UNDERSTANDING PHENOLOGICAL STAGES OF POMEGRANATES *vis-à-vis* FLOWERING AND FRUITING REGULATION

A review

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ABSTRACT

A thorough understanding of plant behavior at different growth stages is of paramount importance for fruit quality improvement, the regulation of production periods, and reduced fruit production costs. There are as many as three waves of flowering in evergreen pomegranate cultivars – i.e., during the spring, rainy, and autumn seasons. However, for securing enhanced production of superior quality fruits as well as profit to the growers, crop regulation is required. This can be achieved by forcing the tree to rest at a particular stage and by producing abundant blossoming and quality fruits during any one of the three flushes. Observations on phenological phases would help in understanding the dates of specific stages of crop development, which in turn enable the growers to plan, organize, and carry out timely schedules of agronomic practices such as irrigation, fertilization, and crop protection. Therefore, there is a need to evaluate the response of pomegranate under different environmental conditions to identify a suitable flowering season to produce a better quality of fruits with consistent yield, and to enable standardization of management practices for optimum production based on phenological stages.

Key words: blossoming periods, flowering and crop regulation, manual and chemical thinning, phenological stages

INTRODUCTION

The pomegranate (*Punica granatum* L.; family Lythraceae), the origin of which is believed to be in Iran, has been recognized as a remunerative fruit crop in India due to its resilient nature and high returns per unit area (Rajkumar et al. 2016, 2017). Pomegranates have high medicinal value and health benefits, such as in the treatment of coughs, urinary infections, sore throats, and skin and digestive disorders (Bhowmik et al. 2013; Fawole & Opara

2013; Pal et al. 2014). Owing to its several health and nutritional benefits, the pomegranate is recognized as a “superfood”. Pomegranate fruit pulp and the seeds are stomachics, and dried powdered flower buds are used as a cure for bronchitis (Bhowmik et al. 2013, Sreekumar et al. 2014).

In terms of area and production, India is the largest producer of pomegranate in the world. During 2017–2018, 2,845 thousand tons of pomegranate fruits were harvested in India from 234,000 hectares area (MAFW 2020). Although Indian productivity

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of 12.15 Mt·ha⁻¹ (MAFW 2020) is very low compared to Turkey (27.25 t·ha⁻¹), Spain (20.00 t·ha⁻¹), USA (16.7 t·ha⁻¹), and Israel (22–22.5 t·ha⁻¹) (NRCP 2015; Ferrara et al. 2021). India exported 80,547.74 MT of pomegranate valued at USD 93853630.21 during 2019–2020 (APEDA 2021). In India, the state of Maharashtra is the largest producer of pomegranates (nearly 65% of the total pomegranate production area in the country), followed by Gujarat, Karnataka, Andhra Pradesh, Madhya Pradesh, Tamil Nadu, and Rajasthan (MAFW 2020). Low average fruit yield in the leading pomegranate-producing states of India could be ascribed to the production losses caused by biotic, edaphic, and environmental stresses and non-adoption of cultural practices such as crop regulation.

At present, pomegranate cultivation in India is growing faster due to great market demand, the crop's drought-hardy nature, low-cost management, and wider adaptability (Patil & Shewale 2003; Rymon 2011; Jain & Desai 2018). The main problem in pomegranate cultivation is the lack of standardized flowering regulation practices, as it flowers continuously under tropical and subtropical conditions. The plants under such conditions may continue bearing flowers and will bear small crops irregularly at different periods of the year, which may not be desirable commercially. Hence, it is imperative to regulate the flowering in such a way that it results in a prolific harvest in any one of the desired seasons determined by the climatological factors and local market demand. Accordingly, there is a pressing need to develop region-specific pomegranate production technologies suitable for various tropical and subtropical regions of the country (Asrey et al. 2007). In recent years, crop phenology (the timing of plant growth and development) has gained attention for its use in facilitating optimized agricultural management practices for increasing productivity (Krishna et al. 2019). Plant development and phenological phases exhibit huge spatial alterations (Baddour & Kontongomde 2009). However, the periodic biological events in plants are affected to the utmost extent by environmental variables such as temperature, photoperiod, and precipitation.

Plant development is influenced by weather and climatic conditions (at micro- and macroscales, respectively), edaphic conditions, pest occurrence, etc., and may vary among individual plants owing to genetic composition and age. Therefore, phenological analyses can be a basis for the evaluation of the sequential phases of crop growth and reproduction in different geographical regions to generate phenological data as input for crop models and for the timing of horticultural practices. Therefore, it is essential to identify the critical phenological stages, using the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) General Scale, to standardize the package of practices for crop regulation in pomegranates (Melgarejo et al. 1997). In the present article, comprehensive information has been compiled to develop sustainable production technology for pomegranates with the consequence of the regulation of flowering at a particular phenological stage and to identify the suitable flowering season with improved fruit yield and quality under different environmental conditions.

Importance of phenological studies in pomegranate with a special reference to flowering and fruiting

Phenology is a key component of life on earth, and it involves the study of the influence of seasons, climatic conditions, and local environmental factors on periodic, sensitive biological life cycle events, such as flowering of trees (Krishna et al. 2019). Understanding the yearly timing of phenophases and their alterability can facilitate the improvement of crop management practices, which ultimately may lead to higher yields coupled with superior quality. Further, the data generated from the studies of phenophases can be utilized for defining the growing season length for a particular region (Chmielewski 2003). Such data can also be used to devise suitable canopy management practices, crop regulation, intercropping, scheduling of irrigation and manuring and fertilization and plant protection measures, etc. Further, those data can be helpful in preparing forecasts of plant development and harvest dates by assessment of weather-associated risks (Chmielewski 2013).

The duration of the cropping season can also be calculated using phenological events: for instance, in pomegranates, the annual cycle starts from a dormant bud stage and ends with the leaf fall stage. The active growing season lasts between 8–9 months; however, some variations do exist among cultivars. The duration of the cropping season also influences the sequence of horticultural practices and the labor load of the orchard.

Similarly, phenological observations can help to identify favorable and unfavorable growing areas for pomegranate cultivation. Further, phenological data can be utilized for site classifications and selecting suitable varieties for given climatic conditions (Schwartz 2013). For instance, ‘Bhagwa’ is better suited for semiarid conditions with assured irrigation facilities. On the other hand, ‘Jalore Seedless’ performs well in an arid climate. Poorly adapted genotypes show higher yield fluctuations and even yield depressions (Chmielewski 2013).

Crop stands have their own microclimate, which can differ substantially from the prevailing climatic conditions. Apart from meteorological (radiation, temperature, rainfall, wind velocity) and plant-morphological factors (plant structure, its cover, height, the density of stand, etc.), the microclimate of crop stands also depends on the plant development. Hence, phenological studies are essential for examining the microclimate in order to ascertain its impact on pest infestation or incidences of physiological disorders (fruit splitting) within the plant canopy. Leaf size, thickness, and canopy volume significantly influence canopy temperature and therefore fruit splitting (Singh et al. 2014). Phenophase “73” is crucial for the occurrence of fruit splitting, which coincides with an increase in pulp volume during stage II of fruit development. Therefore, reduced irrigation during periods of rapid fruit growth without stressing the tree or lowering of fruit surface temperature by altering canopy architecture holds promise in lessening the possibilities of fruit splitting incidence. Likewise, a brief spell of irrigation restriction at the end of the ripening period (85)

results in an early harvest of nutritionally superior products without compromising the fruit size and marketable yield (Galindo et al. 2017). High humidity and moderate temperature within the plant canopy render a favorable microclimate for pests and disease multiplication. Since the microclimate depends on plant development, the risk of infection also varies with plant development. Therefore, monitoring phenophases is essential to devising suitable cultural practices to avoid a build-up of the pest populations (Munhuweyi et al. 2016).

Rajaei and Yazdanpanah (2015) noticed that the leaves of pomegranate ‘Rabbab-e-Neyriz’ remained green in color during fruit set and ripening; however, after harvest, they turned green-yellow from mid-October and gradually dropped. The gradual leaf fall (phenophase 93) ensures efficient N translocation from the leaves to the perennial structures of plants (Nord & Lynch 2009). This indicates that plants need a rest period after a harvest to reinvigorate themselves and prepare for the next crop. For the augmentation of a prolific crop, rest periods in pomegranate are essential (Sharma & Krishna 2014). Further, it has been noticed that the lower part of the midrib and petiole turn red-purple in autumn during fall (Rajaei & Yazdanpanah 2015). The phenolic pigment components accumulated in the leaves could be phytotoxic to other plant species and may inhibit their germination the following spring. Therefore, they act as pre-emergence bioherbicides, which reduces interspecific competition (Keller 2015).

Major obstacles that hinder the production of pomegranate are water deficiency and the occurrence of insect pests and diseases during flowering and fruit development (Sonawane 2017). Therefore, defining the stages of vegetative growth and flowering and fruit set may assist in the adoption of good agricultural practices such as fertilization, irrigation, and pruning schedule to control the occurrence of insect pests and diseases and to optimize the fruit quality as well as yield (Badour & Kontongomde 2009). Previous work done on pomegranate phenological models is scant.

In India, several studies have described the occurrence of flowering throughout the year, but a systematic study relating to the occurrence of vegetative growth, flowering, fruit set, and fruit growth has not been done yet. As a result, a precise management strategy has not been standardized and recommended to the growers. The present review relates the phenological cycle of pomegranate trees grown under various climatic conditions of India, which will provide an advisory for optimal tree management practices based on the phenology of pomegranate cultivars.

Phenological stages of pomegranate trees

Melgarejo et al. (1997) observed various growth stages of pomegranate trees in a Mediterranean climate. These stages, their phenological codes, and their respective duration in the annual growth cycle are illustrated in Figures 1–2 and Table 1.

Selection of flowering season and need for flowering regulation

The flowering behavior of the pomegranate crop depends on the prevailing climatic conditions. Inherently, pomegranates have a tendency to flower throughout the year; consequently this leads to multiple harvests with poor yields having inferior quality fruits (Singh et al. 2006; NRCP 2014a; Bhakti et al. 2016; Lal et al. 2017). Therefore, one of the most important things making crop regulation in pomegranates essential is the peculiarity of flowering under a tropical and subtropical climate as in temperate regions of the world, where the plants flower only once a year. In India, three distinct flowering seasons, spring flowering, rainy season flowering, which coincides with the break of monsoon, and autumn flowering, which occurs in February to March, June to July, and September to October, respectively, have been noticed (Teixeira da Silva et al. 2013). Factors such as climate, pest/disease incidence, and agricultural operations such as manuring, irrigation, and plant protection measures are taken into consideration for better economic returns from a flowering season (Sachin et al. 2015).

The fruit quality and yield depend on the flowering season, and the prioritization of flowering seasons varies from region to region. Each of the three flowering seasons has its own advantages and disadvantages, as shown in Table 2. Considering the patterns of precipitation in India, flowering can be induced in spring in areas with sufficient water during hot weather. Flowering during rains is advantageous in areas with assured rainfall in June to September. Where monsoon begins early and retreats by September, induction of flowering in autumn is feasible (Sachin et al. 2015).

Therefore, to determine the most suitable flowering season out of the three main flowering seasons, the factors summarized in Figure 3 should be taken into account.

Pomegranates generally take 120–210 days from initiation of flowering to harvest, although it depends on the genotype (Ashton 2006; NRCP 2014a). The period of 4–6 months between two harvesting seasons is recognized as a “rest period”. In general, a rest period of three to four months is necessary for a prolific harvest. Therefore, there is a necessity for regulatory operations such as flowering regulation practice, which forces the plants to rest and produce abundant blossoms and fruits in any one of the chosen flowering seasons (Maan 2018).

Spring flowering in northern India is desired due to copious flowering and the prevailing hot and dry climate during fruit development stages, which produces remunerative returns (Singh et al. 2011); there is more incidence of pest and disease attacks during the rainy season, usually damaging the rainy season flowering crop (Singh et al. 2006). However, the provision of irrigation should be taken into consideration when choosing spring flowering as there is a chance of fruit drop in spring flowering owing to moisture stress at the time of fruit set and development under the dryland conditions of Central Gujarat (Raturi & Hiwale 1991).

Figure 1. Growth stages, BBCH phenological codes, and duration percentage (of annual growth cycle) of the pomegranate trees in a Mediterranean climate characterized by hot and dry summers and mild and rainy winters

Due to humid weather during the monsoon and post-monsoon period, imposition of water stress becomes difficult, and thus the practice of autumn flowering becomes impossible under subtropical climate. For a better fruit set and maximum size fruit, rainy season flowering – i.e., June to July flowering – is preferred in the subtropical zones. But this season causes cracking at maturity due to diurnal temperature variation (Lawande 2000).

In general, a pomegranate plant starts bearing fruits after 3–4 years after planting and continues

up to 30 years (Singh 1995; Babu 2010); farmers can get economic yield eight to ten years after planting (NRCP 2014a). The different flowering seasons of pomegranate and their harvesting seasons are shown in Table 3.

Singh and Kingsley (2007) reported that the September through October harvests yield fruits of good quality with the least cracking, fruits with high juice content, TSS, appropriate acidity, and sugar content, and fruits with the least peel thickness.

Figure 2. Different phenophases of pomegranate development

Hiwale (2009) reported that a good crop was obtained when September flowers were retained because the period of fruit development coincided with maximum moisture availability and cool climate, leading to fewer incidences

of insect pests, diseases, and fruit cracking, thereby improving the quality of fruits. Selection of proper planting material, regulation of the flowering season, and spraying of boron and GA_3 are used to control fruit cracking in pomegranates

(Singh et al. 2006); however, in the leading pomegranate-producing states of India, harvesting of pomegranate through the adoption of flowering regulation practices produces the availability

of fruits in the market as shown in Figure 4. By regulating flowering in different parts of states, farmers of Maharashtra and Tamil Nadu can produce pomegranate throughout the year.

Table 1. Description of growth stages with BBCH phenological codes of pomegranate trees in a Mediterranean climate

BBCH code	Growth stage	Description
0	Bud in winter dormancy	Bud color grayish brown, entirely closed, connected to the twig, tip sharply pointed
1	Bud swelling	Bud begins to swell, later turns paler and round
9	Red tip	Bud opens with a spear-shaped new shoot with a red tip
10	Sprouting of the first leaves	First furled bright red leaves with pale green midrib appear
10	Leaf separation	New leaves begin to separate
11	Leaf growth	Leaves grow up in size and change color from bright red to light green
31	Lengthening of internodes	Internodes elongate and steadfast shoot growth
51	Appearance of the flower buds	Sepals are visible and close together. Greenish flower buds turn into red color
55	Swollen calyx	Buds swelling, attain pear shape; differences between male and hermaphrodite flowers noticeable in the shape and the color of the calyx
59	Opening of the calyx	Sepals unfold and exhibit the folded red petals within. Petals open and the pistil/anthers become visible toward the end of this stage
61	Open flower	Calyx unfolds entirely and the protruding petals, which are folded and purple, unfold over the sepals. The petals appear inserted between every two sepals on their inner side, thereby giving the impression of alternating petals and sepals. The anthers of the stamen change to deep yellow when the pollen is ripe, capable of fertilizing, and pollination occurs
67	Petal fall	Petals fall following drying and shriveling; the calyx color changes from red to orange-red; stamens curved toward the longitudinal axis of the flower and the anthers turn grayish-yellow. The terminal part of the style withers
69	Fruit setting	The fertilized ovary and the base of the calyx swells; the stamens are dried up and shriveled and the fruit color changes from orange-red to greenish-brown
71	Young fruit	Fruit size increases rapidly and the color turns from greenish-brown to green
73	Fruit growth	Fruit attains nearly its final size; the sepals form a crown, the dry stamen being inside
39	Second bud sprouting	The recommencement of shoot growth
81, 85	Fruit ripening	The fleshy seeds turn white to pinkish-red or red; the peel of the fruit changes from green to greenish-yellow and to brownish-yellow with reddish patches
93	Leaf fall	Leaves become yellowish and fall; onset of winter dormancy

Table 2. Comparison of different flowering seasons

Flowering season	Spring flowering	Autumn flowering	Rainy season flowering
Preferences	Preferable if irrigation facilities are available	Rarely taken, although suitable for export, preferred in areas infected with bacterial blight (<i>Xanthomonas axonopodis</i> pv. <i>punicae</i>)	Preferable under drought-prone areas
Remarks	More flowering and high yields, the limited incidence of pests and diseases due to dry weather	Fewer incidences of insect pests and diseases, high-quality fruits (attractive rind with dark-colored arils), fetch higher market price due to limited availability of the fruits during this season, optimum water stress cannot be developed as withholding of irrigation happens together with the rainy season, poor flowering, and yield	More chances of insect pests and disease attack, poor fruit quality (fungal fruit spots and cracking in dry regions where diurnal temperature variation is high), should be avoided in areas with heavy rainfall during monsoon season

Figure 3. Factors responsible for the selection of the flowering season

Flowering and fruiting behavior in pomegranates

The bearing habit of pomegranate is greatly impacted by the prevailing climatic condition of the geographical region, that is, wherever it is raised (Saroj & Kumar 2019). In areas experiencing low temperatures during winters, the tree is deciduous; however, in the tropics, it behaves like an evergreen

or exhibits a partial deciduous nature and flowers almost throughout the year (Babu 2010). In the northern hemisphere, flowering mostly occurs during April to May, but it may continue until the end of summer, especially in young trees (Babu 2010). The developmental stages of flowers are shown in Figure 5.

Table 3. Flowering seasons of pomegranates

Seasons of flowering	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Spring	Flowering					Harvesting						
Rainy	Harvesting					Flowering					Harvesting	
Autumn		Harvesting							Flowering			
		Lean period				Peak period			Round the year			
State	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maharashtra												
Karnataka												
Madhya Pradesh												
Tamil Nadu												
Andhra Pradesh												
Gujarat												

Source: NRCP 2017

Figure 4. Period of availability of pomegranate fruits in the market (lean period: when availability is low, prices are higher for the produce; peak period: when availability is high, prices are lower)

Figure 5. Developmental stages of flower buds in pomegranate

Singh (1969) observed pomegranate flowers during the spring season in North India. Thus, in the subtropical climate of the northern hemisphere, flowering occurs from the last week of March until the second week of May (Fouad et al. 1979). In pomegranates, flowering occurs both on newly emerged branches developed during the same year, mostly on spurs or short branches, generally about one month after bud break and on the previous season's growth. Flowers may appear solitary or in pairs or clusters. It is usually noticed that the solitary flowers appear on spurs along the branches, while the cluster flowers bear terminally (Nalawadi et al. 1973; Josan et al. 1979; Holland et al. 2009). Descriptions of types of shoots in pomegranate are provided in Figure 6.

In pomegranate, three types of flowers – hermaphrodite, functionally male, and intermediate forms, have been noticed on the same tree (Čizmović et al. 2016). However, only functionally male flowers and the hermaphrodite flowers are the main forms (Fig. 7). The calyx of the hermaphrodites is noted to be urceolate (pitcher-like “vase shape”) with a broad and well-developed ovary, while male flowers are smaller in size, having a campanulate (bell-shaped) calyx and a rudimentary ovary (Wetzstein et al. 2011). Fruits arising from the intermediate forms show several forms of ovary degeneration and such flowers fall prematurely, or if they reach maturity, fruits are misshapen. In hermaphrodite flowers, the stigmas are on the same level or higher than the anthers and are usually homostylous

or pin-eyed, which not only allows self-pollination but also favors entomophily; male flowers, on the other hand, are thrum-eyed – i.e., the stigmas are beneath, with a rudimentary ovary (Josan et al. 1979; Babu 2010; NRCP 2014a). The fact that governs the degrees of fruit set is the number of hermaphrodite flowers. As a result, cultivars with a higher hermaphrodite-to-male-flowers

ratio will exhibit a higher fruit yield potential (Shulman et al. 1984). The percentage of the vase-shaped flowers among the Indian cultivars is 53–80% (Nalawadi et al. 1973). Authors have also described an intermediate type of flower as homostylous, having a short style and a developed ovary, which is sometimes reported to be fertile (Nalawadi et al. 1973, Assaf et al. 1991).

Figure 6. Different types of shoots in pomegranate: (a) the long vegetative shoot, with expanded leaves, (b) relatively long vegetative-reproductive branch with one terminal or more flower buds, (c) median vegetative-reproductive branch with one terminal or more flower buds, (d) very short reproductive branch with one terminal flower or more buds without leaves

Figure 7. Two major types of flowers in pomegranate: the V-shape, functionally male flowers (top), and the U-shape hermaphrodite flowers (bottom); the male flowers shed few days after full bloom, while the bisexual flowers develop to pomegranate fruit following pollination and fertilization

In pomegranate, both self-pollination and cross-pollination have been reported (Nalawadi et al. 1973). Wind pollination is also noted to take place; however, it has an insignificant role (Morton 1987). It has been indicated that bagging flowers of Indian, Turkmen, Israeli, and Tunisian, pomegranate cultivars lead to self-pollination and produce normal fruits (Mars 2000; Levin 2006; Holland & Bar-Ya'akov 2008). However, among different pomegranate cultivars, the extent of the fruit set varies by self-pollination (Jayesh & Kumar et al. 2004). The range of infertility of pollens varies from 6% to 20% in hermaphrodite flowers and from 14% to 28% in male flowers, respectively. Inconsistency of the size and fertility of the pollen differs among cultivars and seasons (Morton 1987).

The flowering phase diverges depending on geographical situations and cultivars (Pareek & Sharma 1993). In a tropical climates, pomegranate trees flower virtually all through the year, and flower bud differentiation takes place at different times (Singh 1969; Phadnis 1974), whereas in the subtropics of North India, the trees remain inactive in winters, and thus the foremost flowering season is in the subsequent spring season during which temperatures gradually rise and trees start to grow new leaves and flowers all over again (Singh et al. 1967; Singh 1969; Nalawadi et al. 1973), even though one more flush of flowers is also observed during rainy season as well. Depending on the genotype and climatic conditions, the duration between the commencement of the flower bud elongation and anthesis varies, spanning between 14 and 28 days (Shulman et al. 1984; Assaf et al. 1991; Mars 2000; Babu 2010). In the main pomegranate growing areas of the Deccan Plateau of India, the flowering is regulated in three distinct seasons – January to February flowering, June to July flowering, and September to October flowering. Floral buds of the spring flush

are borne on mature wood of the one-year-old shoots in evergreen cultivars, while the flowers are borne between July and August on the current season's growth in deciduous cultivars (Babu 2010). The flowering period of pomegranate in different parts of India is depicted in Table 4.

Alteration of flowering seasons in pomegranate under different climatic conditions

As discussed earlier, in pomegranate trees, the continuous flowering conditions under the provision of water availability may lead to poor-quality crops with uneven-sized fruits, which is not desirable from the viewpoint of commercial cultivation. In order to discourage such situations, trees are forced to flower and produce fruits in a particular season by adopting certain flowering regulation techniques (Fig. 8).

Spring season flowering is favored in regions with sufficient water availability during summers. The fruits are harvested from June to September. During monsoon season, after commencing rains, irrigation may be stopped. Subsequently, shallow plowing is done when trees shed their leaves in October through November; followed by manure and fertilizer application in the months of December through January; afterward, in January, a first, light irrigation is given, which leads to flowering after a month of irrigation. The quality of fruits and yield are better in Maharashtra from the spring season flowering owing to the prevalence of moderate temperatures ($<30^{\circ}\text{C}$) (Chandra et al. 2011a). Such fruits are developed during dry months in semiarid conditions and thus have an appealing color and superior quality, which renders them suitable for export. Besides, the incidences of pest and disease attacks are restricted due to dry weather. However, spring season flowering can be adopted only in areas where assured irrigation facilities exist (Singh et al. 1967; Patil & Karale 1985; Asrey et al. 2007).

Table 4. The flowering period of pomegranate in different parts of India

Region/state	Flowering period	Reference
Central and Western India	Spring (Jan–Feb); rainy (June–July); autumn (Sept–Oct)	Singh et al. (1967); Singh (1969); Mann & Pareek (1974); Phadnis (1974); Patil & Karale (1985)
Karnataka	June–August; March; September	Nalawadi et al. (1973)
Punjab	April–June	Josan et al. (1979)
Delhi	once or twice a year	Nath & Randhawa (1959)
Uttar Pradesh, Bihar	February–March; July–August	Singh et al. (1967); Singh (1969)
Rajasthan	rainy (June–July)	Mann & Pareek (1974)
Himachal Pradesh	April–May	Parmar & Kaushal (1982)

Figure 8. Cultural practices to be followed for flowering regulation in pomegranate

Rainy season flowering is practiced in areas where sufficient water is not available in summer. Rainy season flowering can be obtained by suppressing the growth by withholding irrigation from March to May. As a result, the trees drop their leaves and remain dormant until May. Shallow plowing during April should be followed by manure and fertilizer application along with one or two light irrigations prior to the onset of rains during monsoon season – i.e., May. Blooming occurs in June, and trees will bear a worthy crop. Harvesting for the rainy season flowering crop is done in the months of December to February. In Bangalore, fruits from the rainy season flowering that are maturing in October to November are superior in quality to those from the spring season flowering. The main advantage of the rainy season flowering crop is that the flowering and fruiting period happens together with the rainy season or immediately after rains; therefore, not much irrigation is required. However, the color and sweetness of the fruits are influenced, as the fruits develop during rains and mature in winters in arid regions (Singh et al. 1967; Mann & Pareek 1974).

Autumn season flowering is seldom used. The trees have to be through the dormant phase during August to September to get this blossoming period, except in some parts of Rajasthan where the soil is sandy and

rainfall seldom occurs after July. The harvesting of the fruits from the autumn season flowering is done from March to April. These fruits have an attractive rind and very dark-colored arils. The fruits obtained from autumn season flowering are grown mainly for export purposes, as this fruit fetches a high market price since the availability of the fruits during this season is limited. The main drawback is that during this period, withholding of irrigation coincides with the rainy season, and thus optimal water stress cannot be developed, which results in poor flowering and ultimately lower yield (Sonawane 2017).

Techniques of flowering regulation in pomegranate for crop management

Deblossoming and thinning

Thinning is the removal of some portion of flowers/fruits from the tree before they attain maturity, which is practiced to improve the quality and size of the fruit, enhance the marketable yield, and sustain the vigor and productivity of the tree. During thinning, small, undersized, misshapen, and insect/disease-attacked fruits are usually removed. Chemicals are applied at blooming for blossom thinning; chemicals are sprayed a few days after fruit set – i.e., after petal fall for thinning of fruitlets. Blossom thinning is always risky and adopted after assessing crop potential; fruitlet thinning is done after observing actual crop load.

Hand thinning encourages flower initiation (Singh et al. 2011; Jafari et al. 2014; Fattahi et al. 2020), while chemical sprays inhibit flower induction with the maximum inhibition with Carbaryl (1-naphthyl methylcarbamate) followed by maleic hydrazide (Ahire et al. 1993). The stimulation of flowering by hand thinning might be attributed to endogenous production of ethylene as a result of wounding (Krishna 2012). In pomegranates, the entire crop load is dependent on the percentage of hermaphrodite flowers. The lowest drop in hermaphrodite flowers as well as the least initiation of male flowers was noticed during the early flowering period (Nath & Randhawa 1959). Therefore, deblossoming at early stages may help retain greater numbers of hermaphrodite flowers and thus higher fruit set. Singh et al. (2006) reported that the maximum fruit set was obtained in the trees where deblossoming was started on 7th and 15th April in Ganesh-1 (54.8% and 35.0%) and Kandhari (35.2% and 68.3%), respectively. The trees deblossomed on earlier dates scored more due to the presence of good-sized fruits, which in turn depends on the optimum crop load and higher leaf : fruit ratio. Thus, the deblossoming of unopened flower buds should be carried out between 15th and 22nd April in order to regulate cropping during spring flowering and to obtain the optimum fruit size and higher net market returns in pomegranate cultivars Ganesh-1 and Kandhari under Punjab conditions (Singh et al. 2011). The development of higher proportions of flowers in plants where deblossoming was followed, illustrates that early deblossoming might have exhilarated the latent buds to flower, which otherwise flowered in the next flowering season under Punjab conditions.

Chemical thinning includes flower, fruit, and flower bud thinning to manage the crop load and ultimately to decrease the competition for nutrients or carbohydrates (Bussi & Genard 2014). During flower bud initiation, foliar application of gibberellic acid (GA_3) improves fruit quality due to reductions in the flower buds' differentiation, and thereby the numbers of fruitlets are reduced (González-Ros-sia et al. 2007). Chemical thinning can be done by using Ethephon, an exogenous stimulant of ethylene production, which favors fruit abscission (Wertheim 2000). Naphthalene acetic acid (NAA) and Ethrel

can be used for thinning the flowers in pomegranate to improve the fruit yield and its quality (Sheikh 2015a). Both time and dose of application are very much crucial in the use of chemicals (Krishna 2012). Various physiological mechanisms have been proposed to explain the thinning action of applied chemicals, as they are not universally applicable for all the chemicals. The thinning ability of Ethephon (2-chloroethyl phosphonic acid), which releases ethylene by hydrolysis within the treated tissues, had been assessed in pomegranate. Leaf and fruit abscission can be achieved by application of 2000 ppm Ethephon and 500–3000 ppm Alar (Pal et al. 2014). Desai et al. (1993) reported that Ethrel, NAA, and Carbaryl were used for flower thinning to get an optimum yield of high-grade fruits, gibberellic acid to check the induction of new flowers; and MH to check shoot growth. Therefore, they recommended spraying with 250 ppm NAA + 0.7% Carbaryl 75 days from the beginning of cropping to obtain optimum cropping and better fruit grade. GA is testified to have a flower inhibition effect in diverse fruit crops. Maleic hydrazide (MH) and Carbaryl act as anti-auxins, and their effect on the significant reduction in flower production was observed by Krishnamoorthy (1981). GA induced significantly more male flowers, while Ethrel appeared to induce fewer male flowers. GA also reduced the percentage of hermaphrodite flowers, while Ethrel, Carbaryl, and MH induced more hermaphrodite flowers. In general, chemical fruit thinning is advantageous in terms of saving labor and time costs. Chemical thinning is advised to be done early and at the right time in the season so as to achieve the best results in comparison to manual thinning (Ouma 2012).

Shoot pruning

The commencement of flower buds from lateral buds can be enhanced by the pruning of growing shoots, which will decrease apical dominance and enhance lateral bud development, which in turn will increase the yield. Pomegranate trees generally require the exclusion of dead and diseased branches and suckers to establish strong canopy architecture and therefore do not require abundant pruning. The pomegranate tree requires only partial pruning and bears fruits for three to four years all along with the slow-growing mature wood.

Annual pruning during winter seasons, when trees are mostly dormant, should be restricted to shortening of the previous season's growth to promote fruiting (Chakma 2014, Sonawane 2017). Hiremath et al. (2018) reported that the fruit yield per plant was found to be significant with levels of pruning and 30 cm pruning of apical shoots recorded significantly maximum yield per plant over other levels of pruning in pomegranate 'Super Bhagwa'. The unpruned trees registered the minimum fruit yield per plant. The pruning of growing shoots helps to overcome apical dominance thereby releasing lateral buds from correlative inhibition and changing canopy architecture, which in turn increases flower bud initiation from lateral buds and ultimately manifests in yield enhancement. Chakma (2014) reported that among different pruning intensities, the fruits obtained from shoots with 15 cm fruiting shoot length retained after pruning showed encouraging results with regard to attributes such as shoot extension, fruit retention, fruit size and weight, and fruit physicochemical qualities. However, the fruit set was decreased with increasing pruning intensity, and the maximum fruit set was registered in control. Besides this, pruning was beneficial in managing bacterial blight by removing the infected portions.

Application of chemicals/plant growth regulators (PGRs)/bagging

Time of application and concentration of plant growth regulators depend on fruit crop and environmental conditions. Growth regulators and chemicals were applied to induce flowering in 5-year-old pomegranate 'Bhagwa' during the autumn season flowering. Foliar spray during the month of September at 2 weeks after defoliation enables flowering to take place in pomegranate within 2–3 weeks subsequent to the foliar spray. The number of bisexual flowers was more in plants treated with NAA 10 ppm (192.6 per plant), whereas it was lowest in control (87.5 per plant). The fruit set ranged from 40.0% to 65.0%. The maximum fruit set was recorded by using NAA 10 ppm (65.0%) followed by ammonium nitrate (NH_4NO_3) 0.5% (63.1%); it was at minimum in untreated plants (40.0%) (NRCP 2014b).

Application of 10 ppm CPPU at flowering followed by a spray of 30 ppm CPPU along with GA_3 10 ppm at 21, 42, and 63 days after flowering

significantly enhanced fruit set, yield, fruit weight, and sugar contents in 'Bhagwa' (Khemnar et al. 2019). Apart from PGRs, the application of silicate and fruit bagging resulted in a harvest of larger fruits with improved color and quality in 'Wonderful' (Samra & Shalan 2013; Abdel-Sattar et al. 2017). The positive influence of fruit bagging on fruit color and the nutritional value of arils were also noted by Salama et al. (2018), Griñán et al. (2019), and Asrey et al. (2020). However, results varied to some extent owing to variability in the kind of bag used, the stage of fruit phenological development while bagging, the period of exposure to natural light post-debagging, and cultivar-specific responses. Besides, foliar sprays of kaolin (Sharma et al. 2018), nutrients such as CaCl_2 , ZnSO_4 , KNO_3 (El-Akkad et al. 2016; Chater & Garner 2018), and vapor guard (El-Akkad et al. 2016) have successfully been attempted in pomegranate to improve upon the visual acceptance and aril quality and to reduce the incidences of physiological disorders (sunburn).

Kumar et al. (2016) reported that application of micronutrients (H_3BO_3 and ZnSO_4 : 0.20%, 0.40%, 0.60%, respectively) and plant growth regulators (2,4-D and NAA: 10, 20, and 40 ppm, respectively) improved fruit quality in pomegranate 'Jodhpur Red' and showed that application of 40 ppm 2,4-D leads to more total soluble solids. However, when H_3BO_3 was applied at 15 days after fruit set, ascorbic acid content was increased, although reducing sugar content was significantly increased by the application of 2,4-D at 15 days after fruit set. Thus, application of micronutrients and growth regulators at 15 days after fruit set was more effective in improving fruit quality as compared to an application at 30 days after fruit set. Conversely, application of PGRs on days to maturity after fruit set was nonsignificant, but pomegranate fruits have shown a declined number of days to maturity. The minimum number of days (160 days) required for maturity was observed with the application of 10 ppm NAA, which is attributed to the smaller size of fruits, while the maximum number of days (185 days) for maturity was observed in GA_3 application, which is due to the fact that gibberellin had an effect on cell elongation, which ultimately resulted in larger size of fruits, higher yield as well as superior quality of fruits, net monetary returns, and B : C ratio.

The spray of 40 ppm 2,4-D and 75 ppm GA₃ was found considerably better than the other treatments in Marathwada conditions (Manasa 2017), whereas the production of bigger fruits required more days to reach maturity (Pawar et al. 2005).

Induction of flowering by defoliation and withholding of irrigation

A full-grown pomegranate tree can bear flowers and fruits year-round. A quality crop with a higher fruit yield during a particular period can be obtained by changing the natural flowering tendency of the tree by forcing the plant to enter into a “rest period” using artificial means. It is generally done by withholding irrigation water for about 2 months in advance of normal flowering and also by the use of chemicals/plant growth regulators. The use of growth regulators such as ethephon, Dormex (H₂NCN), thiourea, and urea phosphate has been suggested to defoliate the plant and induce the dormant flower buds to flower (Chandra et al. 2011b; Sheikh 2015b; Supe et al. 2015). After defoliation, a spray of trees with 3 g l⁻¹ KNO₃ helps the induction of flowering. Defoliation by Ethephon aids in the translocation of nutrients back to the branches through leaf senescence. Other agrochemicals, for instance, thiourea and insecticides such as Metacid and Profenofos, induce the formation of an abscission layer in leaves.

The practice of withholding water for about 2 months in advance of normal flowering is usually followed to regulate the flowering. After 2 months, fertilizers and manure are applied along with light irrigation, followed by a provision of normal irrigation at regular intervals. The tree responds quickly to these practices by producing new vegetative growth and blossoming, and finally bears a good crop (Patil & Karale 1985; Asrey et al. 2007; Chandra et al. 2011a; Sachin et al. 2015; Kumar et al. 2016). Water stress substitutes for chilling in areas of the tropics, which have distinct rainy and dry seasons. The principle behind suspending the vegetative growth or withholding irrigation is to provide rest to the plant, which results in the accumulation of food (carbohydrates) in large quantities for the amplification of flowering in the next season (Ravishankar et al. 2014). Reduced ascent of sap and very limited translocation of sugars (carbohydrates)

during the stress period may result in more accumulation of sugars in nearby buds. A higher level of carbohydrates – i.e., a high C/N ratio at the time of fruit bud differentiation, is correlated with fertility (Bally et al. 2000). As a result of water stress, abscisic acid (ABA) is synthesized in plants and causes stomata closing, reduced shoot growth, and reduced water loss through transpiration. Further, it could be hypothesized that the pomegranate buds are continually induced to flower, but the presence of endogenous, root-produced gibberellins kept the frequent recurrence of such events under control. Conditions conducive to inhibition of root growth (such as water stress) would thus reduce the levels of gibberellins which would otherwise be distributed to buds and would depress the flowering of buds (Monselise 1985).

In pomegranate, irrigation plays a very important role in producing new growth, blooming, and bearing a good crop, as the trees respond readily to the irrigation. However, too much soil moisture in the summer can lead to an abundance of vegetative growth, resulting in poor postharvest quality of the fruits, which tend to be softer (Sachin et al. 2015; Parvizi & Sepaskhah 2015; Sonawane 2017). Regular irrigation is essential in the period between flowering and ripening as irregular moisture conditions result in the dropping of flowers and small fruits and may cause cracking of mature fruits. Through avoiding wide variation in soil moisture and maintaining it constantly, the quality of the pomegranate fruits can be managed, although the cultivars, time, and application of irrigation during fruit growth stages also play major roles (Singh et al. 1967; Patil & Karale 1985; Asrey et al. 2007; Kumar et al. 2016).

Chandra et al. (2011a) recommended that irrigation should be stopped at least 30–35 days before possible defoliation in light sandy soil and 40–45 days or even 2 months before defoliation in sandy loam soil. In the last period of water withholding, defoliation is done using 2–2.5 ml l⁻¹ Ethrel, and just after defoliation (80–85% leaf fall), light pruning (15–25 cm) is done. After the stress period, light plowing is followed by light irrigation, and then recommended doses of manure and fertilizer are applied, and regular normal irrigation is started at a prescribed interval.

Excess irrigation at this point should be avoided. Generally, flowering occurs within 30–75 days after first irrigation as the pomegranate trees react readily to irrigation and produce a new flush. Judicious irrigation should be given at the stage of the fruit set. Khattab et al. (2011) reported that reducing the irrigation level up to 7 m³ per tree per year diminishes shoot length, leaf area, and the number of leaves per shoot in pomegranate. Mohsenzadeh et al. (2006) mentioned that the concentration of ABA, a stress hormone, in the leaves increases stress conditions and leads to stomata closure.

Critical phenological stages in pomegranate *vis-à-vis* flowering regulation

Melgarejo et al. (1997) depicted various phenological stages during the development of pomegranate trees as shown in Figure 1 and Table 1. Out of these stages, most critical for fruiting are the following: 51 (emergence of the flower buds), 55 (swollen calyx), 59 (opening of the calyx), 61 (open flower), 67 (petal fall), 69 (fruit setting), and 71 (young fruits). These must be manipulated by withholding irrigation. Flowering regulation in pomegranate can also be achieved by using the practice of withholding irrigation at 1 (bud swelling), 9 (red tip), 10 (sprouting of first leaves), 10 (leaf separation), 11 (leaf growth), and 31 (elongation of internodes) phenological stages. After 45 days of withholding irrigation, there is a need for pruning followed by manuring, fertilization, and light irrigation. Ultimately, this will lead to profuse flowering, and fruiting and harvesting of fruits will occur after 4–5 months of flowering (Singh et al. 1967; Patil & Karale 1985; Asrey et al. 2007; Chandra et al. 2011a; Kumar et al. 2016). Similarly, the phenological stages such as 51 (emergence of the flower buds), 55 (swollen calyx), 59 (opening of the calyx), 61 (open flower) are the most suitable stages for the adoption of the practice of deblossoming to regulate the crop (Singh et al. 2006; Singh et al. 2011). In like manner, Chaudhari and Desai (1993) reported that crop regulation by using the practice of chemical thinning can be done at 51 (emergence of the flower buds), 55 (swollen calyx), 59 (opening of the calyx), and 61 (open flower), 67 (petal fall), 69 (fruit setting), and 71 (young fruits) phenological stages in pomegranate.

Thinning should not, however, be done beyond stage 71 so as to save assimilate from being diverted toward reproductive development.

Potential applications of phenology in precision agriculture of pomegranates

Water deficits can impact plant phenology via restricting or expanding the developmental phases; however, the phenological responses to water deficits have seldom been reckoned. This, consequentially, opens a vista of using a decision support technology software tools such as Phenology MMS (Modular Modeling Software), which has so far been used in annual crops (McMaster et al. 2013). Phenological phases (events) reflect, along with other environmental conditions and genetic factors, the characteristics of the climate. Therefore, the use of a huge gamut of phenological observations is inevitable to sense climate change (Baddour & Kontongomde 2009). Rajaei and Yazdanpanah (2015) observed an advancement in leaf emergence and flowering of pomegranate as a result of an increase in mean air temperature and changes in precipitation. These findings and the swelling data on the influence of climate change on plant biology in various crops indicate the increasing significance of phenological studies to tackle crucial challenges linked with global modeling, its monitoring, and climate change. Altered plant phenology as influenced by climate change would have an effect on resource acquisition as well. This holds more significance for cultivation on marginal lands with low nutrient availability and little access to manures and fertilizers. These production systems are likely to be especially sensitive to either a decreased or an increased acquisition of soil resources by plants so that small differences in resource acquisition may be reflected in yield or in crop quality (Nord & Lynch 2009). The incorporation of crop phenology in simulation models holds promise to improve the predictability of resource acquisitions in pomegranate orchards (Lokupitiya et al. 2009). Further, the traditional phenology studies are heavily dependent on field observations; however, the association of remote sensing can help discern the phenology of pomegranate in large growing tracts and thereby render the observation more effective (Henebry & de Beurs 2013).

CONCLUSIONS

It is concluded, after reviewing the various factors connected to the quality of fruits and higher yields, that only one flowering season should be selected in relation to the suitability of a particular area. Water availability is the key factor for pomegranate cultivation, particularly in the irrigated dry regions. As explained earlier, various methods can be adopted for the selection of an appropriate blossoming period. Pomegranate cultivars that seasonally shed leaves in the autumn season bear spring flowering, whereas evergreen cultivars flower during the spring season, rainy season, and autumn season. Thus, it is recommended that in the areas having normal and regular rains during the monsoon season, flowering in the rainy season is preferable and profitable. However, in the regions where plentiful irrigation water is available during dry weather, spring flowering is the preferable cropping season. In areas receiving early monsoon precipitation and subsequent withdrawal by September, induction of flowering in October (autumn flowering) is possible; however, this is generally chosen for export purposes and to get high-quality fruits, although rarely. However, there is a need to compile the information using phenological models with the objective of developing sustainable production technology for pomegranates with the consequence of regulating the flowering at a particular phenological stage and identification of a suitable flowering season for improved fruit yield and quality under various environmental conditions in India. By determining the extent of each phenological phase in pomegranate cultivars, it is possible to schedule important cultural practices such as fertilizer and other agrochemicals application, irrigation, pruning practices, harvesting, etc. Thus, the occurrence and intensity of major phenological events and their relations with edaphic and climatic factors need to be assessed in pomegranate cultivars in relation to region, in order to appropriately plan the crop management practices for an optimum regulation of orchards under different environmental conditions. Remote sensing and crop modeling would be of great help in our pursuit to precisely design the cultural practices for efficient and timely utilization of resources.

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Conflict of interest

The authors declare that they have no potential conflict of interest regarding the submission and publication of this manuscript.

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