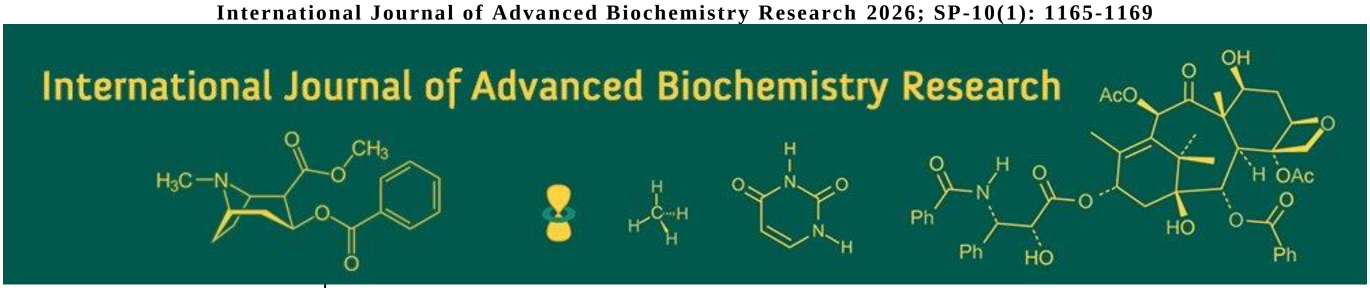

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Influence of tree canopy architecture of bael (*Aegle marmelos* L. Correa) on flowering phenology and fruit yield under rainfed condition of central India

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Abstract
The field study was conducted at Central Research Farm of the ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh during 2023-24 and 2024-25 in a 15 years old Bael orchard. The experiment was laid out in a factorial randomised block design with two cultivars (V_1: CISHB-2 and V_2: NB-9) and four canopy architectures (C_1: Central Leader System, C_2: Modified Leader system, C_3: Open Centre System and C_4: Untrained Tree). Cultivar NB-9 was superior in terms of yield (138.23 q/ha) and production efficiency (0.16 kg/cm^2 trunk cross sectional area). The flower bud initiation was earliest in V_1C_3 (12th May in 2023 and 8th May in 2024) and flower initiation was earliest in V_1C_3 (1st June in 2023 and 7th June in 2024). The end of flowering was earliest in V_1C_3 (2nd July in 2023 and 7th July in 2024) and late in V_2C_1 (17th July 2023 and 18th July in 2024). Maximum flowering duration was exhibited in CISHB-2 and the Central Leader System (30 days and 34 days, respectively). The Open Center System took the minimum number of days (310 days) from fruit set to harvest. The Central leader system recorded a higher fruit yield (153.48 q/ha), while the Open Centre System showed higher production efficiency (0.18 kg/cm^2 trunk cross-sectional area). Overall, trained trees with various canopy architectures performed well in terms of flowering behavior and fruit yield. The Central Leader System significantly increased fruit yield, while the Open center system improved production efficiency and performed well to reduce the fruit development period (from fruit set to harvest).

Keywords: Bael (*Aegle marmelos* L. Correa), tree canopy architecture, flowering duration, yield and production efficiency

Introduction
Bael (*Aegle marmelos* L. Correa) fruit is most important underutilized indigenous fruit crop mostly used for its medicinal, nutritional, and nutraceutical qualities in ancient Ayurvedic medicine (Nagar *et al.*, 2018) [9]. Bael fruits are used for preparing a number of products like candy, squash, toffee, slab, pulp powder and nectar (Singh *et al.*, 2018) [17]. The leaves are very nutritious and contain crude protein which indicates the fodder value (Singh *et al.*, 2019) [19]. It is referred to locally by a variety of names in several languages, including stone apple, Bengal quince, Indian quince, holy fruit, golden apple in English and bael or bilva in Hindi (Maity *et al.*, 2009) [6]. It is one of the hardy fruits can thrive well in a variety of challenging soil and climatic conditions, even in places where other crops cannot grow. Its plant may be grown even at 1200 m above sea level. Temperatures as low as-7 °C do not harm the plants (Chadha, 2013) [1]. It is widely distributed in South and Southeast Asia including India, China, Nepal, Myanmar, Pakistan, Bangladesh, Nepal, Vietnam, Laos, Cambodia, Thailand, Indonesia, Malaysia, Tibet, Sri Lanka, Java, Philippines and Fiji (Saroj *et al.* 2006) [13]. Although it is grown in different states of India (Tiwari *et al.*, 2014). Exact information on acreage and production is not available. However, in the year 2008 there was about 1000 ha area was reported in Bael cultivation (Singh *et al.*, 2018) [17]. With the development of improved cultivar like Goma Yashi, NB-5, NB-9 and CISHB-2, acreage in the bael tree increased and country has produced approximately 70,000 tonnes of fruits (Singh *et al.*, 2021) [18]. The Bael gene pool is spread throughout the nation and exhibits significant variation in both qualitative and quantitative traits.

Morphological traits like leaf shape, size chlorophyll content, leaf weight differed among the evaluated Bael cultivars (Nagar *et al.*, 2018) [9]. Variability in leaf characteristics and yield also observed by Rai *et al.* (2002) [11].

Plant training defines the proportion and distribution in space of the various shoot categories, vegetative versus fruiting shoots, since photosynthesis of whole tree is primarily light limited (Lakso, 1980) [5]. Plant canopy architecture supports to maximizing light interception and optimize light distribution within the canopy helps to maximize the efficiency of light utilization in photosynthesis and fruit growth, fruit bud formation, and fruit color (Jackson *et al.*, 1977) [3]. Higher surface area leaves often absorb more sunlight, which increases biomass accumulation and chlorophyll activity (Taiz and Zeiger, 2010) [20]. In plant, chlorophyll is an essential part of photosynthesis. Light-dependent protochlorophyllide oxidoreductase (LPOR) enzyme plays a vital role in the chlorophyll biosynthesis pathway (Wang *et al.*, 2024) [23]. The temperature and light also play a significant role in modifying of plant physiology and shaded plants showed a delay in all the phenological phases (Micciche *et al.*, 2023) [8]. The percentage of light penetration may influence flower initiation and fruit set (Schaffer *et al.*, 1989 and Sharma *et al.*, 2006) [14, 15]. Fruit trees that are shaded entirely or in part have often shown a reduction in the production of blossom buds as reported by (Peavey *et al.*, 2020) [10].

The canopy designs have influential effect on leaf parameters and flowering behaviour. In general unmanaged orchards showed longer duration from fruit set to harvesing as well as poor yield and production efficiency. Untrained and dense canopies result in shadowing, poor photosynthesis, low light interception and less flower intensity. By increasing light penetration, air circulation, and nutrient-use efficiency, increases tree growth, flowering and fruiting ability in managed canopy architecture. Generally, most of the bael orchards are still unmanaged with suitable canopy architecture. Therefore, this study was undertaken to know the effect of canopy architecture on leaf traits, flowering behaviour and yield of bael in rainfed ecosystem.

Materials and Methods

Experimental Site

The study was carried out at the Central Research Farm of the ICAR-Indian Grassland and Fodder Research Institute in Jhansi, Uttar Pradesh, during 2023-24 and 2024-25.

The site is located in the Bundelkhand region of central India, at an altitude of 275 m above mean sea level, and has a semi-arid, subtropical climate characterized by hot summers, cold winters, and erratic rainfall.

Plant Materials: The present study was carried out during 2023-24 and 2024-25 in a 15 years old bael orchard with uniform, healthy, insect, pest and disease free two cultivars (CISHB-2 and NB-9). The bael plant was planted at 6 m apart in the year of 2008. A total of seventy two uniform, healthy, insect, pest and disease free tress were marked for study. Initially orchard was grown naturally without following training and pruning. Later the experimental trees were prunned according to different types of canopy architecture i.e., Central Leader System, Modified Leader System, Open Centre System and Untrained tree.

Treatments

This experiment conducted under factorial randomized block design which consist two factors (Factor A: Variety and factor B: Canopy architecture) with three replications. Factor A had two varieties (V_1: CISHB-2 and V_2: NB-9) and factor B had four canopy architectures (C_1: Central leader system, C_2: Modified leader system, C_3: Open centre system and C_4: Untrained system). This experiment was composed total 8 treatment combinations i.e., T_1: V_1C_1 (CISHB-2 + Central leader system), T_2: V_2C_1 (NB-9 + Central leader system), T_3: V_1C_2 (CISHB-2 + Modified leader system), T_4: V_2C_2 (NB-9 + Modified leader system), T_5: V_1C_3 (CISHB-2 + Open centre system), T_6: V_2C_3 (NB-9 + Open centre system), T_7: V_1C_4 (CISHB-2 + Untrained system) and T_8: V_2C_4 (NB-9 + Untrained system). In each treatment consisted of three uniform, healthy trees per replication. Each replication contains 24 trees and total 72 tress were marked for study. The different parameters were recorded from marked trees.

Data Collection

Five branches were tagged in each plant of each treatment in three replications from all directions of the plant canopy. The date of the first flower bud initiation was taken into consideration when 50% of the flower buds emerged from all of the tagged branches. The date of the first cyme (inflorescence) commencement was taken into consideration when 50% of the flower buds began to bloom from all of the tagged branches and considered as date of flower initiation. Date of end of flowering was recorded when flowering cessation takes place. It was observed when flower petal falls from the bloom and swelling of ovaries takes place. The flowering duration was measured from the date when the first cyme (inflorescence) of the flower buds began to bloom to the end of flowering. The average time taken in duration of flowering was expressed in days. The orchard visited regularly and number of days from fruit set to harvest was recorded by recording the date of fruit set and the date of harvest. The total duration was calculated and presented in number of days. The projected yield quintal per hectare was calculated based on multiplying the yield kg per tree by total number of trees per hectare (277 trees/ha) and the yield was expressed in quintal per hectare. Productive efficiency (PE) was calculated by using the formula as follows:

$$\text{Production efficiency (PE)} = \frac{\text{Fruit yield (kg) per plant}}{\text{TCSA (cm}^2\text{)}}$$

Statistical Analysis: The recorded data were analyzed using ANOVA, and significance was assessed using the least significant difference test at the 5 percent level.

Results and Discussion

Flowering Phenology

The flowering pattern was influenced by tree cultivars and canopy architecture (Table 1). The flower bud initiation was recorded earliest in V_1C_3 (12th May in 2023 and 8th May in 2024) while late flower bud initiation was exhibited by V_2C_4 (24th May in 2023 and 22 May in 2024). The table 1 showed that the earliest flower initiation was recorded in V_1C_3 (1st June in 2023 and 7th June in 2024) while late flower initiation was exhibited by V_2C_4 (18th June in 2023 and 16th June in 2024). The earliest end of flowering (Table 1) was noted in V_1C_3 (2^{nd} July in 2023 and 7^{th} July in 2024) while late completion of flowering was noted in V_2C_1 (17 July in 2023 and 18^{th} July in 2024).

The result showed that the cultivar CISHB-2 (30.75 days) exhibited significantly higher flowering duration than NB-9 (Table 2). Among the canopy architectures, the Central Leader System (34.5 days) recorded significantly higher than Untrained tree and the interactive effect was non-significant. In 2024-25, the cultivars recorded significantly maximum flowering duration in CISHB-2 (29.75 days) than NB-9 (Table 2). The Central Leader System (33.99 days) recorded significantly more flowering duration than Untrained tree. Interaction effect showed non-significant effect on flowering duration. Similarly, pooled analysis revealed that cultivars had significant difference with maximum in CISHB-2 (30.25 days). The Central Leader System (34.25 days) recorded significantly higher flowering duration than Untrained tree (27 days) while interaction effect showed non-significant difference (Table 2).

There is a beneficial relationship between the amount of sunshine and flower bud initiation (Lakso, 1980) [5]. Fruit trees that are shaded entirely or in part have often shown a reduction in the production of blossom buds as reported by (Peavey *et al.*, 2020) [10]. High crop load during the current season has been shown to have a detrimental influence on floral initiation in fruit trees for next year, due to less photosynthates available for floral transition as reported by (Reig *et al.*, 2006) [12]. May *et al.* (1965) [25] also reported that the shade or darkening decreased the numbers and size of inflorscence primordia.

Fruit set to Harvesting Period

Fruit development period was directly influenced with canopy architecture of tree (Table 2). The Open Center System significantly minimized the fruit developmental period during both year of study as well as in pooled data (307.5, 304.50 and 306.0 days in 2023-24, 2024-25 and pooled data, respectively). The Untrained system taken maximum days of fruit set to harvesting (320.5, 321.5 and 321.0 days in 2023-24, 2024-25 and pooled value, respectively) and the interactive effect showed non-significant effect.

Open Center System exhibited earlier fruit maturity than untrained system might be due to the openness of canopy which facilitated more light penetration and enhanced the photosynthesis with faster supply of assimilates leading to faster physiological development and early maturity than untrained system (dense canopy). This study in line with Sharma *et al.* (2018) [16] who reported delayed maturity in peach due to reduced penetration of radiation in canopy.

Fruit Yield (q ha^{-1})

The bael fruit yield was significantly affected by cultivar and canopy architecture and interactive combinations of cultivars and canopy architectures (Figure 1). In first year of experiment, cv. NB-9 (143.50 q ha^{-1}) produced significantly higher fruit yield (Figure 1) than CISHB-2 (135.26 q ha^{-1}). Among canopy architectures, the Central Leader System (156.78 q ha^{-1}) produced significantly higher fruit yield than Untrained tree (Figure 1). The interactive effect of variety and canopy architecture recorded significantly higher yield in V_2C_1 (158.35 q ha^{-1}). Similar results were obtained in second year and pooled analysis. The pooled analysis revealed that cv. NB-9 (132.97 q ha^{-1}) produced significantly higher fruit yield than CISHB-2 (122.43 q ha^{-1}). Central Leader System (150.19 q ha^{-1}) produced significantly higher fruit yield than other canopy architectures. The interactive effect of variety and canopy architecture had significant effect (Figure 1) and recorded maximum in V_2C_1 (160.98 q ha^{-1}).

Cultivar NB-9 exhibited higher yield than CISHB-2 might be due to the differences in genetic constitution of particular variety, tree size and agroclimatic circumstances. Similarly, Kumar *et al.* (2020) [4] also reported variation in bael fruit yield due to its genetic variations. The trained tree under central leader system and Open Center System exhibited higher fruit yield than Untrained tree. This could be attributed to openness of canopy facilitated more light penetration in the canopy which increased the photosynthetic activity and increased the photo assimilates accumulation toward fruits thus it increased fruit yield. Similar findings were reported by Uberti *et al.* (2019) [22] and Fallahi (1991) [2] in peach.

Production Efficiency

Production efficiency (Figure 2) was recorded significantly maximum in NB-9 than CISHB-2 during both years of study as well as pooled analysis. Among the canopy architectures, Open Center System showed significantly maximum production efficiency (0.20, 0.17 and 0.18 kg/cm^2 TCSA in 2023-24, 2024-25 and pooled data, respectively) followed by Central Leader System (Figure 2). The interactive effect of variety and canopy architecture showed significantly higher in V_2C_3 during both years of study as well as in pooled analysis (0.21, 0.19, and 0.20 kg/cm^2 TCSA in 2023-24, 2024-25 and pooled data, respectively). The result is supported by Mallikarjuna (2021) [7].

Table 1: Effect of bael (*Aegle marmelos* L. Correa) tree canopy architecture on flowering phenology.

Treatments	Date of flower bud emergence		Date of flower initiation		Date of end of flowering	
	2023	2024	2023	2024	2023	2024
V_1C_1	19-May	21-May	10-Jun	12-Jun	15-Jul	16-Jul
V_1C_2	18-May	16-May	09-Jun	10-Jun	08-Jul	08-Jul
V_1C_3	12-May	08-May	01-Jun	07-Jun	02-Jul	07-Jul
V_1C_4	21-May	20-May	14-Jun	15-Jun	12-Jul	12-Jul
V_2C_1	20-May	18-May	13-Jun	14-Jun	17-Jul	18-Jul
V_2C_2	17-May	16-May	10-Jun	11-Jun	08-Jul	08-Jul
V_2C_3	16-May	12-May	03-Jun	08-Jun	03-Jul	07-Jul
V_2C_4	24-May	22-May	18-Jun	16-Jun	15-Jul	12-Jul

Table 2: Effect of bael (*Aegle marmelos* L. Correa) tree canopy architecture on flowering duration and days from fruit set to harvesting.

Treatments	Flowering duration (days)			Number of days fruit set to harvesting		
	2023	2024	Pooled	2023	2024	Pooled
Cultivars						
V_1	30.75a	29.75a	30.25a	313.25a	313.00a	313.13a
V_2	29.75b	28.99b	29.37b	316.25a	315.75a	316.00a
SE ± (m)	0.30	0.23	0.19	2.07	2.26	1.53
LSD($p \leq 0.05$)	0.90	0.69	0.54	NS	NS	NS
Canopy architectures						
C_1	34.50a	33.99a	34.25a	316.50a	318.50a	317.50ab
C_2	28.50c	27.50c	28.00c	314.50ab	313.00ab	313.75b
C_3	30.50b	29.50b	30.00b	307.50b	304.50b	306.00c
C_4	27.50c	26.50d	27.00d	320.50a	321.50a	321.00a
SE ± (m)	0.42	0.32	0.27	2.92	3.19	2.16
LSD($p \leq 0.05$)	1.28	0.98	0.77	8.86	9.68	6.27
Cultivars × Canopy architecture						
V_1C_1	35.00a	34.00a	34.50a	315.00a	318.00a	316.50a
V_1C_2	29.00a	28.00a	28.50a	313.00a	312.00a	312.50a
V_1C_3	31.00a	30.00a	30.50a	305.00a	301.00a	303.00a
V_1C_4	28.00a	27.00a	27.50a	320.00a	321.00a	320.50a
V_2C_1	34.00a	34.00a	33.99a	318.00a	319.00a	318.50a
V_2C_2	28.00a	27.00a	27.50a	316.00a	314.00a	315.00a
V_2C_3	30.00a	29.00a	29.50a	310.00a	308.00a	309.00a
V_2C_4	27.00a	26.00a	26.50a	321.00a	322.00a	321.50a
SE ± (m)	0.60	0.46	0.38	4.13	4.51	3.06
LSD($p \leq 0.05$)	NS	NS	NS	NS	NS	NS

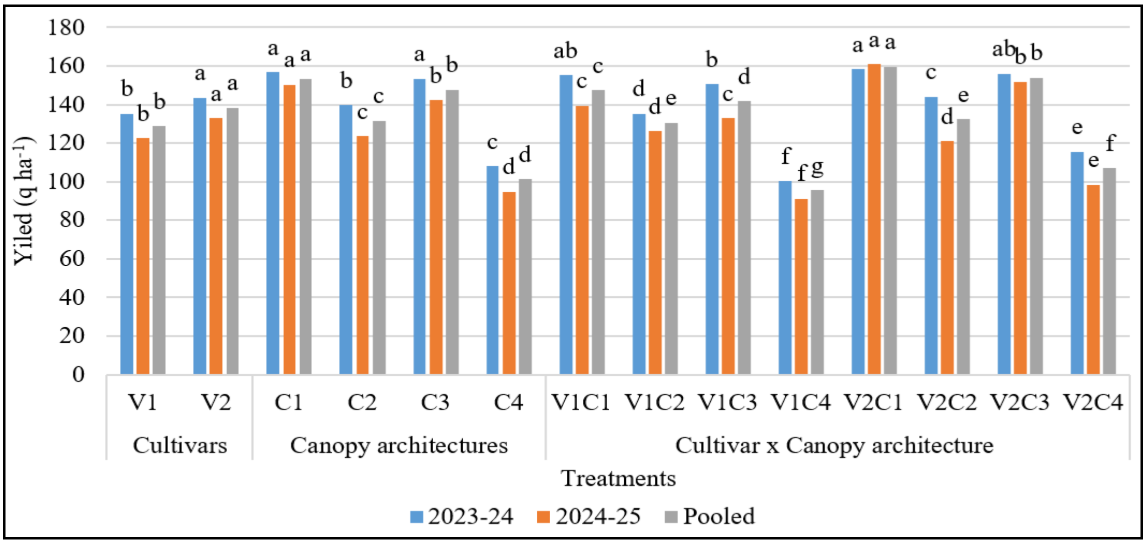

Fig 1: Effect of bael (*Aegle marmelos* L. Correa) tree canopy architecture on fruit yield

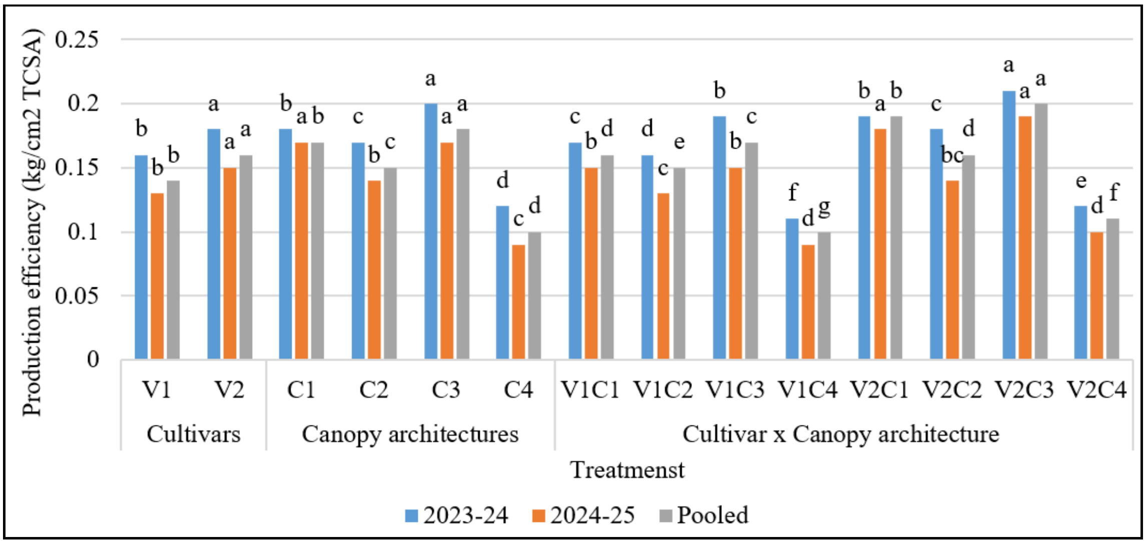

Fig 2: Effect of bael (*Aegle marmelos* L. Correa) tree canopy architecture on production efficiency

Conclusion

Light plays an important role in development of flower buds and its initiation as a flower to set fruits after fertilization. The canopy architecture improved the light penetration and created a suitable microclimate within the canopy which provided significant result. It seeks better use of photosynthates by using it in early developments of flower buds and blooming. The bael cultivars also varied in respect of flowering behaviour and fruit yield. Cultivar NB-9 and Central Leader System recorded higher fruit yield. Based on this, it was concluded that cultivar NB-9 and Central Leader System canopy architecture was the most productive for bael production under rainfed conditions.

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