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Research Article

Enhancing the fruit yield and quality of pomegranate in a new niche area: Insights into site specific agronomic practices

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Abstract

The sustained higher profitability of a pomegranate orchard relies heavily on the production of a greater proportion of high-quality fruits, a goal achievable through the implementation of effective management practices. The objective of this study is to provide site-specific supplementary knowledge regarding the response of pomegranate plants to various management practices under arid conditions. With the aim of enhancing both marketable fruit yield and quality of pomegranate in arid regions, four separate and simultaneous experiments were conducted in the same orchard to evaluate (i) the response of planting materials derived from tissue culture, air layering, and cutting; (ii) the impact of crop (fruit) load; (iii) the response of crop regulation; and (iv) the application response of organo-mineral fertilizers containing potassium (OMF-K) and phosphorus (OMF-P). The results obtained for plant growth, fruit yield, and fruit quality did not exhibit significant differences among pomegranate plants raised through the three different methods of vegetative propagation. Striking results in terms of producing superior-grade fruits, higher marketable yield, and overall fruit quality were achieved with crop loads of 80 fruits per plant. Staggering the crop regulation from June to September effectively extended the harvesting season to four months, from the last week of November to March, with eventual benefit of reduced fruit cracking compared to the standard two-month harvesting period obtained from normal regulation. Soil application of the indigenously developed OMF-K in two equal splits, along with the recommended N and P through inorganic sources, significantly reduced fruit cracking (only 6.23%) compared to the recommended NPK through inorganic sources (26.9%), while maintaining similar physicochemical quality attributes.

Keywords: fruit load; organo mineral fertilizers; *Punica granatum*; yield; quality

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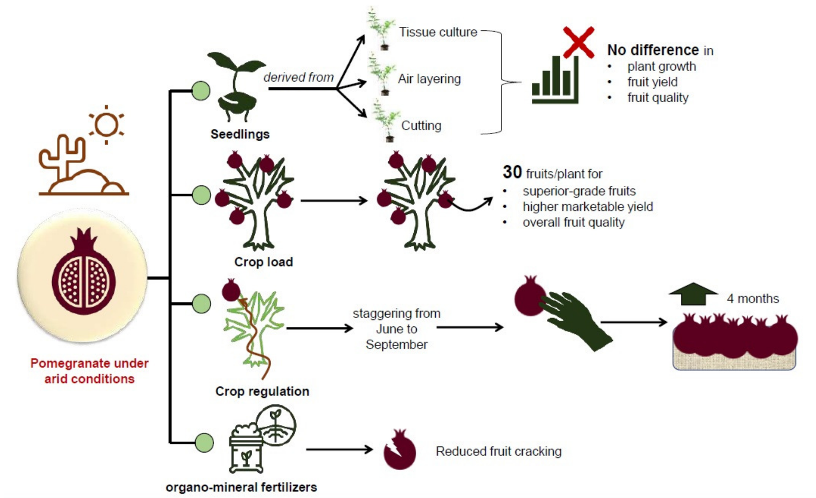

Graphical abstract

Introduction

Pomegranate (*Punica granatum* L.), is an economically important fruit crop of arid and semiarid regions of the world. The global popularity of pomegranate as a commercial cash crop can be attributed to its low water requirements, favorable response to modern horticultural practices, high economic returns, and numerous health benefits (Chandra *et al.,* 2010). Global production of pomegranates is estimated around 6.3 million metric tons (MT) from an area of 556 thousand hectares with international export market to be around 362.6 thousand MT (Sarkhosh *et al*., 2021). Globally India is a leading producer (3186 thousand MT) followed by China (1600 thousand MT), Iran (1100 thousand MT), Turkey (220 thousand MT), the USA (210 thousand MT), Afghanistan (150 thousand MT), and Spain (53.18 thousand MT) (Sarkhosh *et al*., 2021). India has recorded a constant increase in foreign earning by exporting 80,547.74 MT worth USD 92.46 million in 2019–2020 (Anonymous, 2020). During previous year's pomegranate expansion rate in India was around 80% in area and 300% increase in production (Singh *et al*., 2017). India possesses added advantages in pomegranate cultivation due to its diverse climate, enabling year-round production in different regions (Sharma *et al*., 2014). The introduction of the 'Bhagwa' variety, which meets export specifications in terms of its round and globosely shaped fruits, dark rose-red color of fruits and arils, soft seeds, and desirable taste and aroma (Ram Chandra *et al*., 2011), has revolutionized pomegranate cultivation on a national scale. These factors have acted as the primary driving force behind the expansion of pomegranate cultivation beyond its traditional belt in central and southern India to arid and semi-arid regions in north-western Indian states. Moreover, commercial cultivation of pomegranate in north-western Indian states is comparatively new but with the government support through various schemes on irrigation and drip systems, and further research support has made paradigm shift from traditional to commercial cultivation of pomegranate in the region (Meena *et al*., 2018). The growth of pomegranate cultivation in arid Rajasthan can be easily visualized from the acreage expansion from 793 ha during 2010-11 to greater than 13000 ha during 2020-21 (Directorate of Horticulture, Rajasthan, 2021-22). The arid climatic conditions in the region are highly suitable for cultivating the *mrig bahar* crop, which spans from July-August to January-March. However, the prevailing environmental factors during fruit development often have a negative impact on fruit quality. Factors such as intense solar radiation, high wind speeds, and sharp temperature fluctuations between day and night during the ripening period can significantly affect fruit quality. Consequently, issues such as poor color development, sunscald, and fruit cracking are commonly observed in pomegranate in this region (Singh *et al*., 2019). The presence of low-quality fruits ultimately hampers their marketability. To obtain favorable prices for fruits in both domestic and international markets, it is crucial to produce high-quality fruits under the prevailing weather conditions in arid regions. This can be achieved by implementing effective management practices in the orchard.

The choice of planting material, derived through different propagation methods, is a critical factor in ensuring successful pomegranate orchard establishment in the region. There are certain apprehensions among growers and other stakeholders about productivity, quality and storability of pomegranate fruits of same variety raised by different methods of asexual propagation. Traditionally, pomegranate has been propagated through air layering and cutting in different climatic regions, which is very easy and cost effective and can serve the purpose of commercial plantation, or gap filling in established orchard (Panwar and Singh, 2020). However, recently micro-propagation through tissue culture came in big way as commercial and rapid methods of mass multiplication providing uniform disease-free planting material (Mulaei *et al*., 2020). A systematic field study can give proper insights about production and quality responses of pomegranate plants raised through different methods of propagation under arid field conditions.

In the arid region, ensuring that the quality of fruits aligns with the standards set by both national and international markets is a significant concern. Issues such as uneven small-sized fruits, poor color development, fruit cracking, and sun scald pose challenges in this regard. Fruit size plays a crucial role in determining market premiums, as larger fruits generally command higher market values (Nuncio-Jauregui *et al*., 2015). Normally pomegranate produces excessive fruit, resulting in the production of uneven small size fruits with a low-quality within trees of the same genotype grown under similar cultivation practices with given inputs. Likewise other fruit crops, in pomegranate also optimization of fruit load is essential by thinning of unwanted small and irregular fruits to produce uniform large size fruits (Vasantha Kumar, 2006). Due to the high responsiveness of pomegranate to crop season manipulation, implementing crop regulation can serve as an effective strategy for mitigating the aforementioned issues and producing high-quality fruits.

In hot arid regions, the *mrig bahar* crop is typically preferred for pomegranate cultivation in which flowering occurs in July-August during the maximum moisture availability period and fruit matures during December-January, coinciding with wide variations in day-night temperatures resulting fruit cracking. Additionally, the narrow harvesting window during this period often leads to market glut, thus low prices of produce. To address these challenges, extending the harvesting period through staggered crop regulation within the *mrig bahar* season can be beneficial. Pomegranate farmers in arid regions frequently experience significant economic losses, ranging from Rs. 1.0 to 1.5 lakh per hectare, due to fruit cracking. Fruit cracking is a physiological disorder caused by multiple factors that result in variations in turgor pressure within the fruit. Regulating these turgor pressure variations is essential for preventing fruit cracking, and it can be achieved by ensuring a sustained release of phosphorus and potassium in the soil solution. Maintaining optimal levels of potassium (K) and phosphorus (P) in the tissue is crucial for controlling fruit cracking. However, conventional fertilizers often fail to sustain the required levels of K and P due to their pulsating release nature. In an attempt to minimize fruit cracking in pomegranate, newly synthesized organo-mineral fertilizers of potassium (OMF-K) and phosphorus (OMF-P) developed at ICAR-Central Arid Zone Research Institute were utilized. These fertilizers aim to provide a sustained release of K and P, thereby minimizing fruit cracking in pomegranate cultivation.

The primary objective of the present studies was to provide additional insights into the response of pomegranate to various management practices under arid field conditions, with the goal of enhancing marketable yield and producing high-quality crops. The information obtained from these studies can be utilized in the development of site-specific orchard management practices tailored for the production of high-quality pomegranates in arid conditions.

Materials and Methods

The present investigations were carried out at ICAR- Central Arid Zone Research Institute, Jodhpur Rajasthan India (26°18′ N and 73°04′ E; 216 m above mean sea) during 2016 to 2022. The experimental site experiences an arid climate characterized by an average annual rainfall of 350 mm. The majority of this rainfall, approximately 90%, is received during the months of July to September. The maximum and minimum temperature ranged between 45-48 °C and 4.1-14 °C while relative humidity ranged from 35% to 70% along with very high rate of evaporation throughout the year with peak during summer (3.5 to 13.5 mm day^{-1}). A total of 220 plants of pomegranate cv. 'Bhagwa' raised through air layering, hardwood cutting and tissue culture were planted at 4.0 m × 3.0 m distance during August 2016. Pits were dug 20 days prior to planting and drenched with 0.1% Carbendazim. Upper soil was mixed with 5 kg compost, 1 kg vermicompost, 1 kg Neem cake, 25 g *Trichoderma harzianum,* 25 g PSB, 25 g *Paecilimycese lilacinus* and 25 g Carbofuran for pit filling. One day prior to transplanting, seedlings were disinfected with 0.1% Carbendazim. Plants were trained with multi stem (3-4) system. The crop regulation was done by withholding the water in the month of June followed by foliar spray of ethrel (2.0 ml/L) during middle of July. A basal dose of manuring and fertilization was done immediately after complete defoliation. Recommended fertigation schedule was carried out during flowering and fruiting season. All other horticultural practices were kept uniform during the experimentation. Four separate and simultaneous experiments were conducted on the experimental site to assess the impact of various agronomic practices on marketable yield and fruit quality of pomegranate under arid climate of India.

Experimental details

Effect of planting materials derived from different propagation methods

Experiment on response of pomegranate plants raised through different methods of asexual propagation was initiated during August 2016. Pomegranate cv. 'Bhagwa' raised through air layering (Al), hardwood cutting (HWC) and micro propagation (TC) planted at 4.0 m × 3.0 m distance under ferti drip system of irrigation were assessed for two consecutive years (2020-2022) for yield and quality. The experiment was conducted in randomized block design with five replications and each replication having nine plants. Three plants in each replication were considered for data recording from each treatment under different parameters.

Effect of crop load

Experiment to optimize number of fruits per plants for attaining higher marketable yield with bigger fruits was conducted during 2020-2022. 60, 80, 100,120, 140 fruits per plant were retained to ascertain the effect of fruit load on quality and size of fruits. Fruit thinning was done manually just after fruit set retaining respective numbers of fruits in each treatment. The experiment was conducted in randomized block design with three replications. Three plants in each replication were considered for data recording from each treatment under different parameters.

Effect of staggered crop regulation

Manipulating time of defoliation and rest period can be used for extending fruit availability period with minimum cracked fruits. Thus, the prime objective of this study was to ascertain staggered crop regulation to get quality fruits for longer period. Crop was regulated at monthly interval starting from second week of June to September. Withholding of irrigation 20 days prior followed by foliar sprays of ethrel (2 ml/L) and N: P: K 00:52:34 (3 g/L) was applied for leaf defoliation. A basal dose of manuring and fertilization was done immediately after complete defoliation. Recommended fertigation schedule was carried out during flowering and fruiting season. The experiment was conducted in randomized block design with five replications and each replication having nine plants. Three plants in each replication were considered for data recording from each month of defoliation.

Response of organo –mineral fertilizers

In a field experiment, recommended levels of K (250 g/plant) and P (250 g/plant) were substituted with indigenous organo mineral fertilizers –K and P (OMF-K and OMF-P). Theses fertilizers were applied in six different treatment combination either as single dose in August or in two equal splits i.e. in August and October. Application of NPK either in soil or through fertigation served as control. The experiment was conducted in randomized block design with three replications. Three plants in each replication were considered for data recording from each treatment under different parameters.

Observations recorded

Plant growth in terms of plant height and canopy spread (east-west and north-south directions) were recorded during November (middle of fruiting season). Twelve uniform plants were selected from each type of propagation material and sufficient number of flowers was tagged randomly all-around selected plants for recording physico-chemical parameters. At each picking, fruit yield was measured and the average cumulative yield per plant was calculated as kg/plant for each category. Twenty randomly selected fruits from the all side of tree during each picking were harvested, and weight was taken using top pan digital balance and average fruit weight was expressed as gm/fruit. Fruit size as fruit length and fruit breadth was recorded from same fruit using digital vernier calliper. The arils and rind were separated manually from the fruits to estimate total arils and rind weight per fruit. Total aril weight was taken and subsequently, 100 arils were counted manually and weighed. Aril to fruit and rind to fruit ratio were estimated by dividing whole aril and rind weight of a fruit with total fruit weight. Thickness of peel was recorded at three locations of a single fruit (top, mid, bottom of fruit) using digital vernier calliper and average of these was taken for further statistical analysis. Fruit juice was extracted using mechanical juicer and grinder followed by squeezing using muslin cloth and the quantity of juice was measured using graduated measuring cylinder. The fruit juice content was expressed as per cent on fresh fruit weight basis. TSS was determined in laboratory using digital hand-held refractometer (Model: Brix 54, Bellingham + Stanley Ltd., UK), which was calibrated using distilled water before measurements. The acidity of fruit juice was determined following titration method as suggested by Ranganna (2001). Five millilitres of juice was titrated against 0.1(N) NaOH solution using phenolphthalein as an indicator and acidity was expressed in per cent. Anthocyanin content of the pomegranate juice was determined by the pH differential spectrophotometric method (Lee *et al*., 2005). The obtained juice was centrifuged at 5,000 rpm for 15 minutes. The supernatant was separated and used for anthocyanin determination.

Standard buffer solutions of pH 1.0 and pH 4.5 were prepared fresh. For pH 1.0 buffer, potassium chloride 0.025M solution was prepared by dissolving 1.86 g KCl in ca 980 mL distilled water. The pH was adjusted to 1.0 with HCl. The pH 4.5 buffer (sodium acetate, 0.4M) was prepared by adding 54.43 g sodium acetate to ca 960 mL distilled water. The pH was adjusted to 4.5 with HCl. The juice samples were suitably diluted in 50 mL volumetric flasks with pH 1.0 buffer solution until a linear absorbance range was obtained in spectrophotometer at 520 nm. The maximum juice sample should be 10 mL (juice to buffer ratio 1:4). Using the determined dilution factor, two solutions of the juice were prepared with pH 1.0 buffer and pH 4.5 buffer. The absorbance of both the solutions were measured at 520 nm and 700 nm. The total anthocyanin concentration in cyanidin-3-glucoside equivalent mg/L was calculated as follows:

$$\text{Total anthocyanins (cyanidin-3-glucoside equivalents, mg/L)} = \frac{A \times MW \times DF \times 10^3}{\varepsilon \times 1}$$

where, A = Absorbance (A520nm – A700nm) pH 1.0 – (A520nm – A700nm) pH 4.5; MW (molecular weight of cyanidin-3-glucoside) = 449.2 g/mol; DF = dilution factor; l = pathlength in cm; ε= 26 900 molar extinction coefficients, in L $mol^{-1}cm^{-1}$; 10^3 = factor for conversion from g to mg.

For measurement of fruit colour, 10 fruits from each replication were selected randomly during each picking. Fruits colour was measured using colorimeter (Model: WR-18, Make: FRU China) at top, middle and bottom portion of the fruits and average colour was expressed as per CIE L*a*b* colour space model. In the CIEL*a*b* model, L* value of 0 represents complete dark and 100 represents complete white, negative a* values represent greenness and positive a* value represents redness whereas and negative b* value represents blueness and positive b* value represents yellowness. The colour intensity, chroma (C) was further calculated using the equation:

$$C = \sqrt{\left(a^{*2} + b^{*2}\right)}.$$

Storage study was also conducted to assess the shelf life and shrivelling of fruits harvested from plants raised through different planting materials. The uniform and well ripe fruits were harvested and packed in perforated (6 perforation, 10 mm diameter) corrugated fibreboard boxes (5 kg capacity) in three rows and two layers. CFB boxes were sealed and kept at ambient condition (26.0 °C ± 2 °C temperature and 35.0% ± 5% relative humidity). Physiological loss in weight (PLW) was monitored at 5, 10, 20, 25 and 35 days after storage (DAS). PLW was calculated by taking initial and final fruit weight on precision electronic balance using following formula:

PLW (%) = IW-FW/IW × 100

IW, initial/fresh fruit weight (g); FW, final fruit weight (g).

Rind mineral content was carried out on dry weight basis. Rind after extraction of juice was dried at 65 °C for 72 h until weight stabilized. Samples were mineralized through a digestion process in 1N nitric acid solution (HNO_3^-). The sodium (Na^+) and potassium (K^+) contents were measured by flame emission photometry (Jenway PFP7, Bibby Scientific limited, Staffordshire, UK). Calcium (Ca^{2+}) Zn, Fe and P content was analyzed using an atomic absorption spectrophotometer (Analyst 300, Perkin Elmer, Inc., Waltham, MA, USA).

Statistical analysis

The experiment was conducted in randomized block design with five replications and each replication having three plants. Data recorded from each treatment under different parameters were subjected to analysis of variance (ANOVA) and mean comparison were performed using the LSD test ($p<0.05$). All analyses were performed using SAS 9.2 (SAS Institute, Cary, NC, USA).

Results and Discussion

Effect of planting materials derived from different propagation methods

Plant growth in terms of plant height (cm) and canopy spread (cm) of pomegranate raised by different types of planting material did not show any significant variation during both the years (Table 1).

Table 1. Response of different types of planting materials on vegetative growth of pomegranate plants

Planting material	Plant height (cm)	Canopy spread	
		E-W (cm)	N-S (cm)
Tissue culture	204.28	254.20	251.80
Air Layering	201.36	226.60	242.02
Cutting	214.62	245.50	232.68
CD (P=0.05)	NS	13.4	NS

From a marketing perspective, fruit size and fruit weight are the most important economic parameters in pomegranate. In this study, these parameters were found to be similar across all three types of planting material (as shown in Table 3). Marketable fruit yield ranged from 12.53 to 14.15 kg per tree, but there were no significant differences observed among the types of planting material. Rind thickness plays a crucial role in determining the shelf life of pomegranate fruits. One of the main concerns among pomegranate growers is the relatively thinner rind of fruits from tissue-cultured plants compared to air-layered or cutting plants. However, in this study, although the fruits harvested from tissue culture plants had a slightly thinner rind (3.08 mm) but statistically there were no significant differences observed in rind thickness among the fruits from the three types of planting material. The boldness of arils, measured as 100-aril weights, also did not show any significant differences among the fruits from plants raised through different propagation methods. On the other hand, the rind-to-fruit ratio was found to be higher in fruits harvested from plants propagated through hard wood cutting (0.45) compared to air-layered plants or tissue-cultured plants. However, this difference did not further translate into significant variations in the aril-to-fruit ratio, as it was found to be similar across the different types of planting material.

Fruit juice content ranged from 33.84 to 38.33 per cent but was statistically non -significant. Total soluble solids (TSS) which is the main eating quality parameters was non significantly influenced by plants propagated through different methods (range 15.94 to 17.2). Similarly, titratable acidity was also not significantly influenced by plants raised by different propagation methods. Brix to acid ratio is an important index of fruit quality and often better related to palatability of fruit than either total soluble solid content or acidity level alone (Tehranifer *et al.*, 2010). It ranged non-significantly among the fruits raised on plants propagated through different propagation methods (32.80 to 35.87). The anthocyanin content in the juice, which is a key contributor to the total antioxidant activity of pomegranate, exhibited significant variations among fruits harvested from plants propagated through different methods. The fruits obtained from tissue-cultured plants showed the highest level of anthocyanin content in the juice compared to those from air-layered or cutting plants. Sun scald and fruit cracking are major physiological disorders that significantly impact the physical appearance and marketability of pomegranate fruits, particularly in arid conditions. Among the three types of planting material, only nominal variations were observed in the incidence of sun scald and fruit cracking (as shown in Figure 1). Sun scald was recorded at a minimum in tissue-cultured plants, while fruit cracking was more prevalent in air-layered plants. However, statistically, there were no significant differences observed between the two, indicating that they were comparable in terms of sun scald and fruit cracking incidences.

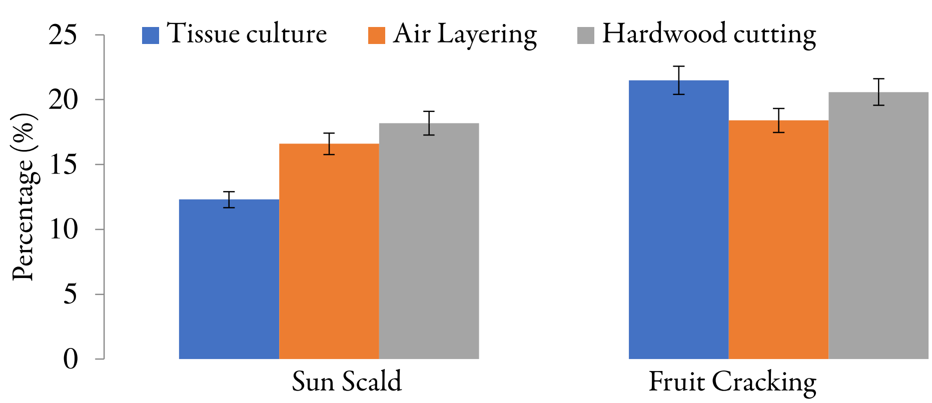

Figure 1. Sun scald (%) and fruit cracking (%) in pomegranate plants raised through different methods of propagation

Table 2. Fruit and yield related parameters of pomegranate in plants raised through different propagation methods

Planting material	Fruit length (cm)	Fruit breadth (cm)	Fruit weight (g)	Yield/ plant (kg/plant)	Rind thickness (mm)	Rind (%)	100 aril weight (g)	Rind /fruit ratio	Aril /fruit ratio
Tissue culture	6.1	6.2	208.5	14.15	3.08	85.39	32.25	0.40	0.562
Air layering	6.7	6.8	226.7	12.76	3.52	96.43	31.58	0.42	0.447
Cutting	6.4	6.6	221.5	12.53	3.54	98.49	35.60	0.45	0.515
CD (P=0.05)	NS	NS	NS	NS	NS	3.1	NS	NS	NS

Table 3. Fruit quality parameters of pomegranate in plants raised through different propagation methods

Planting material	Juice content (%)	TSS (°B)	Acidity (%)	Brix/ acid ratio	Juice anthocyanin content (cyanidin-3-glucoside equivalents, mg/L)
Tissue culture	38.33	15.94	0.46	34.63	545.76
Air layering	33.84	16.40	0.50	32.80	415.76
Cutting	35.60	17.20	0.48	35.87	409.09
CD (P=0.05)	NS	NS	NS	NS	12.56

The rind of pomegranate is the main non-edible part of the fruit, constituting approximately 40% of the fruit's weight (Babu *et al.*, 2015). It contains around 153 different phytochemicals, including minerals, which possess various pharmaceutical properties (Ram Chandra *et al.*, 2011). Therefore, in this study, the major nutrient content in the fruit rind was also assessed to determine whether the nutrient and mineral content is governed by the genetic makeup of the plants rather than the method of asexual propagation within the same variety. The results of the present study clearly indicate that the different types of planting material did not influence the nutrient content in the pomegranate rind. Parameters such as phosphorus, potassium, calcium, zinc, iron, and sodium were found to be similar across the different planting materials, as shown in Table 4. This suggests that the nutrient content in the rind is primarily determined by the genetic characteristics of the plants and is not significantly influenced by the method of asexual propagation within the same variety.

Table 4. Mineral content (mg/100g) of pomegranate peel on dry weight basis

Planting material	Mineral contents in pomegranate peel (mg/100g dw)					
	P	K	Ca	Zn	Fe	Na
Tissue culture	112.7	138.9	329.6	0.93	6.21	62.8
Air layering	116.6	142.3	316.8	0.88	5.83	64.2
Hardwood cutting	114.8	136.8	319.2	0.89	5.96	60.9
CD (P=0.05)	NS	NS	NS	NS	NS	NS

Fruit skin colour is the principal attraction for domestic and export market. Results of the present study revealed that all three types of planting material did not influence significantly on peel colour in pomegranate fruit. The 'L*' value for each scale indicates the level of light or darkness found slightly higher in fruits from tissue cultured plants however red peel color (a* value ranged 35.43-37.54) was non-significantly influenced by different types of planting materials. The maximum 'b*' value was found for fruits on plants raised by cutting (20.37). Chroma value (C*) which is indicative of colour intensity also followed similar pattern (Table 5).

Table 5. Peel colour of pomegranate fruit harvested from plants raised through different methods of propagation

Planting material	L*	a*	b*	Chroma value
Tissue culture	63.29	36.47	18.87	40.78
Air layering	60.26	37.54	18.49	40.84
Cutting	59.14	35.43	20.37	39.14
CD (P=0.05)	NS	NS	NS	NS

The storability and shelf life of pomegranate fruits obtained from plants propagated through different methods is a major concern for pomegranate growers. To address this issue, fruits from all three categories were harvested and stored under ambient conditions to assess their shelf life. Physiological loss in weight (PLW) during storage is an important parameter that affects moisture loss, fruit quality, and marketability. In this study, PLW was found to be similar in fruits harvested from plants raised through different propagation methods during the storage period, as shown in Figure 2. As the storage period progressed, there was a significant increase in physiological weight loss. However, at specific time points, there was no significant variation in physiological weight loss among the pomegranate fruits. These findings suggest that the shelf life of pomegranate fruits, as indicated by physiological weight loss, is not significantly influenced by the type of planting material used for propagation. This implies that the storage characteristics and shelf life of pomegranate fruits are determined by factors other than the propagation method, such as post-harvest handling practices and storage conditions.

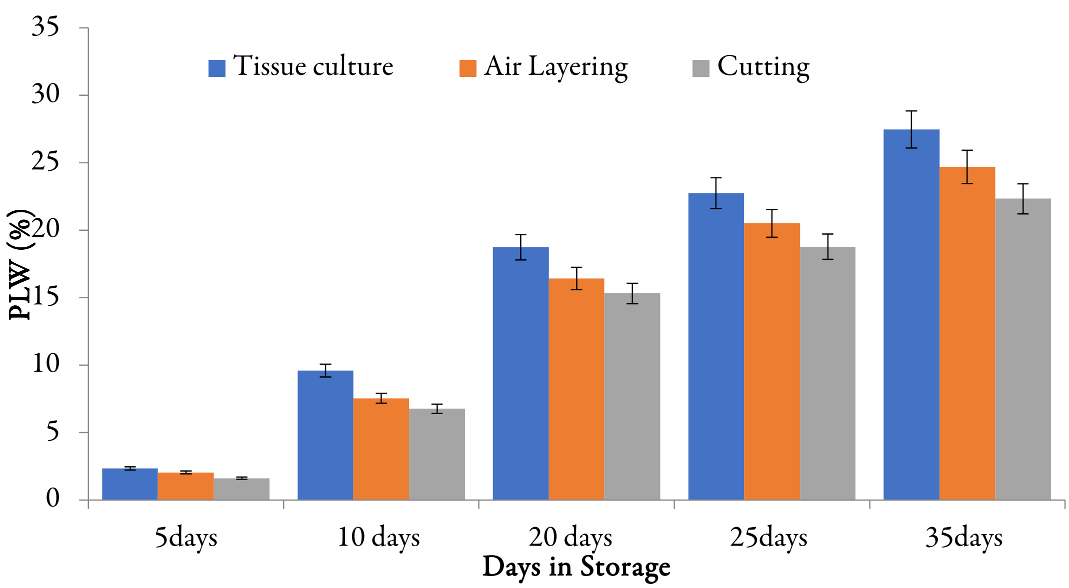

Figure 2. Physiological loss in weight of pomegranate fruits raised through different propagation methods during storage

The growth of pomegranate plants raised from different types of planting material showed non-significant variations. Initial variations in growth parameters may be observed in the pre-bearing orchard, but once recommended pruning practices for fruiting are followed, no significant differences in vegetative parameters are observed between plants raised from different types of planting material (Sharma *et al.*, 2014).

From a marketing perspective, fruit size and fruit weight are the most economically important parameters in pomegranate, and they were found to be similar across all three types of planting material. Fruit yield also did not significantly differ among the different types of planting material.

Rind thickness plays a critical role in determining the shelf life of pomegranate fruits. Concerns have been raised about the poor shelf life of fruits from tissue-cultured plants due to their thinner rind compared to air-layered or cutting plants. While a thinner rind was observed in fruits from tissue-cultured plants in this study, it did not affect the shelf life of the fruits. Additionally, physiological loss in weight (PLW) during storage, which governs moisture loss, fruit quality, and marketability, was similar in fruits harvested from plants propagated through different methods. This finding is supported by the similar rind thickness observed in fruits from plants raised through different types of planting material. Similar trends in PLW during storage in ‘Bhagwa’ fruits were observed by Babu *et al*. (2015).

Arils boldness, rind-to-fruit ratio, fruit juice content, total soluble solids (TSS), and titratable acidity were not significantly influenced by the plants raised through different propagation methods. However, the anthocyanin content in the juice, which is a principal constituent of the total antioxidant activity of pomegranate, varied significantly among fruits harvested from plants raised through different types of planting material. This variation in anthocyanin content may be influenced by several cultural and climatic factors such as exposure to sunlight, sapling procedures, and extraction methods.

Sun scald and fruit cracking, major physiological disorders, showed nominal variations among the different types of planting material. These non-significant variations may be attributed to factors such as plant water status, canopy management, and other cultural operations, as observed in previous studies (Singh *et al*., 2020; Hepaksoi *et al*., 2000; Singh *et al*., 2019). In the present study, the major nutrient content in the fruit rind was assessed to determine whether it is influenced by the genetic makeup of the plants or the method of asexual propagation within the same variety. The results clearly confirmed that the different types of planting material did not have a significant influence on the nutrient content of the rind. Parameters such as phosphorus, potassium, calcium, zinc, iron, and sodium were found to be similar across the different types of planting material. This suggests that the nutrient content in the fruit rind is primarily determined by the genetic characteristics of the plants and is not significantly influenced by the method of asexual propagation within the same variety.

Optimizing crop load for enhancing fruit size and quality

Crop load is a crucial factor that significantly influences fruit size, and thinning fruits to an optimal level is an effective method to improve fruit size. The results clearly demonstrate that as the number of fruits on a tree increases, the individual fruit size decreases, and vice versa. Although the average fruit weight was highest in plants with 60 fruits, satisfactory fruit size was observed up to 100 fruits per plant. However, beyond that point, fruit size decreased significantly. Fruit length and breadth followed similar trends, with the highest measurements observed in plants with 60 fruits per plant and the lowest in plants with 140 fruits per plant, with no significant difference observed among intermediate crop loads.

Total fruit yield did not exhibit significant differences among the different crop loads, except for the highest thinning level of 60 fruits per plant. However, the marketable yield, particularly the contribution of 'A'-grade fruits, was higher in plants that retained a lower number of fruits. Harvested fruits were also categorized based on sizes, and notable differences were observed among the different crop loads. The highest percentage of 'A'-grade fruits was obtained when the lowest number of fruits were retained on the plants, whereas only a small proportion (12%) of 'A'-grade fruits was recorded with the highest number of fruits on individual plants. Based on these findings, it can be concluded that the ideal retention of fruit load may be around 80 fruits per tree in order to achieve a higher marketable yield and better prices.

It is interesting to note that the crop load did not have a significant effect on aril size, although both aril length and breadth slightly decreased with increasing fruit retention, but the difference was not statistically significant. However, the total aril content was significantly higher in fruits harvested from plants with fruit retention up to 100 fruits per plant, and there was a drastic reduction in aril recovery beyond that point. Although rind thickness was not significantly affected by different levels of fruit load, there was an increasing trend with an increasing number of fruits retained.

The results also showed that the number of fruits on the tree has a significant influence on the juice content and total soluble solid (TSS) content. Higher amounts of fruit juice were obtained up to 80 fruits per plant, and then it decreased slightly, but the reduction was not statistically significant within the three consecutive levels of fruit retention. The retention of fruits up to 100 fruits per plant did not have a significant effect on the total soluble solid content, although it was highest in fruits with the minimum number of fruits on the plant (60 per plant).

An important finding of the present study is that optimal crop load can help prevent fruit cracking, which is a major issue in arid regions. It was observed that fruit cracking was at a minimum in plants with the lowest crop load and increased with an increasing number of fruits on the plant. Plants with crop loads of 60 and 80 fruits per plant exhibited significantly higher fruit weight, fruit size, fruit yield, and juice content. This confirms that managing the crop load at an optimum level is a crucial cultural practice for achieving higher marketable yield and superior-grade fruits with the best quality.

The leaf-to-fruit ratio also plays an important role in fruit weight, where a higher number of leaves are dedicated to each fruit, supporting fruit growth and reducing competition among the fruits. Therefore, fruit thinning increases the availability of carbohydrates, which contribute to increased fruit weight and size (Jafari *et al*., 2014). However, it is equally important to consider the optimum crop load from a productivity perspective. After a critical level of thinning, fruit size and weight may increase, but the overall total yield decreases, as observed in the present study and supported by previous research (Jafari *et al*., 2014; Ibrahim *et al*., 2018; Kahramanoglu *et al*., 2018; Elham *et al*., 2020). The source-sink relationship is mainly altered by crop load, as fruit tissue acts as a strong sink for photosynthates, nutrients, and water. Therefore, increasing the number of fruits can negatively affect fruit size and quality due to increased competition among fruits for carbohydrates, nutrients, and water (Rodrigues *et al*., 2019). Fruit thinning allows the remaining fruits to receive more photosynthetic materials, resulting in larger cells, increased weights, and improved quality attributes (Mohsen and Osman, 2015; Sharma and Singh, 2000) (Tables 6 and 7).

Table 6. Effect of fruit load on fruit weight, yield and grading percent

Fruit load/plant	Fruit weight (g)	Fruit length (cm)	Fruit breadth (cm)	Fruit yield (kg/tree)	Fruit Grade		
					>300 g	200-300 g	<200 g
60	326.0	7.2	7.6	16.7	63	30	7
80	305.5	7.0	7.2	18.3	57	31	12
100	243.6	6.6	6.8	17.5	38	42	20
120	183.2	6.3	6.7	17.5	18	38	44
140	163.8	5.8	6.2	18.3	12	30	58
CD (0.05)	17.6	0.80	0.62	0.72	6.8	6.4	7.3

Table 7. Effect of fruit load on fruit quality of pomegranate

Fruit load/plant	Aril length (mm)	Aril breadth (mm)	Aril (%)	Juice (%)	Rind thickness (mm)	TSS (°B)	Fruit cracking (%)
60	9.3	7.4	54.3	34.2	3.2	17.8	12.4
80	9.3	6.7	56.6	32.8	3.2	17.3	16.5
100	8.6	6.6	50.8	29.6	3.1	17.1	20.9
120	8.5	6.8	46.2	29.8	3.5	16.0	27.1
140	8.7	6.7	41.5	26.5	3.4	16.1	29.5
CD (0.05)	NS	NS	5.2	2.8	NS	0.46	4.1

Staggered crop regulation for extending harvesting season

The manipulation of defoliation timing and rest periods can be utilized to extend the availability period of pomegranate fruits with minimum fruit cracking. The results of the crop regulation experiment conducted at monthly intervals from the second week of June to September showed that defoliation performed in June and July required approximately 150-160 days for the first harvest, while defoliation in September resulted in a slightly shorter time to start the first harvest. The horizontal bar diagram (Figure 3) clearly demonstrates that staggering the rest period significantly extended the harvesting period from the second fortnight of November to the second week of March, compared to the normal rest period in July, which only yielded fruits for two months (December and January).

Although the total fruit yield was highest in plants regulated in July and lowest in September, the average fruit weight was highest in September, followed by August defoliation (Table 8). Fruit juice content was not significantly affected by crop regulation, but the total soluble solid (TSS) content was relatively higher in the fruits harvested from the July and August cropping seasons.

Notably, fruit cracking, which is a major challenge in arid regions, was negligible in plants defoliated in either June or September, while the highest incidence of cracked fruits was recorded in plants defoliated in July. Fruit color was relatively lower in fruits from September defoliation compared to June or July, as indicated by the color coordinate 'a*' representing redness, which was highest in fruits from July defoliation, similar to the remaining defoliation periods except for September. Temperature variations between day and night, along with humidity during the ripening stage of pomegranate, significantly influence the extent of fruit cracking and quality (Khub, 2014; Galindo *et al*., 2014; Abd and Raman, 2010). In pomegranate, cracking is induced by differences in growth rates between the fruit peel and flesh, as well as the pressure exerted by the rapidly expanding arils on the stretched peel. Extreme and fluctuating temperatures can further affect the movement of water in and out of the fruit, putting additional strain on the peel and leading to poor quality and increased cracking. These findings are consistent with previous reports (Khub, 2015; Singh *et al*., 2020).

It is crucial to note that adopting staggered crop regulation from June to September can extend the fruit availability period for four months, from the last week of November to March, thereby avoiding peak harvesting during extreme temperature fluctuations. Furthermore, in growing areas where fruit cracking is more prevalent, crop regulation can be conducted either in June or September to obtain crack-free fruits during November or February-March.

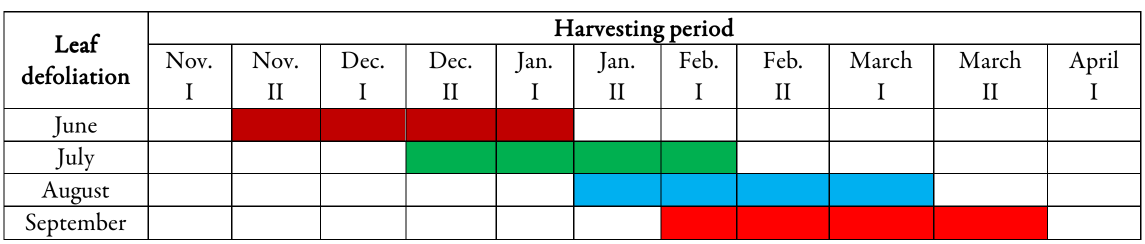

Figure 3. Effect of staggered crop regulation on harvesting period of pomegranate

Table 8. Fruit quality of pomegranate influenced by staggered crop regulation

Leaf defoliation	Fruit yield (kg/tree)	Fruit weight (g)	Juice content (%)	Fruit cracking (%)	TSS (°B)	Fruit colour		
						L*	a*	b*
June	14.6	169.3	36.0	9.95	15.5	70.2	36.73	18.4
July	16.9	171.8	32.9	32.0	16.5	76.4	40.10	17.7
August	13.8	198.0	34.2	26.2	16.2	70.7	35.51	20.8
September	11.9	236.7	30.2	4.8	14.6	62.9	22.95	27.8
CD (0.05)	2.1	9.3	2.3	5.6	0.42	3.6	4.7	3.2

Response of organo –mineral fertilizers

Data contained in Table 8 revealed that total fruit yield, fruit weight, aril weight and rind weight is higher in plants received recommended fertigation closely followed by N, P through inorganic + OMF- K either in two splits or single dose, however it was recorded minimum in NPK through inorganic fertilization. Fruit juice content and total soluble content were non-significantly affected by different combination of fertilizers. Interestingly fruit cracking which is one of most important challenges in pomegranate cultivation in arid regions of India is significantly altered by organo mineral fertilizers. Soil application of both the organo mineral fertilizers either single or splits minimized fruit cracking in pomegranate compared to recommend NPK through inorganic sources. Among the different combination of organo mineral fertilizers application of OMF-K in two equal splits along with recommended N and P through inorganic source reduced fruit cracking significantly with meager proportion of 6.23% compared to recommend NPK through inorganic (26.9%) and recommended fertigation (20.3%). Other way of interpretation of results is around 20 per cent additional yield would be added into total marketable yield. Fruit cracking is a physiological disorder caused by multiple factors resulting in variations in turgor pressure which is to be regulated by sustained release of phosphorous and potassium in soil solution. Because of soil conditions and aridity in the region sustenance of optimum level of K and P is difficult to achieve by conventional fertilizers as release of K and P from them follows a pulsatic nature. However, these indigenous fertilizers are slow and continuous releasing P and K which maintain the optimum level of these nutrients in fruit tissue and this might be the reason of less fruit cracking in plants fertilized with organo-mineral fertilizers. The release and availability of P/K in soil was confirmed with isolations of P- and K- solubilizing fungi from the blocks with OMF along with significantly higher values of available P (0.006 mg/g) and K (0.01 mg/g) recorded from these blocks compared to control chambers. Moreover, the OMF fertilizers did not exhibited any adverse effects on the plants and on soil microflora. The release of soluble P and K from the OMF is attributed to the presence of P and K solubilizers in soil, since conditions favourable for their selective enrichment are created (Saritha *et al*., 2021). Due to release of soluble P and K from OMF-P and OMF-K leads to increase in effective root biomass, active roots which facilitate to increase the plant nutrient uptake. In a study, potassium fertilization was found to generate significant changes in root diameter, which increased linearly with the increase of K rates (Filho *et al*. 2017). Ability of indigenous OMF in favourable adaptation in pomegranate rhizosphere might be the reason in achieving higher fruit yield and reduced fruit cracking (Table 9; Figure 4)).

Table 9. Response of organo –minerals fertilizers on quality and fruit cracking in pomegranate

Treatment	Yield kg/plant	Fruit weight (g)	Rind weight (g)	Aril weight (g)	Juice content (%)	TSS (°B)	Cracking (%)
NPK through inorganic	11.6	188.9	86.0	101.8	33.8	16.5	32.9
NP through inorganic + organo K single dose	12.8	203.8	90.6	112.6	32.6	17.0	15.6
NK through inorganic + organo P single dose	12.5	192.6	87.0	108.6	34.7	15.8	18.9
NP through inorganic + organo K in two splits	14.8	204.5	94.2	103.4	34.5	16.8	6.2
NK through inorganic + organo P in two splits	12.6	190.6	89.4	99.0	34.1	15.3	13.3
Recommended ferti-gation	15.1	208.2	98.4	116.2	32.5	16.2	20.3
CD (0.05)	2.4	8.6	4.3	5.8	1.6	0.38	4.8

F1: NPK through inorganic sources; F2: NP through inorganic sources + organo mineral K single dose

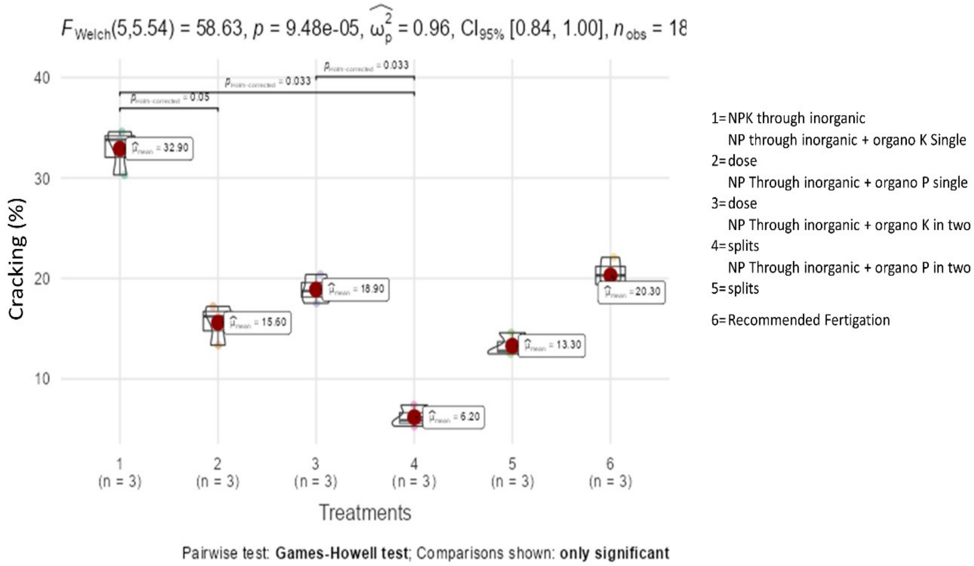

Figure 4. Relationship of fruit cracking with organo-mineral fertilizers

Conclusions

The comprehensive study presented in this research paper has effectively addressed and dispelled various misconceptions while confirming the fact that growth and fruit quality remain consistent regardless of the method of asexual propagation used. Any variations in fruit quality observed among plants raised from different types of planting material of the same variety can be attributed to differences in management practices implemented in the orchard. The management of crop load at an optimum level, specifically 80 fruits per plant, emerges as a crucial cultural aspect for achieving higher marketable yields and superior-grade fruits with the best quality. Additionally, adopting a staggered crop regulation strategy from June to September allows for an extended harvesting season of four months, starting from the last week of November and continuing until March. This represents a significant improvement compared to the standard regulation, which typically spans only two months and is associated with a higher risk of fruit cracking. Among the various combinations of organo-mineral fertilizers tested, the application of OMF-K in two equal splits, along with recommended N and P, resulted in reduced fruit cracking and exhibiting desirable quality attributes. Overall, these findings provide valuable insights for pomegranate growers and emphasize the importance of effective management practices in optimizing crop load, extending the harvesting period, and utilizing appropriate fertilization strategies to enhance fruit quality.

Authors' Contributions

A.S. - Conceptualization, data collection and writing. P.K.- manuscript drafting and editing. P.R.M.- Experiment handing, data collection. P.S. – data collection & data analysis. A.N.- figures plotting, graphical representation. P.S.K - interpretation and editing. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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