS}	-0.291^{NS}	0.314^{NS}	0.445**	0.834**	0.378*	-0.305^{NS}	0.271^{NS}	-0.234*	0.086^{NS}	0.189^{NS}	0.021^{NS}	-0.178^{NS}	1**

*Significant; **Highly Significant (*P*=0.05); ^{NS}Non- significant

(PB, pruning biomass (kg); TOB, Time of bud burst (DAP); ToFB, Time of full bloom (DAP); ToV, time of verasion (DAP); ABW, Average bunch weight (g); BW, 50 berry weight; NOB, number of berries per bunch; BD, Berry diameter (mm); BL, Berry length (mm); TSS, total soluble solid (°B); AD, Acidity(%); CP, Compactness; SF, Skin firmness (%); BuL, Bunch length (cm); BuW, Bunch Width (cm); PL, Peduncle length (mm); PM, Physiological Maturity (DAP); SW, Seed weight (g); NOS ,Number of seed per berry).

The genetic diversity was assessed using Mahalanobis D^2 analysis resulting that all the 75 genotypes were grouped into three clusters. Out of three clusters, cluster I showed maximum number of genotypes (45), followed by cluster III (23) and cluster II (7). The cluster I consisted of cultivars Symphony, Petit Syrah, Gulabi × Bangalore Blue having highest fruit weight, highest TSS (24.56), highest number of berries/bunch (186.0). The intra-cluster distance is used to measure genetic dissimilarity among genotypes within the same cluster, while, inter-cluster distance represents genetic distance between genotypes in any two clusters. The intra-cluster distances were recorded from 3.53 (cluster I) to 3.86 (cluster II) whereas, the inter cluster was highest (4.30) between cluster I and cluster II , followed by cluster I and cluster III (3.59) and cluster II and cluster III (3.40). Clusters with higher inter-cluster distances indicated that grape genotypes within those clusters showed significant genetic differentiation. Anjanawe *et al.*, (2020) noted variability with respect to various fruit traits in wine varieties under Malwa plateau.

CONCLUSION

The present study identified significant genetic variability in wine grape germplasm for fruit yield and quality traits. Traits like pruning biomass, bunch weight, number of berries/ bunch, berry diameter, bunch length, and berry weight strongly correlated with fruit yield. The comprehensive understanding of genetic diversity and yield-contributing traits provides a foundation for targeted breeding strategies aiming to improve wine grape for better productivity and resilience.

REFERENCES

Anjanawe S R, Naruka I S, Sharma A and Mishra P. 2020. Evaluation of Wine Purpose Varieties of Grapes under the Environmental Condition of Malwa Plateau. *Current Journal of Applied Science and Technology* **39(43):** 98-107.

Anupama Hachcholli, Kulapati Hipparagi, Rani S, Ravindranath and Balesh G. 2016. Evaluation of wine grape varieties for growth, yield and quality under northern dry zone of Karnataka. *International Journal of Scientific Research* **51(2):**409-411

Benz M J, Anderson M M, Williams M A, Barnhisel K and Wolpert J A. 2006. Viticultural performance of five Merlot clones in Oakville, Napa Valley. *American Journal of Enology and Viticulture* **57:** 23–37.

Cunha J, Baleiras-Couto M, Cunha J P, Banza J, Soveral A, Carneiro LC and Eiras-Dias J E. 2007. Characterization of Portuguese populations of Vitis vinifera L. ssp. sylvestris (Gmelin) Hegi. *Genetic Resources and Crop Evolution.* **54:**981–988

Gris E F, Burin V M, Brighenti E, Vieira H and Luiz M B. 2010. Phenology and ripening of Vitis vinifera L. grape varieties in São Joaquim, southern Brazil: a new South American wine growing region. *Ciencia e investigación agraria: revista latinoamericana de ciencias de la agricultura* **37(2):** 61-75.

Gupta N, Brar K S, Gill M S and Arora N K. 2015. Studies on variability, correlation and path analysis of traits contributing to fruit yield in grapes. *Indian Journal of Plant Genetic Resources* ***28*(3)**: 317-20.

Jayalakshmi C, Saraswathy S, Subbiah A, Ilamurugu K and Balachandar D. 2019. Evaluation of wine varieties of grapes (Vitis vinifera L.) during winter pruning under Cumbum valley condition of Tamil Nadu. *Journal of Pharmacognosy and Phytochemistry* ***8*(3):** 3770-773.

Laucou V, Lacombe T and Dechesne F. 2011 High throughput analysis of grape genetic diversity as a tool for germplasm collection management. *Theoretical and Applied Genetics.* **122**: 1233–45. https://doi.org/10.1007/s00122-010-1527-y.

Saniya K J, Naruka I S and Singh P P.2018. Genetic variability and association among colour and white seedless genotypes of grape (Vitis vinifera). *Indian journal of agricultural sciences,* **88(5):** 737-45.

Sivcev B, Zunic D and Jovic S. 2000. Production-technological characteristics of some promising grapevine seedlings in the condition of Experimental Station Radmilovac. *Journal of Agricultural Sciences* **45(2):** 93–99.

Somkuwar, R. G., Kakade, P. B., Ghule, V. S., and Sharma, A. K. 2024. Performance of grape varieties for raisin recovery and raisin quality under semi-arid tropics. *Plant Archives* **24(1):** 61-66.

Somkuwar R G, Samarth R R, and Sharma A K. 2023. Grape. In: *Fruit and Nut Crops* (pp. 1-38). Singapore: Springer Nature Singapore.

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Evaluation of teinturier type grape (*Vitis vinifera*) germplasms for wine purpose

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Abstract

The teinturier type grapes (*Vitis vinifera* L.) produce deep coloured wines having bold flavours and distinctive characteristics. Ten teinturier type grapes were evaluated for bunch and berry parameters. Some quality parameters of prepared wines were also assessed. A wide range of variability was observed in days required for full bloom, days from fruit setting to harvesting and growing degree days. There were significant variations in bunch and berry parameters in all genotypes during both the years. Pusa Navrang produced smallest bunches, while Aliquant Bauschet had the longest. The hybrid, Pusa Navrang × Chardonnay, produced boldest berries and maximum bunch weight. Significant differences were also observed in biochemical parameters like total soluble solids (TSS), acidity, phenolic acids, tannins, and anthocyanins. Wines prepared from these grape types also showed significant differences. Wines made from ARI-239 had the highest ethanol levels. The varietal differences influenced the composition and antioxidant potential of wines. Vintage effects were also observed. Based on bunch and berry parameters and wine quality, Manjari Medika, Pusa Navrang, Pusa Navrang × Red Globe, ARI (H-27) and Rubired were found promising.

Key words: Vitis, Bunch Parameters, Berry, Anthocyanins, Ethanol

Grapes (*Vitis vinifera* L.) are considered most important popular commercial fruit globally. It is commercially grown in temperate to tropical conditions in various countries. As per OIV, the grapevines covered an area of 7.2 million ha and production was 74.7 million tons during 2023. It was also recorded that almost 50% of total produce (34.0 million tonnes) was pressed for wine and juice purpose (OIV, 2023). Global wine production was 237 million hectolitre and major wine producers were France, Italy, Spain, USA and Chile (OIV, 2024). Globally about 10,000 grapevine varieties are known. Of them, 13 cover more than one-third of the world's vineyard area, while 33 varieties cover 50% area (OIV 2017). Among wine grape varieties, Cabernet Sauvignon has covered maximum area followed by Merlot and Tempranillo. The selection of wine grape variety is crucial as it directly influences organoleptic characteristics of wine such as colour, aroma and structure. In India, Cabernet Sauvignon, Shiraz, Merlot, Malbec, Zinfandel are mainly red wine grape varieties are grown while Sauvignon Blanc, Chenin Blanc, Chardonnay, Riesling, etc. varieties are grown for white wine-making (Sharma *et al*. 2020).

In grape berries, anthocyanins are synthesized in the skin, not in the pulp. In contrast, in the 'Teinturier type grapevine varieties are deviate from this natural phenomenon by accumulating variable levels of anthocyanins in berry flesh/juice also (Röckel *et al*. 2020). The teinturier varieties have been utilized for blending purpose to increase the colour of pale red wines and remain economically important worldwide (Anderson and Aryal 2015). Anthocyanin content in these varieties varied at large and anthocyanin profile study revealed that not all 21 anthocyanins were recorded in teinturier type varieties (Kőrösi *et al*. 2022). Anthocyanin synthesis begins in the flesh and later extends to the skin. Tian *et al.* (2021) reported that teinturier cultivars contain significantly higher total anthocyanin content than non-teinturier grape varieties. Teinturier grapes have elevated flavonoid concentrations and frequently utilized to improve/modify the colour of red wines, elevate tannin levels and increase ageing potential (Chen *et al*., 2018). Revilla *et al.* (2016) mentioned that several teinturier type varieties, including Alicante Bouschet, are commonly utilized to blend for creation of wines with dark colour from lighter-coloured grape varieties. Enchantment can be used to produce high-quality, deeply red-coloured wines as well as blending purpose also (Mayfield *et al*. 2021). A few Few teinturier type genetic material has been breed in India and mostly studied for juice purpose. But no systematic study is conducted on evaluation of these available teinturier grape genotypes for wine purpose. Considering the importance of teinturier type grapes in winemaking, present study was conducted to compare these genetic materials for grape and wine quality parameters.

MATERIALS AND METHODS

The experiment was conducted at ICAR-National Research Centre for Grapes, Pune, during seasons of

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2022-23 and 2023-24. A total of ten Teinturier type accessions available in the National Active Germplasm Site for Grapes were utilized under this study. The research farm is situated in mid-western Maharashtra (latitude 18°92'32''N and longitude 73°.59'13"E) having elevation of 560 m. The vines were trained to extended Y trellis system of spaced at 2.74 m between rows and 1.21 m between vines. Four vines of each accession were earmarked, and data were recorded.

Growing degree days (GDDs) were calculated for each day based on the daily recorded maximum (Tmax) and minimum (Tmin) temperature. For calculating GDD, 10 °C was used as base temperature (Tbase). GDD under this experiment was calculated from fruit setting to harvesting.

$$GDD = (Tmax + Tmin) / 2 – Tbase$$

Bunch length and bunch weight were calculated as average of 10 bunches. Berry related parameters, *viz.* diameter, length and skin thickness were estimated by using 20 berries collected from different parts of bunches. Skin thickness was estimated by using micrometer. Juice extracted from 20 berries of each was utilized for recording the related parameters like TSS, acidity, phenols, tannins and anthocyanins content. Total phenolic acids were quantified by following the procedure of Singleton and Rossi (1965) against gallic acid. Absorbance was recorded at 765 nm using UV-spectrophotometer. Content of anthocyanins in samples was noted by following method of Fuleki and Francis (1968). Tannin contents in wines were estimated by Folin Denismethod suggested by Singleton and Rossi (1965) where tannic acid was utilized as standard.

Wines were prepared according to methodology suggested by Sharma *et al.* (2018). A SO_2 level of 80 ppm was maintained in wines. Prepared wines were stored at 10 °C and two rackings (30 days duration of each) were performed. Wines stored at 10 °C were utilized for further studies. OenoFoss (FTIR-based wine analyser) was utilized for estimation of wine parameters. The generated data were statistically analysed according to CRD by adopting OPSTAT software.

RESULTS AND DISCUSSION

There were variations in phenological stages of plant types studied. The duration of pruning to full bloom varied 35-41 days during 2023, while it was 36-42 days during 2024 (Table 1). During 2024, days from pruning to full bloom were more. The flowering period varied from 4-8 days during 2023, while it was 5-7 in 2024. Days recorded from fruit setting to harvesting ranged 83-114 and 82-115 during 2023 and 2024, respectively. Growing degree days (GDD) recorded after fruit setting ranged 1109.62-1476.94 and 1176.44-1616.83 during 2023 and 2024, respectively. Occurrence of phenological stages in grapevines is genetically determined feature which is highly variable from one to other variety. Somkuwar *et al.* (2024) also recorded variability among wine grape varieties in regards days required for harvesting.

The phenological stage variation and GDD accumulation up to harvesting affected grape types also (Kamila *et al.* 2024). The genotypes express variability for required GDD across the seasons (Bondade and Deshpande 2021). Different *V. vinifera* genotypes exhibit significant variability between phenological stages. Our findings are in same pattern and variability was recorded among the genotypes of same species, i.e. vinifera. However, prevailing temperature and photoperiod under conditions of region have impact on phenological development of grapevines (Jones 2003). Even vintage variations in weather also affect days required for occurrence of phenological stage. Such variations were recorded in our study also.

Significant variations in bunch and berry quality parameters were recorded in Teinturier type grapes (Table 2). Pusa Navrang recorded with smallest bunch (bunch length 10.5 and 10.2 cm in 2023 and 2024, respectively). While maximum bunch length with 18.9 cm in 2023 and 18.4 in 2024 was recorded in Aliquant Bauschet (Table 2). Accession, Pusa Navrang × Chardonnay, produced bold berries in terms of maximum length and diameter during both the years. Maximum bunch weight was also recorded in same and berry diameter while minimum values for these parameters were registered in ARI-239. Pusa Navrang registered minimum diameter and E26/5 IIHR Hybrid was also at almost same level. Berries of Aliquant Bauschet had thinnest skin, while Manjari Medika berries contained thick skin. Significant differences were observed among the grape types for recorded parameters during both years.

During 2023, TSS ranged 18.2 in A48-1 (Pusa Navrang × Chardonnay) to 22.5 °B in E26/5 IIHR Hybrid. While, minimum TSS (20.4 °B) estimated in Pusa Navrang and ARI (H-27) during 2024 (Table 3). The E26/5 IIHR Hybrid recorded maximum TSS content during both years. More TSS accumulation was observed during 2024. Acidity contents in accessions were suitable for wine making in both harvests. Berries of Pusa Navrang contained minimum acidity (0.50 g/L) in harvest of both years, while berries of Pusa Navrang × Red Globe recorded with maximum acid content. Sugar in berries is considered important for juice making while combination of sugar, anthocyanin and acidity levels are important for wine purpose (Somkuwar and Naik, 2024).

Antioxidant activities of grape juices were recorded

Table 1. Days required for phenological stages and GDD

Variety	Pruning to full bloom (days)		Flowering period (days)		Fruit setting to harvesting (days)		GDD (after fruit setting)	
	2023	2024	2023	2024	2023	2024	2023	2024
E26/5 IIHR Hybrid	38	40	7	6	96	95	1304.25	1360.70
ARI (H-27)	38	39	4	5	111	109	1463.45	1573.31
Pusa Navrang × Red Globe	41	42	8	7	83	82	1198.41	1176.44
Manjari Medika	40	40	7	6	91	92	1257.85	1290.83
Pusa Navrang × Chardonnay	34	36	7	6	89	90	1198.43	1261.48
Aliquant Bauschet	38	39	7	7	111	110	1476.90	1573.31
A48-1 (Pusa Navrang × Chardonnay)	37	38	8	7	85	86	1109.62	1204.79
Pusa Navrang	38	40	4	5	94	92	1154.46	1332.35
Rubired	38	38	6	6	114	115	1476.94	1616.83
ARI-239	35	36	6	5	100	98	1320.85	1417.42

Table 2. Bunch berry quality parameters

Variety	Bunch length (cm)		Bunch weight (g)		Berry diameter (mm)		Berry length (mm)		Skin thickness (mm)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2023
E26/5 IIHR Hybrid	13.2	13.0	220	216	12.3	12.2	13.6	13.9	0.19	0.18
ARI (H-27)	15.4	15.1	250	247	12.5	12.6	14.5	14.7	0.22	0.22
Pusa Navrang × Red Globe	16.3	15.9	165	168	14.8	14.8	16.0	16.4	0.23	0.24
Manjari Medika	15.9	15.8	230	236	16.2	16.0	16.5	16.7	0.25	0.25
Pusa Navrang × Chardonnay	11.0	11.2	320	318	18.2	18.4	23.1	22.8	0.23	0.23
Aliquant Bauschet	18.9	18.4	265	261	15.6	15.7	20.1	19.9	0.15	0.16
A48-1 (Pusa Navrang × Chardonnay)	16.5	16.1	260	268	16.2	16.4	19.4	19.1	0.19	0.20
Pusa Navrang	10.5	10.2	254	253	12.4	12.1	13.7	13.3	0.25	0.25
Rubired	13.6	13.3	290	292	12.8	13.1	14.9	15.1	0.16	0.17
ARI-239	12.2	11.8	56	61	12.4	12.1	13.3	13.2	0.21	0.20
S.E (m)±	0.113	0.13	2.296	2.60	0.111	0.14	0.145	0.17	0.002	0.002
CD @ 5%	0.324	0.40	6.612	7.72	0.320	0.41	0.417	0.51	0.005	0.007

Table 3. Biochemical variations among teinturier type grapes

Variety	TSS (°B)		Acidity (%)		Phenol (mg GAE/g)		Tannin (mg TAE/g)		Anthocyanin (mg/L)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
E26/5 IIHR Hybrid	22.5	22.7	0.61	0.60	3.57	4.58	1.04	1.04	786.12	797.89
ARI (H-27)	19.2	20.4	0.55	0.52	3.45	3.86	1.15	1.13	795.75	807.31
Pusa Navrang × Red Globe	20.0	21.8	0.65	0.61	2.85	3.24	0.91	0.94	855.45	873.84
Manjari Medika	22.1	22.4	0.52	0.52	5.14	6.24	2.19	2.34	754.92	776.32
Pusa Navrang × Chardonnay	20.4	21.8	0.60	0.57	2.83	2.13	1.14	1.63	742.59	783.89
Aliquant Bauschet	20.6	21.6	0.54	0.55	4.75	5.21	1.26	1.61	597.00	608.16
A48-1 (Pusa Navrang × Chardonnay)	18.2	20.8	0.51	0.51	3.36	4.11	1.49	1.84	913.61	792.67
Pusa Navrang	20.2	20.4	0.50	0.50	5.13	5.86	1.67	1.98	749.92	773.94
Rubired	19.5	21.5	0.58	0.60	2.29	2.93	1.67	1.83	729.50	713.53
ARI-239	20.5	21.7	0.59	0.57	3.61	3.91	1.02	1.43	625.89	646.27
S.E (m)±	0.134	0.18	0.046	0.005	0.587	0.05	0.078	0.02	7.71	7.23
CD @ 5%	0.386	0.54	0.133	0.015	1.744	0.14	0.232	0.04	22.92	21.48

Table 4. Variability in wine parameters

Variety	Sugar (g/L)		Acidity (g/L)		pH		Ethanol (%)	
	2023	2024	2023	2024	2023	2024	2023	2024
E26/5 IIHR Hybrid	0.0	0.16	5.30	4.13	3.56	3.14	11.13	10.13
ARI (H-27)	2.53	2.57	4.56	4.14	3.24	3.77	10.13	10.30
Pusa Navrang × Red Globe	1.93	1.03	5.80	6.04	3.72	3.34	10.86	10.50
Manjari Medika	0.63	0.00	4.43	3.81	3.12	3.86	10.74	11.64
Pusa Navrang × Chardonnay	2.36	0.00	5.13	5.02	3.46	3.57	10.83	10.16
Aliquant Bauschet	1.43	0.00	4.60	5.47	3.23	3.59	10.13	10.51
A48-1 (Pusa Navrang × Chardonnay)	0.76	0.00	3.80	5.05	3.05	4.00	10.73	10.40
Pusa Navrang	1.26	0.00	4.60	5.49	3.14	3.64	10.26	11.46
Rubired	1.80	0.63	4.83	4.47	3.35	4.15	10.23	10.10
ARI-239	0.46	0.00	5.16	5.20	3.61	3.90	11.26	11.86
S.E (m)±	0.08	0.08	0.05	0.04	0.01	0.02	0.04	0.21
CD @ 5%	0.14	0.24	0.15	0.11	0.036	0.05	0.125	0.62

in the form of phenolic acid, tannins and anthocyanins. Significant differences were observed among teinturier type grapes for these antioxidant activities during both years (Table 3). The content of phenolic acids in grape juices were measured against gallic acid. Maximum phenolic content 5.14 and 6.24 mg GAE/g was estimated in Manjari Medika berries from 2023 and 2024 harvest years, respectively. While berries of Pusa Navrang × Chardonnay contained minimum phenolic acids in both years. Juice collected from Manjari Medika grapes contained maximum tannins in both years, while juice obtained from Pusa Navrang × Red Globe was registered minimum tannins. Anthocyanins content ranged 597.00-913.61 mg/L in 2023, while this was 608.16-873.84 mg/L in 2024. In 2023, maximum anthocyanins content was recorded in A48-1 (Pusa Navrang × Chardonnay), while it was maximum in Pusa Navrang × Red Globe in 2024.

Genotypic diversity and growing conditions affect biochemical attributes in grapes (Naik *et al.*, 2023). The content of TSS, acidity, tannins, phenols and anthocyanins were affected by grape types in our study. Kunter *et al.* (2024) highlighted the substantial impact of grape varieties on berry composition in sugar and acidity content. The red-fleshed grapes contain much higher contents of total phenolic compounds and anthocyanins (Lu *et al.* 2023). Wide variations in the content of anthocyanins and phenolic compounds across different types of grapes were recorded by Liang *et al.* (2011). Kőrösi *et al.* (2022) also recorded wide level of variability in anthocyanins content among teinturier type grapes.

In present study, variation in anthocyanins content were also recorded. Juice and skins of teinturier grapes contain high degree of tannins. A good tannin contents was estimated in grapes of present study. The variations in contents of phenols, anthocyanins and tannins among grape types was due to genetic makeup as well as expression under growing conditions of the region. Vintage effect was also expressed in variation of biochemical contents in studied grape types. The conditions existing in the individual vintages have influence on degree of ripeness, anthocyanins and colour capacity in grapes. (Balik and Kumsta 2008). While, Minnaar *et al.* (2022) recorded vintage effect was recorded for specific individual phenolics in the harvested grapes. It was concluded that vintage has a limited effect on phenolics. However, data from present study clearly showed vintage effect in phenolic acids content of teinturier type grapes.

During 2023, acidity ranged between 3.80-5.80 g/L, while in 2024 it was 3.81-6.04 g/L (Table 4). Wine made form Pusa Navrang × Red Globe resulted in maximum acidity content in both years (Table 4). Wines prepared from Pusa Navrang × Red Globe, Aliquant Bauschet, A48-1 (Pusa Navrang × Chardonnay), Pusa Navrang and ARI-239, during 2024 were gave more acidity than wines of 2023. But pH of the wines was not in same manner. Across both the year, pH value of wines prepared from A48-1 (Pusa Navrang × Chardonnay) registered a maximum pH of 4.0. Higher pH values showed lower microbial stability. The ethanol content in wines is related to TSS or sugar content in the must.

Wines prepared from ARI-239 were recorded with maximum ethanol in both the years. However, differences among grape types were significant in both the years. Mayfield *et al.* (2021) found Enchantment (a teinturier winegrape) as a suitable for producing varietal or blending purpose. Somkuwar *et al.* (2024) recorded variations in wine quality parameters when evaluated red wine grapes under Pune conditions. Wine parameters varied with genotype, growing conditions, berry traits, winemaking practices, and vintage, as climatic variability markedly influenced quality and aging potential.

CONCLUSION

The Teinturier type grape varieties are widely utilized for blending and improving the colour of wines. The wines prepared from Teinturier type grapes were rich in anthocyanins and phenolics, and these compounds were related to antioxidant properties. Hence, the wines made from teinturier type grapes have potential for health-conscious consumers.

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REFERENCES

Anderson, K and Aryal, N.R. (2015). *Which Winegrape Varieties are Grown where? A Global Empirical Picture*. University of Adelaide Press: Adelaide, Australia.

Bondade, V and Deshpande, K.S. 2021. Studies on determination of critical growing degree days, base temperature (tb) and response of temperature variations on flowering and yield per se in cowpea [*Vigna unguiculata* (L.) Walp.]. *Legume Research* **44**(12): 1430-1436. doi: 10.18805/LR-4262.

Chen, W.K., Wang, Y., Gao, X.T., Yang, X.H., He, F., Duan, C.Q and Wang, J. (2018). Flavonoid and aromatic profiles of two *Vitis vinifera* L. teinturier grape cultivars. *Australian Journal of Grape and Wine Research* **24**: 379–389. doi: 10.1111/ajgw.12336

Kamila, S., Widodo, W/D., Santosa, E and Suhartanto, M.R. 202). Flowering and fruiting phenology in two varieties of grapes (*Vitis vinifera*) in tropical regions, Indonesia. *Biodiversitas* **25**(11): 4593-02. DOI: 10.13057/biodiv/d251158

Kőrösi, L., Molnár, S., Teszlák, P., Dörnyei, Á., Maul, E., Töpfer, R., Marosvölgyi, T., Szabó, É and Röckel, F. (2022). Comparative study on grape berry anthocyanins of various teinturier varieties. *Foods* **11**(22): 3668. https://doi.org/10.3390/foods11223668

Kunter, B., Unal, O.B., Keskin, S., Hatterman-Valenti, H and Kaya, O. 2024. Comparison of the sugar and organic acid components of seventeen table grape varieties produced in Ankara (Türkiye): a study over two consecutive seasons. *Frontier in. Plant Science* **15**:1321210. doi: 10.3389/fpls.2024.1321210

Liang, Z.C., Owens, C.L., Zhong, G.Y and Cheng, L.L. (2011). Polyphenolic profiles detected in the ripe berries of Vitis vinifera germplasm. *Food Chemistry* **129**: 940–950.

Lu, L., Yang, Y., Zhong, G.-Y., Liang, Z and Cheng, L. (2023). Phytochemical composition and content of red-fleshed grape accessions. *Horticulturae* **9**: 579. https://doi.org/10.3390/ horticulturae9050579

Mayfield, S.E., Threlfall, R.T., Leis, D., Howard, L.R., Leitner, E and Clark, J.R. 2021. Investigating the winemaking potential of enchantment, a new *Vitis* hybrid teinturier cultivar. *American Journal of Enology and Viticulture* 72:194-207. DOI**:** 10.5344/ajev.2021.20052

Minnaar, P., Van Der Rijst, M and Hunter, J. (2022). Grapevine row orientation, vintage and grape ripeness effect on anthocyanins, flavan-3-ols, flavonols and phenolic acids: I. *Vitis vinifera* L. cv. Syrah grapes. *OENO One* **56**(1): 275–293. https://doi.org/10.20870/oeno-one.2022.56.1.4857

Naik, S., Tiwari, J., Singh, B and Sharma, D. (2023). Biochemical attributes of grapes grown at high elevations in Himachal Pradesh. *Grape Insight* **1**(1): 23–31. https://doi.org/10.59904/gi.v1.i1.2023.8

OIV, 2024. State of the world vine and wine sector in 2023. https://www.oiv.int/sites/default/files/documents/OIV_STATE_OF_THE_WORLD_VINE_AND_WINE_SECTOR_IN_2023_1.pdf (accessed 28 May 2025).

OIV. (2017). Distribution of the world's grapevine varieties. https://www.oiv.int/public/medias/5888/en-distribution-of-the-worlds-grapevine-varieties.pdf (accessed 20 September 2019).

OIV. 2023. Annual assessment of the world vine and wine sector in 2023. https://www.oiv.int/sites/default/files/documents/Annual_Assessment_2023_0.pdf (accessed 5 January 2024).

Revilla, E., Losada, M.M and Gutiérrez, E. (2016). Phenolic composition and color of single cultivar young red wines made with Mencia and Alicante-Bouschet grapes in AOC Valdeorras (Galicia, NW Spain). *Beverages* **2**:18.

Röckel, F., Moock, C., Braun, U., Schwander, F., Cousins, P., Maul, E., Töpfer, R and Hausmann, L. 2020. Color intensity of the red-fleshed berry phenotype of *Vitis vinifera* teinturier trapes Varies Due to a 408 bp Duplication in the Promoter of *VvmybA1*. *Genes* **11**(8), 891. https://doi.org/10.3390/genes11080891

Sharma, A.K., Somkuwar, R.G., Banerjee, K., Jogaiah, S and Kabmble, N. (2018). Crop levels and pruning timing affect must and wine quality of Cabernet Sauvignon wine grape. *Indian Journal of Horticulture* **75**(3): 384-391. *DOI: https://doi.org/10.5958/0974-0112.2018.00066.X*

Sharma, A.K., Upadhyay, A.K and Somkuwar, R.G. (2020). Grape growing: opportunities for better returns. *Prog Hort* **52**(2): 134-143. DOI: 10.5958/2249-5258.2020.00018.4

Somkuwar, R.G and Naik, S. 2024. Precision viticulture: a review. *Current Horticulture* **12**(1): 23–34. DOI: 10.48165/chr.2023.12.1.02

Somkuwar, R.G., Sharma, A.K., Gobade, N and Ausari, P.K. 2024. Performance of red wine varieties under Pune region of Maharashtra. *International Journal of Advanced Biochemistry Research* **8**(5): 981-988. https://doi.org/10.33545/26174693.2024.v8.i5l.1227

Tian, M-B., Yuan, L., Zheng, M.Y and Xi, Z-M. 2021. Differences in anthocyanin accumulation profiles between teinturier and non-teinturier cultivars during ripening. *Foods* **10**(5): 1073. https://doi.org/10.3390/foods10051073

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Identification of feeder root zones for optimal nutrient and water uptake in subtropical fruit crops

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Abstract

The experiment was conducted to pinpoints the location-specific root system in two depths from soil surface and five horizontal distances from the tree trunk. The horizontal distance was marked in H1 (0-30 cm), H2 (31-60 cm), H3 (61-90 cm), H4 (91-120 cm) and H5 (121-150 cm), at two depths, D1 (0-30 cm) and D2 (31-60 cm). The soil of 30 cubic cm was removed with the help of a sharp spade and sieved with large mesh size to extract fine roots. The soil was soaked in water and sieved and roots were studied.The maximum root number in guava (*Psidium guajava* L.) and aonla (*Emblica officinals* L.) were recorded at 31-60 cm horizontal distance (HD) and 31-60 cm soil depth from soil surface, while in jamun it was maximum at 31-60 HD and 0-30 cm depth of from main trunk. Total root biomass represented the rooting density per unit area, maximum root mass (38.2 ± 5.74 g) in guava was recorded in 0-30 cm deep from soil surface and horizontal distance. Jamun and aonla under HDP system had maximum root biomass 31-60 cm deep from SS and 0-30 cm horizontal distance (HD) from tree trunk. The roots in length in all crops were maximum at 0-30 horizontal distance and soil depth except guava where maximum root length was noted at 31-60 cm soil depth. Guava, aonla, bael (*Aegle marmelos* L.) and jamun (*Syzigium cuminii* L.) planted under high-density planting system have maximum root number which absorb water and nutrient and supporting their trees at 0-60 cm horizontal distance and depth of 0-60 cm.Fresh root mass recorded at 31-60 cm horizontal distance from the tree trunk up to 60 cm deep from soil surface.

Key words: Aeration, Organic carbon, Root number, High density planting, Root biomass

The roots in the soil provides anchorage, storehouse of food reserve, absorb and transport essential elements and bio-molecule to aerial parts of the trees for the vital functions, soil management factors such as tilling, mulching, water management, nutrient application, weeding etc. affect aeration, soil texture, water and nutrient availability, soil organic carbon content and root distribution pattern. Bael (*Aegle marmelos*), aonla (*Emblica officinale*), jamun (*Syzigium cuminii*) and guava (*Psidium guajava*) fruit crops are grown in wide range of soil and climatic conditions with degraded and marginal land without assured irrigation. However, for good quality fruits and high yield some crucial irrigation is required, though mostly farmers apply water through flood irrigation. A global report suggests that, 70% planet fresh water is used by farmers and 95% farmers used flood irrigation due to most energy efficient techniques. Flooding entire fields are not economical as water availability are depleting very fast. Further farmers do not have technical know-how about where and how much to apply water; hence flooding to entire field resulting wastage of water of 60-70 %. Srivastava *et al.*(2024) studied root distribution pattern, growth and yield of guava planted at 3 m × 3 m spacing on raised bed. Tree roots play physiological and biological functions have been discussed in grape. The roots lie vertically and horizontally in soil, they can penetrate up-to 600 cm in soil horizon in grape. Srivastava *et al.* (2024) reported that soil condition influence the root growth and total biomass of the fruit plants. Different fruits crops in same condition of soil profile may have different behavior (Southey and Archer, 1988; Williams and Smith, 1991) noted the tree genetic factor may affect root density, therefore genetically different fruit trees may have different root distribution pattern. The distribution of roots is the complex function decided by various factors, viz. species, variety, tree age, soil texture, cultural practices (Singh and Mishra, 2000). Root distribution study is location-specific owing to soil pedology and edaphic factor of location while root density is genetically controlled. Therefore, an experiment was conducted to identify feeder root zones in subtropical fruit crops.

MATERIALS AND METHODS

The experiment was conducted at ICAR-Central Institute for Subtropical Horticulture, Rehmankhera, Lucknow, representing subtropical climate located at 26° 51' 0.0000'' N and 80° 56' 59.9892''E withannual rainfall of 750-800 mm. The soil is coarse, sandy loam, clay contentof 1.6-3.1% and pH ranging 7 to7.5. The trees during 2021and 2022 were>20 years old planted at 5 m× 5 m. The rooting pattern was studied in two depths from soil surface and five horizontal distances from tree trunk. The entire tree basin was divided in different blocks as per horizontal distance from trunk and depth wise with the help of measuring scale (Figs 1 and 2) and root excavation was carried out during spring season. The horizontal distance was marked in H_1 (0-30 cm), H_2 (31-60 cm), H_3 (61-90 cm),

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H_4 (91-120 cm), H_5 (121-150 cm) with two depths, D1 (0-30 cm) and D2 (31-60 cm) from soil surface. Soil of 30 cubic cm was removed with the help of a sharp spade or shovel collected in plastic try, weed roots removed and was sieved with large mesh size after that again filled the soil in bucket and filled with water to extract fine roots too.

The soil strained 2-3 times till all the roots were collected from. Total roots from each block were counted carefully and expressed in number. Total root collected from each block which ranged from 0.2 cm thick to more than 1.5 cm thick was weighted with digital weighing balance and expressed in gram. The root length was measured using digital vernier caliper and screw gauge (model Yuzuki). The root thickness was recorded with digital vernier caliper or digital screw gauge. Two factorial randomized complete block design was employed to analyze the data. The data was analyzed using Rprogramming. Tukey's Honest Significant Difference (HSD) test was performed as a post hoc test to assess the significance of differences between pairs of group means.

RESULTS AND DISCUSSION

In guava, highest number of roots was observed at a horizontal distance of 31–60 cm from the trunk and at a vertical depth of 31–60 cm (54.2±9.3)(Fig. 1). However, this was not significantly different from the number of roots found at a horizontal distance of 0–30 cm and a depth of 31–60 cm (44.2±7.93). A total of 27 roots were found at a horizontal distance of 31–60 cm and a depth of 0–30 cm. The analysis clearly showed that the highest root density occurs at a depth of 0–30 cm. In aonla, root number per 30 cm of soil volume varied, with maximum root counts of 31.2±2.87 at a 30–60 cm horizontal distance and 0–30 cm depth, and 30.8±2.06 at a 0–30 cm horizontal distance and 31–60 cm depth (Fig 2). Minimum root numbers (2.5 ± 1.73, 3.0 ± 0.81 and 4.5 ± 1.29) noted in 121-150 cm horizontal distance, 31-60 and 0-30 cm deep respectively, root numbers were moderately recorded at 61-90 horizontal distance, 0-30 cm deep, 31-60 cm horizontal distance up to0-30 cm soil depth and 0-30 cm horizontal distance and 0-30 deep in aonla.

Maximum roots (56 ± 4.55) were recorded at 0-30 horizontal distance, 31-60 cm deep, while as moderate root number40.2 ± 4.11, 38.8 ± 7.37 at 31-60horizontal distance and 31-60 cm deep from soil surface, 31-60 cm horizontal distance and 0-30 cm deep from soil surface respectively, while minimum roots (1.75 ± 0.957, 8± 1.63) were noted in 91-120 cm horizontal distance with 0-30 cm deep from soil surface in bael. In jamun, highest root counts, 65.8 ± 7.93 and 60.5 ± 9, were observed at soil depths of 0–30 cm and 31–60 cm within the 31–60 cm and 0–30 cm horizontal distances, respectively. A moderate number of roots, 45.8 ± 4.92, was recorded at a 0–30 cm horizontal distance and 0–30 cm depth. The lowest root numbers, 4.5 ± 1.29, were noted at a 61–90 cm horizontal distance and at soil depths of both 0–30 cm and 31–60 cm.

Total root weight having fibrous type recorded in all four crops at different horizontal distance and depth. Maximum root mass (g) 38.2 ± 5.74 (g) were recorded in 0-30 cm, horizontal distance and 0-30 cm deep and moderate roots in mass recorded (17.8 ± 4.2 g) in 0-30 cm horizontal distance and 31-60 cm deep from soil surface. However, minimum roots 2.65 ± 0.507 g, 2.85 ± 0.889 g, noted in 91-120 cm horizontal distance 31-60 cm deep from soil surface and 121-150 cm horizontal distance, and 0-30 cm deep from soil surface respectively in guava (Table 1). In aonla, highest root mass (49.2 ± 5.94 g) was found at a 0–30 cm horizontal distance and 31–60 cm depth.

Moderate root mass (21.4 ± 10.5 g) appeared at 31–60 cm distance and 0–30 cm depth, while the lowest (3.52 ± 3.75 g) was at 121–150 cm distance and 31–60 cm depth (Table 1). In bael, highest root mass (58.5 ± 6.81 g) was found at 31–60 cm horizontal distance and 0–30 cm depth, with moderate roots (23.2 ± 2.5 g) at 61–90 cm distance and 31–60 cm depth. The lowest root mass (5.25 ± 2.0 g) was recorded at 61–90 cm distance and 0–30 cm depth, as well as at a 91–120 cm distance at both 0–30 cm and 31–60 cm depths (Table 1). For jamun, maximum root mass (133 ± 4.24 g, 141 ± 9.76 g) occurred at 0–30 cm distance at 0–30 cm and 31–60 cm depths, while moderate roots (73.5 ± 2.65 g, 43.5 ± 2.65 g) were at 31–60 cm distance at both depths. The minimum root mass (8.65 ± 2 g, 8.18 ± 0.98 g) was observed at a 91–150 cm distance at 31–60 cm and 0–30 cm depths (Table 1).

The data revealed that longest root (22.8 ± 7.14 cm, and 19.2 ± 1.7 cm)was noted in 0-30 cm horizontal distance from tree trunk, 0-30 cm depth of soil surface in guava,while smallest roots (10.5 ± 6.6 and 10.8 ± 8.81 cm)was recorded in 31-90 cm horizontal distance and 0-60 cm deep from soil surface (Table 2). Aonla recoded longest roots 28.2 ± 2.6 cm at 0-30 cm horizontal distance at 31-60 cm depth of soil surface and medium root length (17.8 ± 7.37 cm) recorded in 0-30 cm horizontal distance at 0-30 cm depth of soil surface. Smallest roots 8.25 ± 6.6 cm, 8.75 ± 4.19 cm were recorded in 121-150 cm horizontal distance and 0-60 cm depth from soil surface (Table 2).

Longest roots (19.21 ± 8.18 cm) noted in 0-30 cm horizontal distance at 0-30 cm depth from soil surface, smallest roots of 6.8 ± 2.56 cm, recorded in 121-150 cm horizontal distance and 31-60 cm deep in Jamun (Table 2). The average root number which comprise fibrous, thin, thick and very thick roots vary from main trunk to out wards in all crops planted under high density system.In guava, aonla and bael maximum average roots recorded 31 cm to 61 cm of horizontal distance from tree trunk in contrary to the jamun 0-30 cm horizontal distance exhibited maximum rootsper block. Similarly, more quantity of roots was noted in 0-60 cm of horizontal distance from tree trunk up to 0-30 cm soil depth in guava, aonla, bael and jamun under high density planting system.

These results are in agreement with (Darmwal*et. al.*,2018) in mandarin citrus during spring season. Misra and Jaiswal, (2001), reported maximum concentration of weight of fibrous nature roots in Karonda recorded at 0-20 cm deep from soil surface it decreased with increasing the soil depth.Root dry weight indicating the amount of carbon in root system which gives an initial estimate of carbon costs of producing and minatory the roots.As we move outward from main trunk of tree the dry weight of all category of roots were reduced significantly decreased, as reported by (Singh and Misra, 2000) in bael during spring season, similar findings were also reported by (Misra and Jaiswal 2001, Misra and Dabral, 2005) reported that in litchi, maximum weight of active roots were recorded at 0-30 cm deep from soil surface and root concentration drastically decreased with increasing soil depth, in 31-60 cm depth from soil surface.

Similar observations were recorded by (Rathore *et.al.*,2013) that root density was found maximum at nearest radial distance from tree trunk in aonla. Nagrojah, (1987) also reported root concentration in 40-60cm depth and decreased after wards. Root length influenced the nutrient and water uptake in the plant system rather than root mass (Gardener 1964, Nye and Tinker 1969). The root length densities of most crops decreased with the depth and horizontal distance from tree. The branching model of root is the indicator of different root functions (Van Noordwijk and Willigen, 1991). Length of longest root roughly explains the exploration of the soil zones. Proximal root diameter and total root length of all root link depend upon root branching pattern (Van Noordwijk*et al.*,1991).

Majority of roots at deeper layers of soil surface in Aonla and Jamun under HDP system indicated that the trees having ability to extracts water from lower horizons. Importance of deeper tree roots was described by (Stone and Kalisz, 1991) and (Akinnfesi *et. al.* 2004). He further stated that rooting depth of different species in plant system is crucial to determine competition for water and nutrients, however the roots are shallow in annual crops.

CONCLUSION

It is concluded that maximum roots in guava and aonla were recorded at 31-60 cm horizontal distance and 31-60 cm depth from soil surface, while in jamun roots were maximum at 31-60 HD and 0-30 cm depth from soil surface from main trunk.Jamun and aonla planted under high-density planting system having maximum root biomass 31-60 cm deep from SS and 0-30 cm horizontal distance(HD) from tree trunk, while in bael and guava maximum roots biomass were observed at 0-30 cm deep from soil surface and 0-30 cm HD from tree trunk except in bael where more root mass were noted 31-60 cm HD.

REFERENCES

Akinnifesi FE, Rowe S, Livesley F, Kwesign B, Vanlauwe and Alegre J. 2004. Tree architecture. Below ground

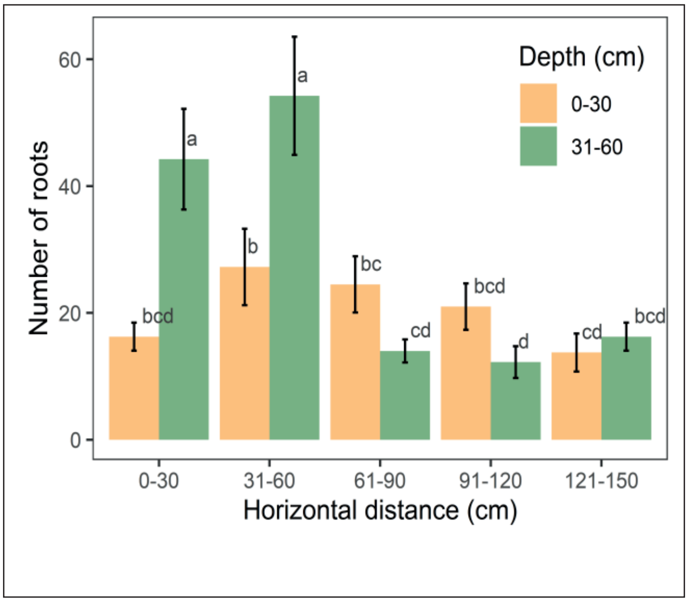

Fig. 1: Effect of horizontal distance and depth on number of roots in guava

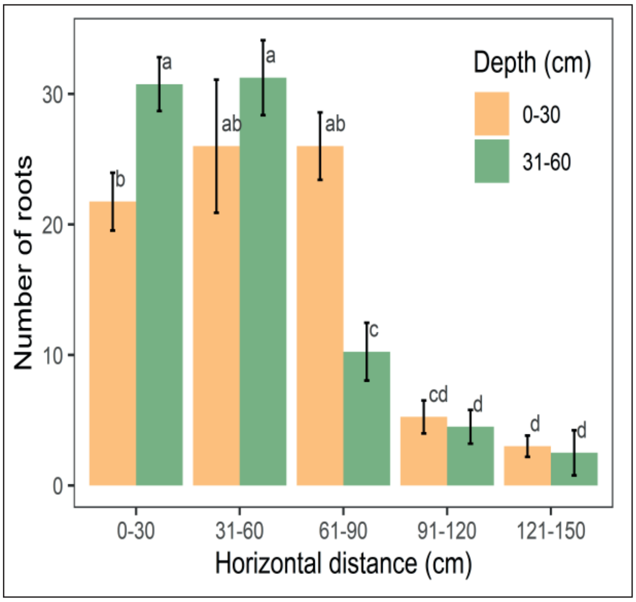

Fig. 2: Effect of horizontal distance and depth on number of roots in aonla

Table 1: Effect of horizontal distance (HD) and depth on root weight (g)

Horizontal distance (cm)	Depth (cm)	Guava	Aonla	Bael	Jamun
0-30	0-30	38.2±5.74a	10.8±6.34bcd	13.5±2.51b	133±4.24a
0-30	31-60	17.8±4.27b	49.2±5.94a	11.7±5.39b	141±9.76a
31-60	0-30	12±3.16bc	7.24±1.9cd	58.5±6.81a	73.5±2.65b
31-60	31-60	7.75±2.22cd	21.4±10.5b	23.2±2.5b	43.5±2.65c
61-90	0-30	8.75±2.06cd	18.2±10.3bc	5.25±2.06b	21.7±4.98d
61-90	31-60	6.48±2.07cd	11.4±11.4bcd	22.1±24.7b	12±2.16de
91-120	0-30	9.6±4.24cd	12.2±10.4bcd	9.07±1.35b	33.8±4.2c
91-120	31-60	2.65±0.507d	8.5±2.38bcd	7.71±1.25b	8.65±2.06e
121-150	0-30	2.85±0.889d	7.75±4.27cd	17.4±1.7b	8.18±0.984e
121-150	31-60	5.82±2.79cd	3.52±3.75d	15.2±2.88b	7.62±1.11e

Table 2: Effect of horizontal distance (HD) and depth on root length

Horizontal distance (cm)	Depth (cm)	Guava	Aonla	Bael	Jamun
0-30	0-30	19.2±1.71a	17.8±7.37a	13±7.83a	19.2±2.06a
0-30	31-60	22.8±7.14a	11±7.16a	11±6.83a	16±1.83a
31-60	0-30	11.5±6.56a	11.8±7.59a	11±8.04a	14±8.21a
31-60	31-60	10.5±6.61a	11.2±7.14a	13±9.59a	11±6.58a
61-90	0-30	10.8±8.81a	13.1±8.57a	9.5±5a	13±5.72a
61-90	31-60	15.5±5.2a	10±7.53a	9.5±5.51a	15.2±13.3a
91-120	0-30	13±5.16a	28.2±28.6a	14.5±8.19a	8.75±1.26a
91-120	31-60	13.5±2.38a	9.25±5.44a	7±3.92a	11.8±4.79a
121-150	0-30	17.8±3.3a	8.25±6.6a	9.75±6.95a	10.2±4.11a
121-150	31-60	12.8±3.3a	8.75±4.19a	11.5±6.45a	6.75±1.71a

interaction in Tropical Agroeco system: Concepts and Models with Multiple plant concepts.Van Noordwijk M, Cadisch G and Ong C. (Eds). CABI International, Wallingford, U.K., pp: 61-82.

Darmwal MNK, Mishra KK, Mishra and Devi Pooja 2018. Studies on effect of season, radial distance and depth on root distribution pattern of Kinnow mandarin. *International Journalof Chemical Studies* **6**(4):1005-1008.

Gardener WR. 1964. Relation of root distribution to water uptake and availability. *Agronomy Journal* **56:**41-45.

Srivastava KK, Kumar Dinesh, Saroj P L, Singh S R and Barman Prananath 2024. Effect of container size on yield and root morphology of different fruit crops.*Current Horticulture* **12**(3): 24–29, DOI: 10.48165/chr.2024.12.3.02

Misra KK and Babral M. 2005. Studies on root distribution pattern of litchi. *Progressive Horticulture* **37**:124-27.

Misra KK and Jaiswal HR. 2001. Studies on the root distribution pattern of Karonda. *Advances in Horticulture science* **8**(75):80.

Nagrojah S. 1987. : Effect of soil texture on the rooting pattern of 'Thompson Seedless [10] vines on own roots and on Ramsey rootstock in irrigated vineyard. *American Journal of Enology and Viticulture* **38**:54-58.

Nye PH and Tinker PB. 1969. The concept of root demand coefficient. *Journal of Applied Ecology* **6:**293-300.

Rathorem RS, Kaushik RA and Poonia MK. 2013. Studies the rooting pattern of Aonla by rooting pattern of aonla by root excavation technique. *Progressive. Agriculture* **13**(1):15-19.

Singh AK and KK Mishra 2000.Seasonal variation in root distribution pattern of bael (*Aegle marmelos*). *Indian Journal ofAgrilculturalSciences* **70**(10):717-18.

Southey JM and Archer E. 1988. The effect of rootstock cultivar on grapevine root distribution and density. In: The Grapevine Root and its Environment Viticultural and Oenologicxal Research Institute. Pretoria, South Africa, pp: 57-73.

Stone EL and Kalisz PJ. 1991. on the maximum extent of tree roots,*Forest Ecology and Management* **46**:59-102.

Van Noordwijk, Hairiah MKM, Syekhfani and Flach B. 1991a. Peltophorumpterocarpa- a tree with a root distribution suitable for alley cropping. *In: Plant Roots and their Environment.* Person, H. and Mc Michael, B L (eds.) Elsevier, Amsterdam, The Netherlands, pp: 526-532.

Williams LE and Smith RJ. 1991. The effect of rootstock on the portioning of dry weight, nitrogen and potassium and root distribution of Cabernet sauvignon grapevine. *American Journal of Enology and Viticulture* **42:**118- 22.

Current Horticulture **13**(4): 74–77, October–December 2025
DOI: 10.5958/2455-7560.2025.00059.X
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Performance of pomegranate (*Punica granatum*) cultivars under semi-arid condition of Haryana

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Abstract

The experiment was conducted at Department of Horticulture, CCS HAU, Hisar, to evaluate the growth performance of ten different pomegranates germplasm, viz Mridula, Bhagwa, Kandhari, Ganesh, Jodhpur Red, Jalore Seedless, Basein Seedless, Wonderful, S1 and S2 in semi-arid condition of Haryana, during 2018-19. Data revealed that maximum plant height (3.39 m) was observed in cv. Bhagwa and minimum (2.34) in S1. Plant spread was recorded maximum in cv. Bhagwa in the both direction (3.15 m E-W and 3.05 m N-S) and minimum in Mridula (2.05 m) in E-W direction and S1 (2.01m) in N-S direction. Majority of pomegranate varieties had spreading type of growth habit except Mridula and Bhagwa which had drooping type. Number of thorns was maximum (29) in Mridula and minimum (21) in Basein Seedless. Maximum leaf blade length and width was recorded in Mridula (8.30 cm and 2.82 cm) and minimum in Bhagwa (4.82 cm and 1.65 cm). Mridula, Bhagwa, Basein Seedless, Kandhari, Wonderful, S1 and S2 had lanceolate type of leaf blade shape, whereas Jodhpur Red, Ganesh and Jalore Seedless had broad elliptic type. Leaf petiole length was observed maximum (9 mm) in Kandhari and minimum (5.66 mm) in Jodhpur Red.

Key words: Growth, Plant height, Petiole, Semi-Arid, Tropical, Subtropical, Rain fed

Pomegranate (*Punica granatum* L.) is one of the important fruit crops of tropical and subtropical regions of family Punicaceae (Sarkhosh *et al.*, 2025). A native fruit of Iran (Nemati *et al.*, 2012), it is grown in India, Baluchistan, China, Japan, USA and Afghanistan (Sarkhosh *et al.*, 2009). In India, it grows in about 2.7 lakh ha and producing 30.86 lakh tonnes (Government of India 2023). The tree can thrive well in wide range of soil types and climate, but it requires long, hot and dry season to produce better yields (Holland *et al.*, 2009). The crop is drought tolerant and winter hardy (Soloklui *et al.*, 2012) and can be effectively grown even under the purely rain fed condition. It can also tolerate moderate saline, calcareous and slightly alkali soils. Pomegranate cultivation has quickly expanded because of its superior adaptability, resistance to diverse stresses, high remuneration value and multipurpose nature of the fruit (Solanki *et al.*, 2023). However, for its commercially utilization, the evaluation of genotype is the area of major concern. The semi-arid conditions of Haryana proved to be partially suitable for its cultivation, consequently it can be considered as a potential fruit for Haryana state. Hence an experiment was conducted to study the adaptability of its different varieties on the basis of growth performance of different germplasm.

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MATERIALS AND METHODS

The experiment was conducted out at Department of Horticulture, CCS HAU, Hisar, during 2018-19. The experiment site is positioned at an elevation of 215.2 m above sea-level, marked by coordinates of 29° 10" N latitude and 75° 46" E longitudes. Hisar has semi-arid climate characterized by hot and dry summer and exceedingly frigid winter. It receives annual rainfall of about 450 mm, mostly during the month of July - September, and also receive some drizzling during December to February due to western disturbances. Evaluation of 10 pomegranate germplasm (Mridula, Bhagwa, Kandhari, Ganesh, Jodhpur Red, Jalore Seedless, Basein Seedless, Wonderful, S1 and S2) was carried out in a randomized block design with three replications. For research work, seven years old uniformly grown trees were randomly selected and kept under uniform condition of orchard management where every facet of orchard management adhered rigorously to the prescribed package of practices. Different vegetative parameters were recorded at appropriate growth stages, following the guidelines outlined in the NBPGR descriptor as well as directives for DUS testing of Plant Protection Variety and Farmers Rights (PPV&FRA, 2016).

For measuring bush/tree height (m) three individual bush/tree of each germplasm randomly selected and were marked as replications in the field. The height was gauged using graduated measuring pole from ground level to the tip of the highest shoot. Plant spread (m) was assessed in both directions, i.e. from north to south and east to west with the help of the graduated measuring bar. The growth habit of tree was noticed and recorded as per its visual appearance and expressed as upright/spreading/drooping. The number of thorns/m of shoot length was counted and interpreted as per the guidelines of DUS testing of PPV and FRA (PPV&FRA, 2016). Foliage density of a pomegranate tree was observed in running per meter and elucidated as sparse (less foliage density), medium (the density of foliage lies between dense and sparse) and dense (leaf were observed so close on branches). Five leaves were randomly selected from each side of each tree/replication for leaf blade length (cm) and width (cm) and it was measured using measuring scale.

The average value of replications was calculated. Shape of the leaf blade was visually observed and depicted as elliptic lanceolate (leaves are significantly longer and broader in the middle and the two ends narrow equally), lanceolate (leaves are significantly longer than wide and widest below the middle gradually tapering toward the axis) and broad elliptic (leaves are oval in shape widest from the middle part). Leaf apex shape was observed visually and interpreted as acute (leaf margin tapers to a point at the apex), obtuse (the leaf apex is blunt to rounded and a little pointed) and rounded (leaf apex is totally rounded). For petiole length (mm)**,** from each side of each tree/replication five leaves were randomly selected and measured with the help of measuring scale. The petiole anthocyanins coloration was observed visually and interpreted as per cent part covered as low (<25 %), medium (25-50 %) and high (>50 %) given in the guidelines for DUS testing of PPV and FRA (Anonymous, 2016). The data collected were statistically evaluated using Fishers (1958) analysis of variance (ANOVA) technique. The mean value of different parameters was compared using critical difference. The entire statistical analysis was carried out by statistical software OPSTAT.

RESULTS AND DISCUSSION

The plant height of different pomegranate germplasm varied from 2.34 m to 3.39 m. Maximum plant height was noticed in Bhagwa (3.39 m), which was statistically at par with Jodhpur Red (3.31 m), whereas minimum was in S1 (2.34 m) (Table 1). The difference in plant height might be also due to the individual growth behaviour of genotype (Dubey *et al.*, 2002). These variations may also be attributed to genetic makeup of plant. However, the variations in plant height of the same varieties in a different area may be due to adaptability and performance of varieties with the prevailing local climatic condition. The results are similar to those of Wani *et al.* (2012). Plant spread was recorded maximum in Bhagwa in both directions. Whereas, minimum plant spread was noticed in variety Mridula (2.05 m) in E-W direction and S1 (2.01m) in N-S direction. Meena *et al.* (2011) also reported that minimum plants spread in N-S and E-W direction was observed in Sur Sakkar and Jyoti, whereas, 'Jodhpur Red' exhibited maximum E-W spread and 'Ganesh' maximum N-S spread.

Data on growth habit (Table 1) elucidates that majority of pomegranate varieties, Ganesh, Kandhari, Jodhpur Red, Jalore Seedless, Basein Seedless, Wonderful and, S1 and S2 had spreading type of growth habit, whereas Mridula and Bhagwa had drooping type of growth habit. The differences in growth of varieties might be due to their genetic makeup, prevailing climatic condition and/or the interaction effect of genotype with environment. The cultivars must be selected on the basis of their performance under particular condition because the same variety behaves differently with a change in agroclimatic conditions. The results are in accordance with Sharma *et al,* 2010. Foliage density was observed dense in pomegranate varieties, viz. Mridula, Bhagwa, Ganesh, S1 and S2, whereas it was medium in Kandhari, Jodhpur Red, Jalore Seedless, Basein Seedless and Wonderful.

The difference in foliage density among genotypes might be due to a genetic feature of a particular variety. This type of variation was also noticed by Shalu *et.al* (2017) and Sharma *et.al* (2010) in guava and Mor *et. al* (2022) in Phalsa. Data on number of thorns showed significant variations among different varieties (Table 1). The number of thorns/m of shoot length ranges from 21 to 29. The maximum (29) was reported in variety Mridula which was statistically at par with Ganesh, whereas the minimum (28) number of thorns was observed in variety Basein Seedless (21). The observed differences in numbers of thorn among germplasm under different agroclimatic condition might be due to their genetic makeup. Khanizadeh *et al.* (2016) and Srivastava *et al.* (2023) also observed variations in number of thorns in pomegranate cultivars.

In Mridula, maximum leaf blade length (8.30 cm) was recorded, which was statistically at par with Basein Seedless (7.76 cm). The minimum leaf blade length was recorded in cultivar Bhagwa (4.82 cm). The results are more or less in close conformity with those of Singh (2012). Leaf blade width ranged from 1.65 cm to 2.82 cm. The maximum leaf blade width (2.82 cm) was recorded in variety Mridula which was statistically at par with Jalore Seedless (2.45 cm), Basein Seedless (2.57 cm) and Wonderful (2.56 cm). While, minimum leaf blade width was observed in variety Bhagwa (1.65 cm). Singh (2012) observed maximum leaf width in variety Kurvi-2EL-24685 and minimum in Kali Sirin. Mridula, Bhagwa,

Table 1: Bush/ tree height, spread, growth habit, foliage density and number of thorns of pomegranate varieties under semi-arid condition of Haryana

Variety	Plant height (m)	Plant spread (m) E-W	Plant spread (m) N-S	Growth habit	Foliage density	Number of thorns/m shoot length
Mridula	2.40	2.05	2.02	Drooping	Dense	29
Bhagwa	3.39	3.15	3.05	Drooping	Dense	26
Ganesh	2.65	2.34	2.21	Spreading	Dense	28
Kandhari	2.95	2.58	2.46	Spreading	Medium	25
Jodhpur Red	3.31	2.98	2.88	Spreading	Medium	23
Jalore Seedless	2.35	2.06	2.03	Spreading	Medium	23
Basein Seedless	2.64	2.19	2.12	Spreading	Medium	21
Wonderful	2.61	2.18	2.06	Spreading	Medium	22
S1	2.34	2.08	2.01	Spreading	Dense	26
S2	2.42	2.10	2.02	Spreading	Dense	26
CD (P=0.05)	0.12	0.12	0.10	--	--	1.1

Table 2: Leaf blade size, shape, leaf petiole length, leaf apex shape and anthocyanin's coloration in pomegranate varieties

Variety	Leaf blade length (cm)	Leaf blade width (cm)	Leaf blade shape	Leaf petiole Length (mm)	Leaf apex shape	Anthocyanins coloration
Mridula	8.30	2.82	Lanceolate	6.67	Obtuse	Medium
Bhagwa	4.82	1.65	Lanceolate	6.00	Obtuse	Medium
Ganesh	5.00	2.02	Broad elliptic	6.00	Rounded	High
Kandhari	7.14	2.17	Lanceolate	9.00	Obtuse	Low
Jodhpur Red	6.44	2.39	Broad elliptic	5.66	Acute	High
Jalore Seedless	6.52	2.45	Broad elliptic	7.34	Obtuse	Medium
Basein Seedless	7.76	2.57	Lanceolate	8.67	Obtuse	Low
Wonderful	6.54	2.56	Lanceolate	7.33	Acute	High
S1	6.54	2.23	Lanceolate	6.67	Obtuse	High
S2	7.04	2.19	Lanceolate	7.33	Obtuse	High
CD (P=0.05)	0.95	0.45	--	0.33	--	--

Basein Seedless, Kandhari, Wonderful, S1 and S2 showed lanceolate type of leaf blade shape, however Jodhpur Red, Ganesh and Jalore Seedless had broad elliptic type of leaf shape. The variation in shape of leaf blades among different germplasm might be due to a genetic trait of a particular variety. Nath and Randhawa (1959) also observed similar type of variation. They found ovate lenceolate leaf shape with the acute apex. Muscat White, broadly lanceolate leaf shape with the blunt apex in cv. GBG-1 and lanceolate leaf shape with acute apex in Dholka.

Leaf petiole length was maximum in Kandhari (9 mm), which was significantly higher than all other varieties except Basein Seedless (8.67 mm) which was statistically at par with variety Kandhari. However, minimum leaf petiole length (5.66 mm) was observed in variety Jodhpur Red. The possible reason for difference in petiole length and petiole width among the pomegranate germplasm might be due to genetic makeup and environmental factors. Mridula, Bhagwa, Kandhari, Jalore Seedless, Basein Seedless, S1 and S2 had an obtuse type of leaf apex shape, Jodhpur Red and Wonderful had an acute type, whereas Ganesh had rounded type of leaf apex shape (Table 2). The variation in leaf apex shape might be due to a genetic feature of a particular variety. Data on petiole anthocyanins coloration in pomegranate varieties was represented as low, medium and high (Table 2). Results showed that varieties Kandhari and Basein Seedless had low anthocyanins coloration, Mridula, Jalore Seedless, Bhagwa had medium and Ganesh, Jodhpur Red, Wonderful, S1 and S2 had high petiole anthocyanins coloration.

CONCLUSION

There was ample variation in different pomegranate germplasm in plant height and plant spread were found maximum in Bhagwa. Leaf blade size and shoot thorniness were maximum in Mridula and petiole length was maximum in Kandhari.

REFERENCES

Dubey P S, Hoda M N and Singh S. 2002. Studies on growth behaviour of guava germplasm under Sabour conditions for rainy season fruiting. *Indian Journal of Horticulture* **57**(4): 326-28.

Fisher R A. 1958. Statistical Methods for Research Workers (13th edn). Oliver and Boyd, London.

Government of Haryana. 2023. Final data Area and Production 2022-2023. Horticulture Department. https://hortharyana.gov.in/en/statistical-data

Government of India. 2023. Area and Production of Horticultural Crops for 2021-2022 (Final). Department of Agriculture and Farmers Welfare. https://agricoop.nic.in/en/StatHortEst

Hasnaoui N, Mars M, Ghaffari S, Trifi M, Melgarejo P and Hernandez F. 2011. Seed and juice characterization of pomegranate fruits grown in Tunisia: Comparison between sour and sweet cultivars revealed interesting properties for prospective industrial applications. *Industrial Crops and Products* **33**(2): 374-81.

Holland D, Hatib K and Bar-Ya'akov I. 2009. Pomegranate: Botany, Horticulture, Breeding. *Horticultural Reviews* **35**(2): 127-91.

Khanizadeh S, Jafarpour M and Shenas M R V. 2016. Investigation of morphological and phenological traits of ten cultivars of pomegranate in the Yazd and Mehriz weather condition. *International Journal of Advance Biotechnological Research* **7**: 466-95.

Meena K K, Singh R, Pareek S, Kashyap P, Sheikh M, Mokashi A and Rokhade A. 2011. Evaluation of pomegranate (Punica granatum L.) genotypes for morphological and flowering characteristics under semi-arid climate. *Acta Horticulturae* **890**: 233-37.

Mor R, Kumar M, Kumar S, Kumari S and Jat M L. 2022. Decipheration of flowering and fruiting characters in phalsa (Grewia subinaequalis) germplasm under semi-arid region of Haryana. *Current Horticulture* **10**(2): 62-65.

Nemati Z, Tehranifar A, Farsi M, Kakhki AM, Nemati H and Khayat M. 2012. Evaluation of genetic diversity of Iranian pomegranate cultivars using fruit morphological characteristics and AFLP markers. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **40**: 261-68.

PPV & FRA. 2016. Guidelines of PPV and FRA for the conduct of test for distinctiveness, uniformity and stability on Indian gooseberry (*Emblica officinalis* Gaertn.). *Plant Variety Journal of India* **10**(2).

Sarkhosh A, Zamani Z, Fatahi R and Ranjbar H. 2009. Evaluation of genetic diversity among Iranian soft-seed pomegranate accessions by fruit characteristics and RAPD markers. *Scientia Horticulturae* **121**: 313-19.

Shalu R, Sharma J R and Jakhar M S. 2017. Assessment of genetic diversity and diversity relationship in different varieties of guava using morphological characterization. *Plant Archives* **17**(1): 307-311.

Sharma A, Sehrawat S K and Singhrot R N. 2010. Morphological and Chemical Characterization of Psidium species. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **38**(1): 28-32.

Singh A K, Yadav V, Yadav L P, Rao V A, Rane J and Sahil A. 2025. Fruit crops of Indian semi-arid regions: significance, conservation and utilization strategies—a review. *Current Horticulture* **13**(2): 13-27.

Singh D B. 2012. Characterization and evaluation of pomegranate germplasm under Indian arid ecosystem. *Indian Journal of Plant Genetic Resources* **25**(2): 139-45.

Solanki S M, Jat R K, Lunagariya R J, Jat M L and Kumar M. 2023. Effect of biofertilizers and growing media on growth of air-layers of pomegranate (*Punica granatum*). *Current Horticulture* **11**(2): 74-75.

Soloklui A A G, Ershadi A and Fallahi E. 2012. Evaluation of cold hardiness in seven Iranian commercial pomegranate (*Punica granatum* L.) cultivars. *HortScience* **47**(12): 1821-825.

Srivastava K K, Kumar D, Saroj P L, Singh S R and Barman P. 2023. Effect of container size on yield and root morphology of different fruit crops. *Current Horticulture* **11**(2): 29-32.

Wani I A, Bhat M Y, Lone A A, Ganaie S A, Dar M A, Hassan G I, Mir M M and Umar I. 2012. Screening of various pomegranates *Punica granatum* L.) selections of Kashmir valley. *African Journal of Agricultural Research* **7**(30): 4324-330.

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Standardization of organic cultivation practice for enhancing yield and quality of turmeric (*Curcuma longa*) in terai region of West Bengal

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Abstract

A field experiment was conducted at ICAR–National Institute for Research on Commercial Agriculture, Research Station, Dinhata, West Bengal to standardize organic nutrient management for turmeric (*Curcuma longa*) (Lakadong). The trial was laid out in randomized block design with twelve treatment combinations. The results revealed that application of recommended fertilizer dose (120:80:120 kg ha-^{1}) gave total fresh rhizome yield of 9.7 t/ha which was on a par with FYM (40 t/ha) + microbial consortium with total fresh rhizome yield (9.5 t/ha). The highest curcumin (4.5 %) was obtained in the application of Vermi compost @ 10 t/ha followed by 4.3 % in application of FYM (40 t/ha) + microbial consortium which were statistically at par. Therefore, application of FYM (40 t/ha) + microbial consortium can be recommended for cultivation of Lakadong turmeric in terai region of West Bengal.

Key words: Turmeric, Organic, Yield, Curcumin

Turmeric (*Curcuma longa* L.), a perennial spice of the family Zingiberaceae, is one of India's most important crops, valued for its culinary, medicinal, and cultural uses. In Ayurveda, it is known for its antioxidant, antimicrobial, anti-inflammatory, and anticancer properties (Verma *et al.*, 2019; Mandi *et al.*, 2025). India leads globally in turmeric production and export, noted for high curcumin content and superior quality. However, in West Bengal, the area (18,000 ha) and productivity (2.5 t ha-^{1}) remain below the national average (4.7 t ha-^{1}) (Dutta *et al.*, 2017; Verma *et al.*, 2019; Mandi *et al.*, 2025). Being a nutrient-exhaustive crop, turmeric requires balanced nutrition for optimum yield. Overuse of chemical fertilizers deteriorates soil health, while organic manures enhance soil structure, microbial activity, and sustainability (Dinesh *et al.*, 2010; Parikh *et al.*, 2020). Previous studies reported higher yield and quality in Lakadong with integrated organic nutrient management involving vermicompost, FYM, and microbial inoculants (Verma *et al.*, 2019; Yumnam and Swami, 2022). However, such organic practices are yet to be standardized for the *terai* region of West Bengal. Hence, the present study aimed to identify suitable organic nutrient sources for enhancing yield and quality of Lakadong turmeric under *terai* conditions.

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MATERIALS AND METHODS

The experiment was carried out at ICAR-NIRCA Research Station Dinhata, Cooch Behar, West Bengal, during 2021-22, 2022-23 and 2023-24. The experiment was laid out in Randomized Block Design (RBD) with three replications in variety Lakadong. Different treatments in this experiment were as T_1: Control; T_2: Recommended dose of NPK (120: 80:120), T_3: FYM (40 t/ha); T_4: maize straw compost (MSC) (50 t/ha); T_5: pond settled mud (50 t/ha); T_6: vermicompost (10 t/ha); T_7: FYM (40 t/ha) + microbial consortium ; T_8: maize straw compost (40 t/ha) + microbial consortium; T_9: pond settled mud (50 t/ha) + microbial consortium; T_{10}: FYM (20 t/ha) + vermicompost (5 t/ha); T_{11}: maize straw compost (20 t/ha) + vermicompost (5 t/ha) + microbial consortium; T_{12}: Pond setlled mud (25 t/ha) + vermicompost (5 t/ha) + microbial consortium.

Observations on different morphological and yield attributing characters were recorded from three randomly selected plants from each plot. Rhizome yield per hectare was calculated on the per plant weight basis. Curcumin content of dry turmeric rhizome was estimated as suggested by Jansirani *et al.* (2014). The replicated data of yield and quality parameters of three years were pooled and subjected to statistical analysis using software available at https://www.kaugrapes.com/analysis-of-experiments/rbd-analysis. Data were subjected to analysis of variance (ANOVA) to evaluate the significance of treatment means. Means were separated using at 5 % level of significance (Gomez & Gomez, 1984). Correlation was also performed between different growth, yield and quality parameters and correlated them with total fresh rhizome yield.

RESULTS AND DISCUSSION

The pooled data of different growth parameters varied significantly by application of different organic and inorganic treatments. The plant height varied from 61.2 cm to 136.4 cm. In pooled analysis, highest plant height (136.4 cm) was observed with application of recommended dose of NPK (120: 80:120 kg/ha) which was significantly different from all the treatments Table 1). The similar observation was recorded by Ronya *et al.* (2020) where maximum plant height was obtained in recommend fertilizer dose. The second highest plant height (114.6 cm) was observed with application of FYM @40 t/ha which was statistically at par with application of FYM (20 t/ha) + vermicompost (5 t/ha) with plant height of 109.4 cm. The higher values in plant height might be due to balanced availability of all the essential mineral nutrients resulted in better growth and development of the plant. Yumnam and Swami (2022) found higher plant height with the application of 50% RDN through urea + 50% N through vermicompost. Our study contradicts the finding of Dutta *et al.* (2017) where maximum plant height was found with application of green leaf manure @ 12 t/ha + rock phosphate @ 200 kg/ha + *Azospirillium* @5 kg/ha + wood ash @ 1 t/ha + PSB @ 5 kg/ha. The number of leaves/plant varied significantly under different treatment combinations. The maximum number of leaves/plant (10.2) was obtained in application of FYM @40 t/ha + microbial consortium which was statistically at par with the application of pond settled mud (25 t/ha) + vermicompost (5 t/ha) + microbial consortium having same number of leaves (10.2). The lowest number of leaves (5.4) was obtained in control treatment. Kadam and Kamble (2020) and Ronya *et al.* (2020) found maximum number of leaves/plant in recommended dose of fertilizer which contradicts the present findings.

There was significant difference between the treatments for fresh rhizome weight per plant. The highest fresh rhizome weight per plant (116.9 g) was observed in the application of recommended fertilizer dose followed

Table 1. Plant height, number of leaves per plant, total fresh rhizome weight per plant, total fresh rhizome yield of turmeric variety Lakadong under different treatments (Pooled data of 3 years)

	Plant height (cm)	Number of leaves/plant	Fresh rhizome weight (g) plant	Total fresh rhizome yield (t/ha)
T^1	67.7^{ef}	5.4^{i}	76.3^{g}	6.3^{g}
T^2	136.4^{a}	9.1^{b}	116.9^{a}	9.7^{a}
T^3	114.6^{b}	8.8^{bc}	108.1^{b}	9.0^{b}
T^4	77.7d^{e}	6.6^{h}	86.7^{f}	7.2^{f}
T^5	61.2^{f}	7.2^{fg}	101.9^{cd}	8.4^{cd}
T^6	75.5d^{e}	7.5^{ef}	88.7^{f}	7.3^{f}
T^7	105.2^{bc}	10.2^{a}	114.7^{a}	9.5^{a}
T^8	82.3^{d}	6.9^{gh}	91.5^{ef}	7.6^{ef}
T^9	76.3^{de}	6.8^{gh}	100.4^{cd}	8.3^{cd}
T^{10}	109.4^{b}	8.0^{de}	96.7^{de}	8.0^{de}
T^{11}	81.5^{d}	8.4^{cd}	114.8^{a}	9.5^{a}
T^{12}	95.6^{c}	10.2^{a}	105.2^{bc}	8.7^{bc}
S.Em.±	6.6	0.1	1.7	0.1
CD at 0.05 (P=0.05)	10.1	0.5	5.0	0.4
CV (%)	6.6	3.7	3.0	3.0

T_1: Control; T_2: Recommended dose of NPK (120: 80:120), T_3: FYM (40t/ha); T_4: maize straw compost (MSC) (50t/ha); T_5: pond settled mud (50 t/ha); T_6: vermicompost (10t/ha); T_7: FYM (40 t/ha) + microbial consortium; T_8: maize straw compost (40 t/ha) + MC; T_9: pond settled mud (50 t/ha) + MC; T_{10}: FYM (20 t/ha) + vermicompost (5 t/ha); T_{11}: maize straw compost (20 t/ha) + vermicompost (5 t/ha) + microbial consortium; T_{12}: pond settled mud (25 t/ha) + vermicompost (5 t/ha) + microbial consortium (##treatments with same letters are not significantly different)

Table 2. Pearson's correlation between different parameters

	Plant Height (cm)	Number of leaves per plant	Fresh rhizome weight per plant (g)	Total fresh rhizome yield (t/ha)	Curcumin content (%)
Plant Height (cm)	1				
Number of leaves/plant	0.678*	1			
Fresh rhizome weight/ plant (g)	0.617*	0.819**	1		
Total fresh rhizome yield (t/ha)	0.628*	0.819**	1***	1	
Curcumin content (%)	-0.095	0.313	0.222	0.217	1

*** Correlation is significant at 0.001 level; ## ** Correlation is significant at 0.01 level; ## * Correlation is significant at 0.05 level

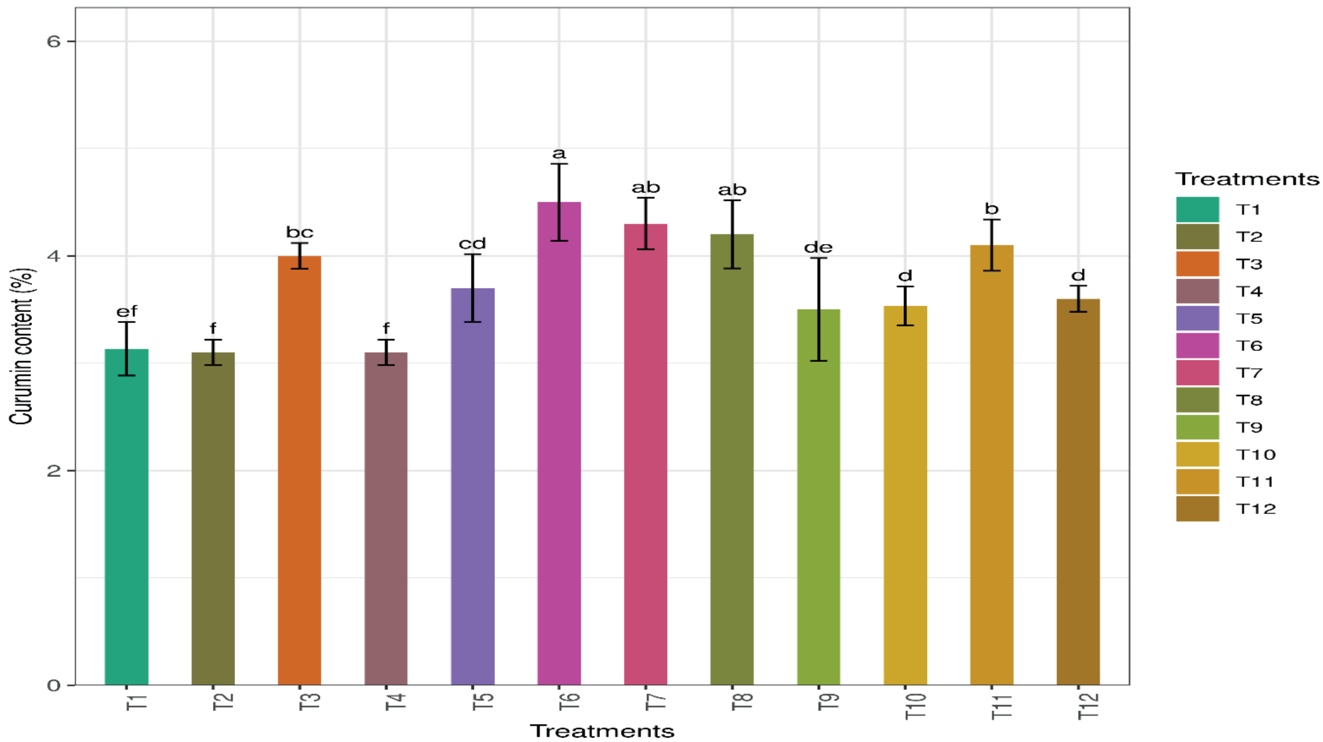

Fig. 1. Effect of different treatment combinations on curcumin content (%) (treatments with same letters are not significantly different at 5% level) T_1: control; T_2: recommended dose of NPK (120: 80:120), T_3: FYM (40 t/ha); T_4: maize straw compost (MSC) (50 t/ha); T_5: pond settled mud (50 t/ha); T_6: vermicompost (10 t/ha); T_7: FYM (40 t/ha) + microbial consortium; T_8: maize straw compost (40 t/ha) +MC; T_9: pond settled mud (50 t/ha) + MC; T_{10}: FYM (20 t/ha) + vermicompost (5 t/ha); T_{11}: maize straw compost (20 t/ha) + vermicompost (5 t/ha) + microbial consortium; T_{12}: pond settled Mud (25 t/ha) + vermicompost (5 t/ha) + microbial consortium (##treatments with same letters are not significantly different)

by 114.8 g in application of maize straw compost (20 t/ha) + vermicompost (5 t/ha) + microbial consortium and 114.7 g in FYM (40 t/ha) + microbial consortium which were all statistically at par. Our result revealed that FYM have more effect in enhancing fresh rhizome weight per plant. Total fresh rhizome yield per hectare of turmeric varied significantly with the application of different treatments. The results revealed that application of recommended fertilizer dose with total fresh rhizome yield of 9.7 t/ha which was statistically at par with that of FYM (40 t/ha) + microbial consortium and maize straw compost (20 t/ha) + vermicompost (5 t/ha) + microbial consortium which showed same total fresh rhizome yield (9.5 t/ha). Our result showed that the organic treatment such as FYM, vermicompost, microbial consortium have great influence in enhancing yield of turmeric. Yumnam and Swami (2022) reported higher fresh rhizome yield in the same Lakadong variety. In our study, yield is less over the years which could be due to environmental effect as this variety recommended for Meghalaya region. Therefore, organic treatment combinations can be tested for other economically important commercial variety of the region for enhancing yield and quality of turmeric.

Application of organic components like FYM and microbial consortium improved soil fertility and yield in turmeric (Velmurugan *et al.*, 2007; Dinesh *et al.*, 2010). Organic manure and biofertilizers enhanced vegetative growth and biomass (Mohapatra and Das, 2009), while different organic combinations positively influenced growth and yield (Sarma *et al.*, 2015). Improved performance may result from enhanced nutrient availability and microbial activity promoting photosynthate translocation to rhizomes (Dinesh *et al.*, 2010). Parikh *et al.* (2023) reported the highest rhizome weight (301.4 g/plant) and yield (32.2 t/ha) with 5% organic liquid nutrients. Vermicompost also enhances microbial activity, N_2 fixation, and phosphate mobilization, improving nutrient uptake (Kale *et al.*, 1992).

Turmeric powder and curcumin are key value-added products, with curcumin content varying from 3.1% to 4.5% across treatments (Fig. 1). The highest curcumin (4.5%) was recorded with vermicompost @ 10 t/ha, followed by FYM (40 t/ha) + microbial consortium (4.3%), both being statistically at par. Similar enhancement with vermicompost was reported by Manohar Rao *et al.* (2005). Organic manures provide balanced nutrients throughout growth, improving curcumin content (Velmurugan *et* *al.*, 2007) and enhancing yield and quality over inorganic fertilizers (Singh *et al.*, 2015). Yamawaki *et al.* (2013) also observed higher curcumin with arbuscular mycorrhizal fungi application. Parikh *et al.* (2023) recorded 3.86% curcumin and 3.23% essential oil with 0.2% humic acid. According to Anandaraj *et al.* (2014), yield is mainly environment-dependent, while curcumin content is influenced by both genotype and environment, including factors such as temperature, rainfall, and soil fertility.

Total fresh rhizome yield showed a strong positive correlation with fresh rhizome weight per plant ($r = 1.0$, $p < 0.001$) and number of leaves/plant ($r = 0.819$, $p < 0.01$). Number of leaves/plant was also positively correlated with plant height ($r = 0.678$, $p < 0.01$). Fresh rhizome weight/plant and number of leaves per plant were similarly correlated ($r = 0.819$, $p < 0.01$). A weak, non-significant positive correlation was observed between fresh rhizome weight per plant and curcumin content ($r = 0.217$) (Table 2).

CONCLUSION

The total fresh rhizome yield of turmeric variety Lakadong was significantly influenced by different organic sources. Application of FYM (40 t/ha) + Microbial consortium and Maize straw compost (20 t/ ha) + Vermicompost (5 t/ha) + Microbial consortium produced the best growth and yield. Among these, FYM + Microbial consortium proved most effective in maximizing rhizome yield and curcumin content, making it a suitable recommendation for Lakadong cultivation in the *Terai* region of West Bengal.

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REFERENCES

Anandaraj, M., Prasath, D., Kandiannan, K., Zachariah, T.J., Srinivasan, V., Jha, A.K., Singh, B.K., Singh, A.K., Pandey, V.P., Singh, S.P., Sobha, N., Jana, J.C., Kumar, K.R. and Maheswari, K.U. (2014). Genotype by environment interaction effects on yield and curcumin in turmeric (*Curcuma longa* L.). *Industrial Crops and Products* **53**: 358–64.

Dutta, S., Jana, J.C., Bhaisare, P.T. and Nimbalkar, K.H. (2017). Effect of organic source of nutrients and biofertilizers on growth, yield and quality of turmeric (*Curcuma longa* L.). *Journal of Applied and Natural Science* 9(4): 1981–1986.

Dinesh, R., Srinivasan, V., Hamza, S. and Manjusha, A. (2010). Short-term incorporation of organic manures and biofertilizers influences biochemical and microbial characteristics of soils under an annual crop [*Turmeric (Curcuma longa* L.)]. *Bioresource Technology* 101: 4697–4702.

Gomez, K.A. and Gomez, A.A. (1984). *Statistical Procedures for Agricultural Research*, 2nd edn. John Wiley and Sons, New York, pp. 13–175.

Jansirani, D., Saradha, R., Salomideborani, N. and Selvapriyadharshini, J. (2014). Comparative evaluation of various extraction methods of curcuminoids from *Curcuma longa*. *Journal of Chemical and Pharmaceutical Sciences* **12**(1): 286–88.

Kadam, J.H. and Kamble, B.M. (2020). Effect of organic manures on growth, yield and quality of turmeric (*Curcuma longa* L.). *Journal of Applied and Natural Science* **12**(2): 91–97.

Kale, R.O., Mallesh, B.C., Bano, K. and Basvaraj, D.J. (1992). Influence of vermicompost application on the available micronutrients and selected microbial population in a paddy field. *Soil Biology and Biochemistry* **24**: 1317–20.

Mandi, S., Saha, P., Saha, N.D., Bindu, J.P., Barman, J.K.R., Nambari, R., Dam, S.K., Satyanarayana, K. and Krishna, S.K. (2025). Influence of time of planting and spacing on yield and quality of turmeric (*Curcuma longa* L.) in *Terai* region of West Bengal. *Current Horticulture* **13**(3): 37–42.

Mohapatra, S.C. and Das, T.K. (2009). Integrated effect of biofertilizers and organic manures on turmeric (*Curcuma longa* L.). *Environment and Ecology* **27**(3A): 1444–45.

Parikh, R.P., Bhalerao, P.P. and Patil, S.J. (2023). Effect of foliar application of organic liquids on yield and quality of turmeric (*Curcuma longa*). *Current Horticulture* **11**(1): 30–32.

Ronya, T., Buragohain, N., Gautam, B.P., Langthasa, S., Choudhury, H. and Sarma, P.K. (2020). Effect of organics on growth, yield and quality attributes of turmeric (*Curcuma longa* L.) cv. Tall Clone. *Journal of Pharmacognosy and Phytochemistry* **9**(2): 1151–55.

Sarma, I., Phukon, M. and Borgohain, R. (2015). Effect of organic manure, vermicompost and neem cake on growth, yield and profitability of turmeric (*Curcuma longa* L.) variety Megha Turmeric-1. *Asian Journal of Biological Sciences* **10**(2): 133–37.

Singh, R.P., Jain, P.K., Verma, A. and Jhade, R.K. (2015). Yield and quality parameters of turmeric as influenced by application of biofertilizers and organic manures. *Environment and Ecology* **33**(1): 50–54.

Velmurugan, M., Chezhian, N. and Jwaharlal, M. (2007). Studies on the effect of organic manures and biofertilizers on rhizome yield and its attributes of turmeric cv. BSR-1. *The Asian Journal of Horticulture* **2**(2): 23–29.

Verma, V.K., Patel, R.K., Deshmukh, N.A., Jha, A.K., Ngachan, S.V., Singha, A.K. and Deka, B.C. (2019). Response of ginger and turmeric to organic versus traditional production practices at different elevations under humid subtropics of north-eastern India. *Industrial Crops and Products* **136**: 21–27.

Yamawaki, K., Matsumura, A., Hattori, R., Tarui, A., Hossain, M.A., Ohashi, Y. and Daimon, H. (2013). Effect of inoculation with arbuscular mycorrhizal fungi on growth, nutrient uptake and curcumin production of turmeric (*Curcuma longa* L.). *Agricultural Science* **4**: 6–71.

Yumnam, V. and Swami, S. (2022). Performance of Lakadong turmeric (*Curcuma longa* L.) under integrated application of farm yard manure, vermicompost and chemical fertilizers. *Biological Forum – An International Journal* **14**(3): 515–20.

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Assessment of frontline demonstration technology on fenugreek (*Trigonella foenum-graecum*) in cultivation Jhajjar, Haryana

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Abstract

Frontline demonstrations (FLDs) on fenugreek (*Trigonella foenum-graecum* L.) variety AFg-5 were conducted by Krishi Vigyan Kendra, Jhajjar during 2022–23 and 2023–24 on the fields of ten farmers each year. The demonstrations were carried out with active farmer participation to disseminate improved production technologies aimed at realizing the potential yield of fenugreek. The interventions included the use of a high-yielding variety, seed treatment, recommended fertilizer doses, and other non-monetary inputs. Data were recorded on plant height (cm), number of branches /plant, pest incidence (%), and seed yield (q/ha) and compared with the farmers' existing practices. The improved variety AFg-5 produced higher seed yields of 15.90 q/ha and 17.20 q/ha during 2022–23 and 2023–24, respectively, as compared to the local variety. The demonstrations revealed a mean extension gap of 2.0 q/ha, a technology gap of 3.45 q/ha and a technology index of 17.25%. The improved technology also resulted in better economic returns, recording a higher benefit–cost ratio (2.89) compared to the local check (2.59). Overall, the FLDs demonstrated a positive and significant impact of the improved technology on fenugreek seed yield and profitability over traditional practices.

Key words: Economics, Seed yield and Technology dissemination, Frontline demonstrations

Fenugreek (*Trigonella foenum-graecum* L.) is one of the important seed spice crop and oldest medicinal plant originated in Central Asia since approximately 4000 BC (Aher *et al.,* 2016). India is the major producer and consumer of fenugreek in the world with an area of 1,45,366 ha with production 2,28,649 tons seed per annum. In India, Rajasthan, Madhya Pradesh, Maharashtra, Gujarat, Punjab, Haryana, West Bengal, Uttar Pradesh and Uttarakhand are the major fenugreek producing states. In Haryana, fenugreek crop area is 1555 ha and seed production 3010 tons per year. Indian spices have high reputation in the international market because of their peculiar quality (Parewa *et al.*, 2020). The productivity of fenugreek remains very low, primarily due to limited awareness among farmers. The interventions of frontline Demonstrations (FLDs) at farmers' fields can play a crucial role in bridging this gap (Dashora *et al.*, 2020; Jethava *et al.*, 2024; Nehra and Malik, 2024; Rolaniya *et al.*, 2025). Therefore, to motivate farmers to adopt improved technologies for enhancing the productivity and profitability of fenugreek cultivation.

MATERIALS AND METHODS

The Front Line Demonstrations (FLDs) were conducted during 2022–23 and 2023–24 with the participation of 10 farmers each year. The demonstrations were laid out over an area of 2.50 ha, while an adjacent 2.50 ha area under farmers' practice served as the control for comparison. Farmers were randomly selected based on surveys conducted by KVK Jhajjar, Haryana. The FLDs were implemented using the improved fenugreek variety AFg-5, with seeds treated using Carbendazim 50% WP @ 2.0 g/kg seed + *Trichoderma viride* @ 10 g/kg seed. The recommended dose of fertilizers (NPK @ 25:50:0 kg/ha) was applied, and other improved production practices—like seed rate of 20 kg/ha, sowing in first week of November, line sowing at 30 cm × 10 cm spacing, and manual weeding at 50 DAS, were followed. These interventions were compared with the farmers' traditional practices under irrigated conditions to assess their effectiveness in enhancing the productivity and profitability.

Data on growth, yield and yield traits, expenditure incurred by the farmer and expenditure of demonstration plots were collected and analyzed. Gross income was calculated based on local market prices of fenugreek and net income by subtracting the total cost of cultivation from gross income. The benefit: cost ratio was computed by dividing gross returns by the variable cost. The per cent incidence of pests was calculated by the formula used by Vinay *et al.* (2023). To estimate the technology gap, extension gap and technology index, the following formulae were used as suggested by Lal *et al.* (2017) and Samui *et al.* (2000).

RESULTS AND DISCUSSION

The cumulative effect of demonstrated package over two years revealed that the tallest plant (54.44 cm)

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$$\text{Pest incidence (\%)} = \frac{\text{Number of damaged plants}}{\text{Total number of plants observed}} \times 100$$

$$\text{\% increase in yield} = \frac{\text{Demonstration yield - Farmers yield}}{\text{Farmers yield}} \times 100$$

Extension Gap = Demonstration yield (Di) – Farmers yield (Fi)
Technology Gap = Potential yield (Pi) – Demonstration yield (Di)

$$\text{Technology index} = \frac{\text{Potential yield – Demonstration yield}}{\text{Potential yield}} \times 100$$

was observed in AFg-5 as compared to farmer's practice (48.02 cm). The average number of branches/ plant was maximum (5.62) in AFg-5 compared to local variety (5.23). Minimum pest incidence (13.20%) were reported in demonstration whereas maximum in the check variety (36.30%). The total seed yield per hectare under the front line demonstrated obtained 15.90 and 17.20 q/ha, while 14.10 and 15.0 q/ha in farmers practice during 2022-23 and 2023-24, respectively (Table 1). The effects of technological particulars over two years revealed that the higher average total seed yield (16.55 q/ha) were recorded in the demo as compared to control (15.55 q/ha). Similarly, the total yield per hectare of fenugreek increased by 13.72% over the yield obtained in farmer's practice. The year-to-year fluctuations in growth, seed yield and cost of cultivation can be explained based on variations in the existing social, economic, soil, climatic and microclimatic conditions of the location. Bhati *et al.* (2017) recorded fenugreek yield was found to be substantially higher than that under local check during all the years. The findings of Dashora *et al.* (2020) clearly indicated that yield of fenugreek can be significantly increased through the adoption of recommended production technologies.

The seed was sold ₹ 62/ kg and ₹ 65/kg during 2023 & 2024, respectively. The net returns of demonstration plot were significantly higher than farmer's practice during both the years (Fig. 1). Higher average gross returns (₹ 105190 /ha) of FLDs were recorded as compared to the farmer's practice (₹ 92460 /ha). Similarly, higher

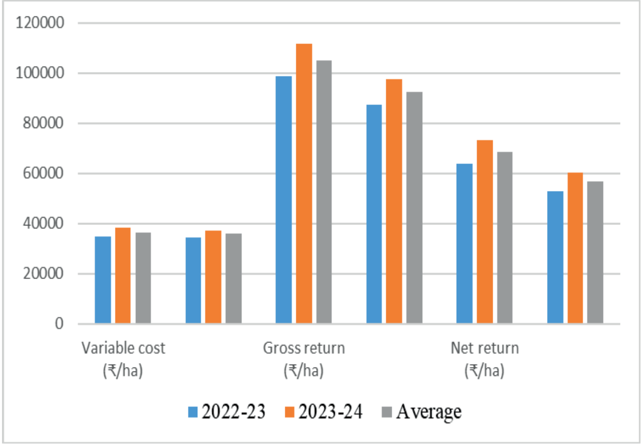

Fig. 1. Economics of technological components of fenugreek

average net returns (₹ 68695 /ha) of the demonstration were recorded as compared to farmer's practice (₹ 56660 /ha). The benefit: cost ratio for cultivation of AFg-5 was recorded at 2.85 and 2.92 during 2022–23 and 2023–24, respectively, while for local variety, it was 2.54 and 2.63 during the corresponding years. Similar findings were reported by Dashora *et al.* (2020) Meena and Singh (2021) reported that adoption of improved production technologies in fenugreek resulted in a higher benefit: cost ratio, ranging from 2.6 to 3.6 with an average of 3.2, as compared to the local checks (2.5) cultivated by farmers.

Extension gaps of 1.80 and 2.20 q/ha was observed during 2022-23 and 2023-24, respectively (Table 1.) The gap might be accredited to adoption of latest production technologies, especially high yielding varieties with balanced fertilizers and appropriate plant protection measures. The technology gap was lowest (2.80 q/ha) and the highest (4.10 q/ha) during 2023-24 and 2022-23, respectively. The average technology gap was 3.45 q/ha. It may be due to climatic conditions, soil fertility, recommended varieties and recommended technologies. On the basis of two years front line demonstration program, overall 17.3% technology index was recorded, which was the highest (20.5%) during 2022-23 and lowest (14.0%) during study of 2023-24. As a result, it clearly shows the success of scientific interventions. This awareness and

Table 1: Vegetative growth, yield, yield attributes, and technological gap analysis of fenugreek

Year	Plant height (cm)		No. of branches/ plant		Pest incidence (%)		Seed yield (q/ ha)		% increase over FP	Potential yield (q/ ha)	Extension gap (q/ ha)	Technology gap (q/ ha)	Technology index (%)
	Demo	FP	Demo	FP	Demo	FP	Demo	FP					
2022-23	53.68	48.45	5.48	5.07	14.60	39.20	15.90	14.10	12.77	20	1.80	4.10	20.5
2023-24	55.20	47.60	5.77	5.40	11.80	33.40	17.20	15.0	14.67	20	2.20	2.80	14.0
Average	54.44	48.02	5.62	5.23	13.20	36.30	16.55	14.55	13.72	20	2.0	3.45	17.25

adoption of improved varieties with package of practices increased the yield performance of fenugreek variety AFg-5. These findings are in the conformity with the results by Lal *et al.* (2017); Meena and Singh (2021) and Chaudhary *et al.* (2022).

CONCLUSION

There it can be concluded that yield gap and economic analysis between traditional practices and improved production technology can be reduced by organized front line demonstration at farmer's fields. The FLDs made a positive and significant impact on fenugreek yield as compared to the local varieties. The low yielding local varieties would be replaced due to FLDs in adopted villages.

REFERENCES

Aher R R, Belge S A, Kadam S R, Kharade S S, Misal, A V and Yeole P T. 2016. Therapeutic importance of fenugreek (*Trigonella foenum-graecum* L.): A review. *Journal of Plant Science and Research* **3**(1): 149-53.

Bhati B S, Soni R L, Rathore R S, Ramawtar, Singh R and Chhipa B G. 2017. Effect of front line demonstrations on yield enhancement of fenugreek: A case study in tribal belt of Rajasthan. *International Journal of Current Microbiology and Applied Sciences* **6**(7): 1132-1136. https://doi.org/10.20546/ijcmas.2017.607.137.

Chaudhary N, Sharma Y K, Lal G, Meena, R D, Meena N K, Meena R S, Lal S, Meena S S, Meena M D and Jangir C K. 2022. Promotion of fenugreek organic farming through front-line demonstrations in Sikar district of Rajasthan. *International Journal of Seed Spices* **12**(1): 70-74. https://doi.org/10.18805/LR-5113

Dashora A, Solanki R L, Urmila, Chhipa B G and Singh P B. 2020. Impact of front line demonstration on the yield and economics of fenugreek in Southern Rajasthan. *International Journal of Current Microbiology and Applied Sciences* **9**(06): 1397-1402. https://doi.org/10.20546/ijcmas.2020.906.174

Jethava B A, Patel K M and Panchal B H. 2024. Response of integrated nutrient management and micronutrients on quality, nutrient content, uptake and soil of tomato (*Solanum lycopersicum*). *Current Horticulture* **12**(2): 75-79. https://doi.org/10.48165/chr.2024.12.1.012

Lal G, Mehta R. S., Meena R S, Meena N K and Choudhary M L. 2017. Assessment of front line demonstrations on yield enhancement of fenugreek under TSP area in pratapgarh district of Rajasthan. *International Journal of Seed Spices* **7**(1):60-64.

Meena M L and Singh D. 2021. Dissemination of fenugreek varieties through frontline demonstrations approach for sustainable fenugreek production in Pali district of Rajasthan, India. *International Journal of Seed Spices* **11**(1): 15-22. https://doi.org/10.56093/IJSS/160641

Nehra M K and Malik J K. 2024. Effect of copper and zinc as a supplement fertilizer on growth of radish (*Raphanus sativus*) root and foliage. *Current Horticulture*, **12**(2): 67-69. https://doi.org/10.48165/chr.2024.12.1.012

Parewa H P, Jain L K, Choudhary A and Ratnoo S D. 2020. Effect of integrated nutrient management on fenugreek (*Trigonella foenum graecum* L.) growth and yield attributes. *International Journal of Seed Spices* **10**(2): 44-47. https://doi.org/10.56093/

Rolaniya O P, Garhwal, O P and Bhateshwar M C. 2025. Impact of zinc and iron, their applicability techniques, and PGRs on yield of fennel (Foeniculum vulgare). *Current Horticulture* **13**(3): 57–60. https://doi.org/10.5958/2455-7560.2025.00042.7

Samui S K, Mitra S, Roy D K, Mandal A K and Saha D. 2000. Evaluation of front-line demonstration on groundnut. *Journal of the Indian Society of Coastal Agricultural Research* **18**(2): 180-83.

Vinay N, Rajababu V and Naidu G S. 2023. Incidence of banana leaf roller, *Erionota torus* Evans (Lepidoptera: Hesperiidae) in Visakhapatnam, Andhra Pradesh. *The Pharma Innovation Journal* **12**(3): 1323-26.

Current Horticulture 13(4): 85–88, October–December 2025
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Assessing impact of nitrogen application and weed management on onion (*Allium cepa*) production

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Abstract

The study was carried out at SKN College of Agriculture, Jobner, to assess the effect of climatic variations of various treatments on onion (*Allium cepa* L.) production grown in loamy sand soil during *rabi* seasons in 2016-17 and 2017-18. The weed control efficiency and yield of onion were influenced by weed management practices and nitrogen levels due to seasonal variation of climatological factors during both years. The combination of two hand-weeding and application of 100 kg of nitrogen/ha, or use of pendimethalin plus oxadiargyl 40 days after transplanting along with the same amount of nitrogen gave significantly higher yield than the control. These methods demonstrated effect of climatic conditions on efficacy of weed management and subsequent yield of onion.

Key words: Weed management practices, Weed control efficiency, Hand weeding, Climate.

Weather is a critical factor influencing the production onion (*Allium cepa* L.). Profound effect of climatic conditions on productivity of crops is well established (Ahir *et al*., 2006 and Schlenker, 2006). Weather is a principal parameter which brings year to year variation in crop productivity, despite of consistency in other inputs and practices of crop husbandry. The onion holds significant status globally as a widely cultivated vegetable crop. In India, onion is grown in an area of 1.27 million ha with a production of 21.564 million tonnes, with a productivity of 16.97 tonnes/ha (MoA & FW, 2017). Onion among vegetables has very poor competitive ability with weeds due to its inherent characteristics such as shallow root system, narrow upright leaves and non-branching habit. The losses in crop yield has direct correlation with weed competition and has been recorded to 40-80 per cent (Channapagoudar and Biradar, 2007). Hence, study was done to find out variation in weed control efficiency and yield of onion.

MATERIALS AND METHODS

The study was carried out at the SKN College of Agriculture, Jobner, Jaipur, Rajasthan, during *rabi* season of 2016-17 and 2017-18. The split plot design methodology, replicated thrice was used. The size of each plot was 1.50 m × 1.50 m, adhering to a planting distance of 15 cm between rows and 10 cm between the plants within a row. The onion variety RO-252 was transplanted during second week of December in both the years in flat beds. The treatments comprising seven weed management practices in main plots, viz. no weeding (control), hand weeding once at 20 DAT, Hand weeding twice at 20 and 40 DAT, Pendimethalin (PP) + Oxadiargyl at 40 DAT, Pendimethalin (PP) + 1 hand weeding at 40 DAT, Oxyflourfen (PP) + Oxyflourfen at 20 DAT and Oxyflourfen (PP) + 1 hand weeding at 40 DAT and the impact of four distinct nitrogen application rates, viz. 0, 50, 100, and 150 kg/ha in sub plots. All recommended packages of practices were adopted.

Geographically, Jobner is situated at 26^0 05' North latitude and 75^0 20' East longitude and an altitude of 427 meters above mean sea level. This region experiences significant temperature fluctuations during summer and winters, coupled with scant precipitation and fairly moderate humidity levels. Maximum temperature in summers remain as high as 49^0C, whereas minimum temperature in winters falls around 0^0C. The average rainfall of the locality is approximately 400 to 500 mm; most of which is received in rainy season from July to September. Yearly pan evaporation ranges from 1.3-17.5 mm per day. Since climatic conditions influence growth, yield and quality of agricultural produce, therefore, the mean weekly weather parameters for the crop growing seasons were recorded at meteorological observatory, Jobner (Table 1 and 2).

The efficiency of weed control (WCE) for each treatment was determined by applying the formula recommended by Mani *et al,* 1973, with the results being presented as a percentage. The weed control efficiency was derived at 30 DAT, 60 DAT, 90 DAT and at harvest stage of crop.

The observation on bulb yield data for onions was subjected to statistical analysis following the methodology outlined by Panse and Sukhatme (1985).

$$\text{Weed control efficiency (\%)} = \frac{\text{Weed population in control} - \text{weed population in treatment}}{\text{Weed population in control}} \times 100$$

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Table 1. Mean weekly weather parameters recorded during 2016-17 and 2017-18

SMW No.	Period	Temperature (°C)				Mean R.H. (%)		Evaporation (mm)		Rainfall (mm)		Sunshine (hrs/day)	
		Maximum		Minimum									
		2016-17	2017-18	2016-17	2017-18	2016-17	2017-18	2016-17	2017-18	2016-17	2017-18	2016-17	2017-18
50	Dec. 10 to Dec. 16	27.1	23.0	9.7	7.9	55	67	04.0	02.9	000.0	000.0	8.8	4.9
51	Dec. 17 to Dec. 23	23.2	22.1	8.6	3.6	65	63	03.5	02.7	000.0	000.0	5.1	7.1
52	Dec. 24 to Dec. 31	19.5	22.7	4.8	2.4	65	63	01.9	02.8	000.0	000.0	6.2	8.9
1	Jan. 01 to Jan. 07	20.1	20.9	2.3	6.6	63	71	02.2	02.6	000.0	000.0	4.9	4.0
2	Jan. 08 to Jan. 14	20.1	24.4	3.7	3.9	64	59	02.2	03.4	000.0	000.0	6.5	8.9
3	Jan. 15 to Jan. 21	19.4	21.1	4.9	4.9	76	64	02.1	03.3	007.8	000.0	4.6	7.5
4	Jan. 22 to Jan. 28	18.5	18.2	10.4	9.5	77	82	02.7	02.3	006.0	010.2	5.5	3.1
5	Jan. 29 to Feb. 04	22.3	23.0	8.3	6.3	60	58	03.1	03.1	000.0	000.0	7.6	9.5
6	Feb. 05 to Feb. 11	23.9	23.9	6.6	7.3	60	59	03.9	03.6	000.0	000.0	7.6	9.5
7	Feb. 12 to Feb. 18	22.0	27.8	5.6	10.0	61	55	03.3	04.0	000.0	000.0	8.4	9.0
8	Feb. 19 to Feb. 25	24.1	31.1	9.7	12.7	57	55	03.6	04.8	000.0	000.0	7.4	9.0
9	Feb. 26 to Mar. 04	24.6	25.3	10.1	11.0	67	63	02.8	03.7	013.6	004.0	5.0	5.5
10	Mar. 05 to Mar. 11	27.8	27.1	10.6	10.0	59	51	05.3	04.5	000.0	000.0	7.9	8.9
11	Mar. 12 to Mar. 18	30.1	24.9	12.7	13.4	54	67	06.4	03.9	004.8	018.2	6.1	4.8
12	Mar. 19 to Mar. 25	32.1	31.3	14.2	15.1	55	47	06.5	04.5	009.6	000.0	8.3	8.9
13	Mar. 26 to April 01	32.2	35.5	16.3	18.7	47	49	06.4	05.7	000.0	000.0	7.9	7.5
14	April 02 to April 08	35.1	31.9	13.8	18.4	44	61	07.0	04.5	000.0	012.2	9.4	6.5
15	April 09 to April 15	35.9	32.3	15.5	17.2	41	63	07.0	05.0	000.0	015.0	9.3	6.6
16	April 16 to April 22	31.8	37.0	14.4	19.7	55	45	05.3	06.4	005.8	000.0	7.8	9.3
17	April 23 to April 29	37.9	39.9	19.2	20.7	38	32	08.9	08.2	000.0	000.0	10.7	10.6
18	April 30 to May 06	40.6	40.8	22.1	20.6	38	32	09.6	09.1	000.6	000.0	9.6	10.9
19	May 07 to May 13	38.2	40.9	21.0	23.3	41	37	07.8	09.5	002.4	000.0	9.6	10.6
20	May 14 to May 20	36.5	40.7	21.3	24.8	41	37	07.4	09.1	002.0	000.0	10.0	10.0
21	May 21 to May 27	39.9	42.2	23.5	27.3	37	33	09.0	11.3	012.8	000.0	10.2	10.7
	Average	**28.6**	**29.6**	**12.2**	**13.0**	**55**	**54**	-	-	-	-	-	-
	Total									**65.4**	**59.6**		

Source: Agro-meteorology Observatory, Department of Agronomy, SKN Agriculture University, Jobner (Rajasthan) India.

Table 2. Mean seasonal weather parameters and their measures of dispersion during crop season (computed from daily observation)

Weather parameter	Statistical parameters					
	Mean (X)		S.D. (σ)		CV (%)	
	2016-17	2017-18	2016-17	2017-18	2016-17	2017-18
Temperature (^{0}C)						
Maximum						
Seasonal	31.56	30.66	7.41	6.58	23.47	29.45
From 6th-15th weeks	27.47	29.45	4.10	3.52	14.93	11.95
Minimum						
Seasonal	12.82	9.97	6.89	7.59	53.74	8.97
From 6th-15th weeks	9.81	8.97	2.59	3.92	26.39	43.72
Relative humidity (%)						
Seasonal	51.57	45.25	10.53	9.39	20.41	46.50
From 6th-15th weeks	54.50	46.50	9.16	4.22	16.80	9.08
Sunshine hours						
Seasonal	8.46	8.50	1.72	0.85	20.31	8.50
From 6th-15th weeks	7.20	8.50	1.32	0.71	18.40	8.41

Table 3. Effect of weed management techniques and nitrogen levels on bulb yield of onion (q/ha)

Treatment	2016-17	2017-18
Main plots (weed management)		
W_0 - Weedy check (control)	148.65	136.27
W_1 - One hand weeding (HW) at 20 DAT	223.75	214.90
W_2 - Two hand weeding (HW) at 20 & 40 DAT	300.96	288.19
W_3 - Pendimethalin (preplant) + Oxadiargyl at 40 DAT	296.29	281.06
W_4 - Pendimethalin (preplant) + 1 hand weeding (HW) at 40 DAT	298.17	282.84
W_5 - Oxyfluorfen (preplant) + Oxyfluorfen at 20 DAT	237.09	224.83
W_6 - Oxyfluorfen (preplant) + 1 hand weeding (HW) at 40 DAT	251.99	239.12
MEAN	**250.99**	**238.17**
SEm±	**5.32**	**7.30**
CD (P=0.05)	**16.38**	**22.49**
Sub-plots (nitrogen levels)		
N_0 - Control	229.11	210.88
N_1 - 50 kg N/ha	252.61	240.79
N_2 - 100 kg N/ha	259.87	249.59
N_3 - 150 kg N/ha	262.36	251.43
SEm±	**3.39**	**3.25**
CD (P=0.05)	**9.66**	**9.28**

RESULTS AND DISCUSSION

The data revealed that *rabi* season of 2016-17 witnessed comparatively higher mean maximum and minimum temperatures and relative humidity compared to 2017-18. The differences were also pronounced during peak bulb development period. It is coupled with less variation in mean maximum and minimum temperature that led to lesser fluctuations in temperature, exposing the crop to chilling period for a lesser duration in 2016-17. The higher relative humidity, especially during bulb development period, combined with higher CV observed during 2016-17 (Table 2) favoured faster and more bulb development compared to 2017-18. These weather conditions favoured a congenial environment for accelerated synthesis and translocation of photosynthates towards sink during 2016-17, which not only led to better bulb development and yield but also improved quality of onion bulbs.

The yield was 5.38 % higher of bulbs during 2016-17, which was significantly higher compared to mean yield of 238.17 q/ha during 2017-18 (Table 3). It is an established fact that plants can express their genetic potential under an ideal range of environmental factors, i.e. weather conditions to which plants are subjected during their life-cycle, as well as internal environmental conditions, i.e. availability of metabolites and nutrients. The variation in crop productivity between the years of experimentation seems to be due to the interactive effect of environmental conditions that prevailed during the critical stages of crop growth which in turn might have influenced the overall growth and development and finally the crop yield.

The comparatively favourable environmental conditions during 2016-17, especially during bulb development could be ascertained as one of the most probable reasons for increased photosynthesis resulting into higher dry matter accumulation, yield attributes and ultimately the more yield. A relative summary of seasonal weather parameters (Table 2) indicated that during 2016-17, comparatively lower mean maximum temperatures and relatively higher RH were observed with higher CV at the reproductive stage that led to greater translocation of photosynthetic assimilates towards bulb formation and its development in size in comparison to 2017-18. An increased quality bulb yield of onion with pre-post herbicides applications showed significant effect (Kumar

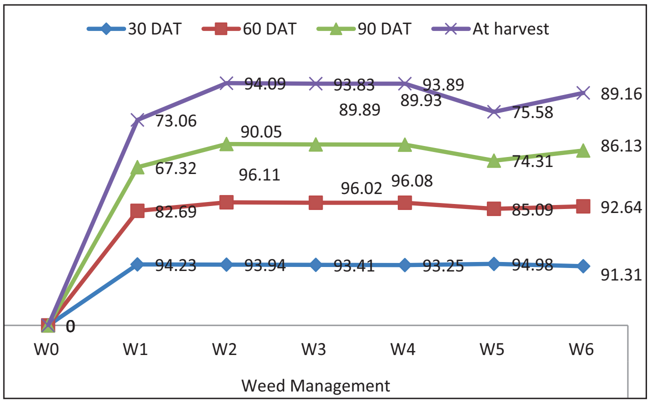

Fig. 1: Effect of weed management techniques on weed control efficiency (%) at different stages of crop during 2016-17

and Gupta, 2024). These findings are in agreement with Chattopadhyay *et al.* (2016) in onion, Singh (2024) in fennel and Schlenker, 2006.

The flush of weeds was controlled by two hand weeding at 20 and 40 days after transplanting (DAT), followed by Pendimethalin + one hand weeding at 40 days after transplanting (DAT) or Pendimethalin + Oxadiargyl at 40 DAT effectively during 2016-17 (Fig. 1 and 2). The higher weed control efficiency during 2016-17 under some herbicide treatments with or without hand weeding might also be due to higher efficiency of herbicides by favourable weather conditions (Sable *et al.*, 2013). The variation in weed control efficiency is directly associated with amount of weed biomass accumulated under different treatments. The present findings corroborated with the findings of Gandolkar *et al.* (2015), Sahoo *et al.* (2017) and Ahir *et al.* (2006) in wheat.

CONCLUSION

Despite large weather variations in both years, higher weed control and onion yield were consistently achieved with certain treatments. These included two hand weedings with 100 kg N/ha, or using Pendimethalin (PP) + Oxadiargyl at 40 days after transplanting with 100 kg N/ha. Another effective option was Pendimethalin (PP) followed by one hand weeding at 40 days after transplanting with 100 kg N/ha. All these treatments showed similar performance in 2016–17, being statistically at par with each other and were more effective compared to 2017–18.

REFERENCES

Ahir I.S.A.T., Akata N.N., Li A.M.A., Ustafa H.M.M., Aad A.S.I.S., Akata K.T., Shikawa O.S.A. and Bdalla O.S.A. 2006. Genotypic and temperature effects on wheat grain yield and quality in a hot irrigated environment. *Plant Breeding* **125**: 323 - 30.

MoA & FW, 2017. *Horticultural Statistics at a Glance 2017*. Horticulture Statistics Division, Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, New Delhi

Channappagoudar B.B. and Biradar N.R. 2007. Physiological studies on weed control efficiency in direct sown onion. *Karnataka Journal of Agricultural Sciences* **20** (2): 375 -76.

Chattopadhyay N., Mahalanabish S., Hore J.K. and Maity T.K. 2016. Effect of different herbicides on growth and yield of onion (*Allium cepa* L.). *Journal of Crop and Weed* **12** (1): 112 – 15.

Gandolkar K., Halikatti S.L., Patil P.S. and Pattarand P.L. 2015. Effect of sequential application of herbicides for weed management in drill sown onion (*Allium cepa* L.) under rainfed condition. *BIOINFOLET - A Quarterly Journal of Life Sciences* **12** (3): 748 - 55

Kumar R. and Gupta P.K. 2024. Evaluation of oxyfluorfen and quizalofop-ethyl weedicides for weed control in onion (*Allium cepa*). *Current Horticulture* **9** (2): 60–63. https://doi.org/10.48165/

Panse V.G. and Sukhatme P.V. 1985. *Statistical Methods for Agricultural Workers,* Indian Council of Agricultural Research, New Delhi, pp. 167 – 74

Sable P.A., Kurubari A.R. and Hugari A. 2013. Effect of weed management practices on weed control and nutrient uptake in onion (*Allium cepa* L.). *The Asian Journal of Horticulture* **8** (2): 444-47.

Sahoo S.K., Chakravorty I.S., Soren L., Mishra C. and Sahoo B.B. 2017. Effect of weed management on growth and yield of onion (*Allium cepa* L.). *Journal of Crop and Weed* **13** (2): 208-11

Schlenker W. 2006. Inter-annual weather variation and crop yields. *http://nber15.nber.org/c/2006/si2006/ee / schlenker. pdf.* Retrieved on 18/8/2005.

Singh D. 2024. Effect of weed management on yield-attributing characters of fennel (*Foeniculum vulgare*). *Current Horticulture* **11** (1): 37–39. https://doi.org/10.48165/

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