Journal of Environmental Biology
p-ISSN: 0254-8704 • e-ISSN: 2394-0379 • CODEN: JEBIDP

JEB®

Original Research Paper
Volume 47 Issue 4 July 2026 pp. 830-841
DOI: http://doi.org/10.22438/jeb/47/4/MRN-5753

J. Environ. Biol., 2026
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Journal website : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Factors affecting fruit drop problem in bael (*Aegle marmelos* Correa)

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Received: 23 April 2025 **Revised:** 24 July 2025 **Accepted:** 09 February 2026

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Abstract

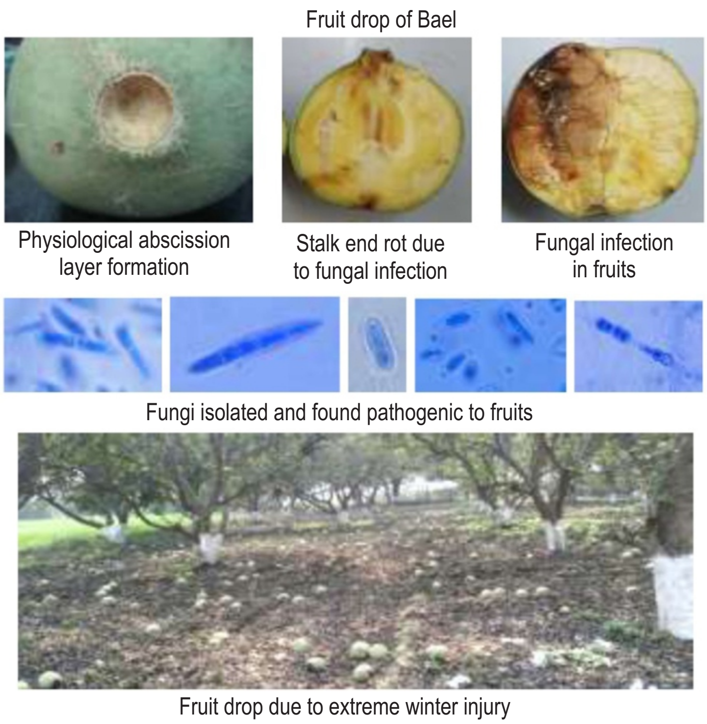
Aim: To assess the extent of fruit drop and effect of pathogenic, physiological and weather factors in bael (*Aegle marmelos* Correa), a subtropical deciduous fruit tree suffering from severe fruit drop.

Methodology: The extent of fruit drop at different stages of fruit development was recorded through roving survey in farmers' orchards and in a fixed plot at weekly intervals. Pathogenic, physiological and weather parameters were recorded for evaluating their role in fruit drop.

Results: During roving surveys the maximum incidence of infection was observed in fallen fruits (95%) followed by fruits on tree (55.5%). In the fixed orchards, the maximum fruit drop was found in the cultivar CISH B-2, followed by Pant Shivani during the months of July-August and January-February. The maximum temperature, wind velocity and sunshine hours had positive relationship with the extent of fruit drop. Under cold condition, decrease in the total chlorophyll content in leaves, vapor pressure deficit, transpiration rate and photosynthetic rate was recorded.

Interpretation: The findings of the study indicate that severe bael fruit drop due to low temperature, and the fungal infection make the bael production less remunerative.

Key words: *Aegle marmelos,* Fruit drop, Infection, Weather



Triveni Enterprises (Educational Services Set-up)

How to cite: Shukla, P.K., A. Kushwaha, A.K. Trivedi, N. Kumari, S.K. Shukla, H. Singh, A. Singh and S. Pandey: Factors affecting fruit drop problem in bael (*Aegle marmelos* Correa). *J. Environ. Biol.*, **47,** 830-841 (2026).

Introduction

Bael (*Aegle marmelos* Correa) is a subtropical deciduous fruit tree of considerable religious, nutritional, and medicinal significance in India. Known for its hardy nature and multipurpose utility, bael has been an integral component of traditional agroforestry systems and home gardens for centuries. The species is widely adapted to a range of agro-ecological conditions, from arid to semi-arid regions, and occurs naturally up to altitude of approximately 1200 m across several Indian states (Pandey *et al.,* 2023). Its ability to thrive under marginal conditions, including low-fertility soils, moderate drought, and soil alkalinity, makes it a resilient crop for regions where other fruit species may fail (Pandey and Misra, 2006, 2007; Pandey *et al.,* 2008). Beyond India, bael is cultivated in several South and South-east Asian countries, including Sri Lanka, Pakistan, Nepal, Myanmar, Bangladesh, Vietnam, Laos, Cambodia, Thailand, the northern Malay Peninsula, Java, Timor Leste, the Philippines, and Fiji, reflecting its ecological versatility and adaptability to diverse climatic and soil conditions.

Bael fruits are nutritionally rich and recognized for their medicinal properties. They contain appreciable amounts of carbohydrates, proteins, fats, vitamins, and minerals, along with bioactive compounds that confer therapeutic benefits. The fruits are traditionally used for treating digestive disorders, diabetes, and other ailments. In addition to fresh consumption, bael fruits are extensively processed into value-added products, including squash, jams, candies, syrups, and pharmaceutical formulations, which have gained increasing consumer demand due to their nutritional and medicinal attributes. Various plant parts also possess pharmacological importance; the roots exhibit anti-inflammatory and wound-healing properties; the bark is used in anti-diabetic formulations, and the seed locule gum has industrial applications as an adhesive and waterproofing material (Pandey *et al.,* 2023). This multipurpose utility underscores the socio-economic importance of bael and highlights its potential as a commercially viable crop for both food and pharmaceutical industries.

Despite its adaptability and economic relevance, bael productivity is often inconsistent. A primary factor limiting yield is severe fruit drop, which occurs at multiple stages of fruit development and significantly constrains the adoption of bael for commercial cultivation (Shukla *et al.,* 2022). Fruit abscission is governed by a complex interplay of physiological, pathological, and environmental factors. Early-stage fruit drop, particularly during the small fruitlet phase, is mainly associated with embryo abortion and incomplete fruit development, often exacerbated by pathogen activity. Later-stage fruit drop is predominantly linked to pathogen-induced disorders, with environmental stresses further aggravating abscission (Misra and Srivastava, 2003). Such losses not only reduce the number of marketable fruits but also compromise fruit quality, affecting profitability and sustainability of orchards. Several fungal pathogens are known to infect bael, causing both pre- and post-harvest losses. *Fusarium* species, for instance, are commonly associated with stalk-end rot, root rot, and fruit decay (Sharma and Gaur, 2014), whereas *Syncephalastrum racemosum* is responsible for soft rot of harvested fruits (Misra *et al.,* 2016). In addition, a wide array of fungal species has been isolated from seeds and foliage, including *Aspergillus niger, A. flavus, Alternaria alternata, Fusarium* spp., *Rhizopus* spp., *Mucor* spp., *Curvularia* spp., *Penicillium* spp., *Fusarium roseum, Scytalidium aeglicola,* and species of *Cercospora, Chaetothyrium,* and *Stenella aegles* (Madaan and Gupta, 1985; Arya *et al.,* 1986; Wadikar *et al.,* 2009; Maurya *et al.,* 2016). These studies indicate that pathogens play a critical role in fruit drop; however, the relative contribution of pathogens in relation to cultivar susceptibility, phenological stage, and prevailing environmental conditions remain poorly quantified.

Environmental and physiological factors are equally important in determining fruit retention. Temperature extremes, especially low winter temperatures, can induce chilling injury in young fruits and supporting twigs, leading to premature fruit abscission. Similarly, soil moisture stress, high wind velocity, and prolonged dry periods negatively affect water relations and nutrient translocation, reducing fruit retention. Physiological stress, including decreased chlorophyll content, impaired photosynthetic efficiency, and limited carbohydrate availability, often interacts with pathogen pressure, collectively influencing the magnitude of fruit drop. Despite recognition of these interactions, there is a lack of integrated long-term studies that quantify the interplay between cultivar response, developmental stage, pathogen infection, and weather variables (Misra and Srivastava, 2003; Pandey *et al*., 2023).

Genotypic variation further complicates the management of fruit drop. Improved cultivars with high fruit set and large fruit size have been developed to meet the growing demand for processed bael products. However, high fruit load can increase physiological stress, making certain cultivars more susceptible to environmental stress and pathogen invasion, leading to greater fruit abscission. Understanding these genotypic differences is essential for targeted cultivar selection and effective orchard management. Given the economic and ecological importance of bael, and the significant yield losses caused by fruit drop, the present study was designed to address the following hypotheses: fruit drop intensity varies among cultivars and phenological stages; pathogenic infection significantly enhances fruit drop at both early and late developmental stages; and adverse environmental conditions, particularly temperature extremes and associated physiological stress, exacerbate fruit abscission. The study aimed to quantify fruit drop during different developmental phases, assess cultivar-specific variation, evaluate pathogen involvement, and analyze the influence of weather and physiological parameters over a four-year period (2021–2024).

The outcomes of this investigation are expected to provide a scientific basis for cultivar selection, optimized orchard management, and the development of effective strategies to minimize fruit drop. By identifying the relative contributions of genotype, pathogen, and environment, the study seeks to enhance the sustainability, profitability, and commercial viability of bael cultivation, thereby supporting its role as a nutritionally and medicinally valuable fruit crop. This research will also fill critical knowledge gaps regarding the integrated factors influencing fruit retention, offering insights for both researchers and practitioners involved in bael production.

Materials and Methods

Roving survey: Roving surveys were conducted over four consecutive years (2021–2024) to systematically assess fruit drop at different developmental stages in bael across multiple districts of Uttar Pradesh. The survey targeted both organized orchards and scattered tree clusters, ranging from a few trees to larger groups within fields, roadside plantings, and homestead gardens. At each site, detailed observations were recorded for each tree, including the total number of fruits retained on the tree, classified as healthy or exhibiting visible symptoms of infection, as well as the total number of fruits fallen on the orchard floor. Visible external symptoms, such as lesions, discoloration, cracking, and fungal sporulation, were noted, and representative fruit samples were collected and carefully transported to the laboratory under controlled conditions for further examination. Fallen fruits that appeared externally healthy were also dissected to detect internal symptoms, including pulp discoloration, rot, or pathogen colonization. The roving survey provided a baseline assessment of stage-specific patterns of fruit drop, highlighting the variation across locations, cultivars, and developmental stages under natural field conditions. This extensive survey allowed the identification of potential hotspots for pathogen prevalence and environmental stress contributing to fruit abscission.

Fixed orchard observations: In parallel with roving surveys, detailed observations were conducted in a fixed experimental orchard located at ICAR-CISH, Rehmankhera, Lucknow, throughout the flowering and fruiting seasons, with assessments carried out at standard meteorological week (SMW) intervals. The orchard comprised three to four healthy, mature trees of each of eight bael cultivars: Narendra Bael (NB)-5, NB-9, NB-17, Pant Aparna, Pant Sujata, Pant Shivani, CISH B-1, and CISH B-2. To systematically capture fallen fruits and facilitate precise quantification of fruit drop, a circular basin with a 250 cm radius around each tree trunk was demarcated. Fallen fruits were collected periodically from these basins, and both retained and fallen fruits were recorded to calculate fruit retention and drop percentages. Representative fruits were sampled for external and internal symptom assessment and for fungal isolation to confirm pathogen involvement. Disease incidence was expressed as the percentage of fruits exhibiting any form of disease symptom relative to the total number of fruits observed. These continuous observations over multiple seasons allowed evaluation of cultivar-specific susceptibility, stage-wise fruit drop patterns, and temporal progression of pathogen incidence.

Isolation and identification of fungi: Diseased stalk-end and fruit samples collected from both roving surveys and fixed orchard were subjected to isolation and identification of pathogenic fungi. The samples were thoroughly washed under running tap water to remove surface debris. Small tissue segments (2–4 mm) from visibly infected areas were excised, rinsed, and surface-sterilized using 0.1% mercuric chloride for 30 sec, followed by two rinses in sterile distilled water. Sterile tissue pieces were blotted dry between layers of sterile blotting paper and aseptically transferred onto potato dextrose agar (PDA) plates (Armentrout and Baudoin, 1990). Plates were incubated at 28 ± 2°C in a BOD incubator to promote fungal growth. Actively growing mycelium from colony margins was subcultured onto fresh PDA plates and slants to obtain pure cultures. Morphological identification was performed based on colony characteristics and spore morphology, and selected isolates were further characterized using molecular tools to confirm species identity. Pathogenicity was validated under both field and laboratory conditions using detached fruit assays in accordance with Koch's postulates (Koch, 1884). This approach enabled not only the identification of fungi associated with fruit drop but also an assessment of their virulence and developmental stage-specific effects.

Physiological studies: To understand the physiological factors influencing fruit retention, total chlorophyll content in fully expanded fresh leaves was determined following Strain *et al.* (1971). Gas exchange parameters, including net photosynthetic rate, stomatal conductance, transpiration rate, and vapour pressure deficit (VPD), were measured using a CIRAS-3 portable photosynthesis system (PP Systems International Inc., Amesbury, USA). Measurements were conducted under ambient conditions for CO_2 and H_2O reference, with absorber columns kept empty. After stabilizing the system for approximately 10 min, readings were recorded between 10:00 and 11:00 hr on alternate months from July to March. For each tree, the fourth fully expanded leaf from the apex was selected, and five readings were recorded per leaf. A total of 20 leaves per observation (five from each cardinal direction: east, west, north, and south) were sampled to account for positional variability. Monthly mean values were calculated for all parameters, and since year-to-year variation was statistically non-significant, pooled means were used for analysis. These physiological measurements allowed evaluation of environmental stress impacts, particularly low temperature and water stress, on leaf function and subsequent fruit retention.

Weather data: Weather data were obtained from the institute's meteorological observatory and included daily records of maximum and minimum temperature, relative humidity, rainfall, number of rainy days, wind velocity, and sunshine hours. These parameters were used to analyze the influence of weather conditions on fruit drop at different phenological stages. Correlation and regression analyses enabled quantification of relationship between specific climatic factors and fruit abscission, providing insights into environmental triggers of fruit loss.

Statistical analysis: All data were subjected to rigorous statistical analysis using R version 4.3.1 through R Studio as a graphical user interface (R Core Team, 2023; R Studio Team, 2023). Analyses included correlation, regression, and analysis of variance (ANOVA) to assess the effects of cultivar, phenological stage, pathogen incidence, physiological stress, and weather variability on fruit drop. Interaction effects between genotype, environment, and year were evaluated to determine the relative contribution of each factor. Statistical outputs facilitated precise quantification of cultivar-specific differences, environmental effects, and the interplay between physiological, pathological, and climatic determinants of fruit drop.

This integrated methodological approach, combining roving surveys, systematic orchard observations, pathogen isolation, physiological assessment and weather analysis, allowed comprehensive evaluation of the factors influencing fruit abscission in bael. The approach ensured that both biotic and abiotic determinants of fruit drop were thoroughly investigated, providing a robust framework for developing cultivar-specific and environmentally informed management strategies to minimize losses and enhance productivity.

Results and Discussion

Roving surveys conducted across Uttar Pradesh during 2021–2024 revealed that organized bael orchards were limited to only 15 locations, whereas most plantings consisted of small, scattered clusters of 4–16 trees (Table 1). This pattern highlights the fragmented nature of bael cultivation in the region, reflecting its status as a semi-commercial and backyard crop in many districts. Fruit drop incidence varied considerably across survey sites, indicating that both environmental conditions and local management practices contribute to losses.

The highest fungal infection was recorded at ICAR–Central Agroforestry Research Institute (CAFRI), Jhansi, where 55.5% of fruits retained on trees exhibited infection, with an alarming 95% of fallen fruits showing pathogen-induced rot (Table 1). Conversely, no infection was observed in fruits on trees at Akraouli (Bulandshahr), IOC Petrol Pump Samamayi (Hathras), and Srinagar (Hathras), suggesting the influence of localized environmental factors or orchard management in suppressing fungal activity. The lowest disease incidence in fallen fruits (47.8%) was recorded at Kushmaura, Lucknow, emphasizing the wide spatial variation in fruit losses across the state.

At Jhansi, the fruit drop per tree was relatively low (20% at ICAR-Central Agroforestry Research Institute and 15.8% at ICAR–Indian Grassland and Fodder Research Institute), regardless of cultivar. However, 20–30% of fruits exhibited cracking, likely attributable to low post-monsoon soil moisture and dry weather. Minimum winter temperatures remained above 7°C in 2022–23, likely mitigating chilling injury and reducing abscission. These observations suggest that both temperature and water status significantly influence fruit retention and cracking patterns (Table 1). Phenological studies indicated that the duration from fruit set to ripening ranged from 44 to 49 weeks

Table 1: Survey for assessment of fruit drop of bael and infection in fruits in farmers' orchards

Date	Location	No. of trees	GPS Coordinates	Age of orchard (Year)	Av. No. of fruits on tree	Infected fruits (%)	
						On tree	Fallen
25.02.22	Shadipur, Badaun	15	27°54.927, 78°11.281	18	59.9	13.6	70.0
25.02.22	Shadipur, Badaun	7	27°54.805, 78°11.214	15	23.0	13.0	80.0
25.02.22	Shadipur, Badaun	25	27°54.310, 78°11.024	15	11.5	13.0	70.0
25.02.22	Alapur, Badaun	103	27°55.053, 78°13.543	15	68.6	3.4	50.0
26.02.22	Bithur, Kanpur	64	26°36.287, 80°15.746	20	54.3	11.9	90.0
19.04.22	CoE, Basti	48	26°46.574, 82°39.123	25	7.3	54.8	90.0
19.04.22	Kumarganj, Ayodhya	70	26°33.005, 81°50.590	9	9.4	34.0	90.0
27.10.22	SVBPUAT, Meerut	120	29°05.297 77°41.792	22	41	4.9	90.9
27.10.22	Akraouli, Bulandshahr	4	28°40.974 77°47.105	15	39	0.0	80.0
27.10.22	Samamayi, Hathras	16	27°47.368 78°05.248	22	17	0.0	66.7
27.10.22	Srinagar, Hathras	4	27°39.159 78°04.084	18	21	0.0	80.0
31.10.22	Kushmaura, Lucknow	7	26°53.629 80°47.902	50	113.5	3.1	57.9
31.10.22	Kushmaura, Lucknow	7	26°53.516 80°47.952	55	93.4	9.3	77.7
31.10.22	Kushmaura, Lucknow	7	26°53.383 80°48.033	52	108.0	1.9	47.8
31.10.22	Kakori, Lucknow	41	26°53.629 80°47.902	12	23.8	6.0	93.5
29.11.22	Singlamau, Auraiya	12	26°34.676, 79°27.490	6	14.0	7.1	50.0
29.11.22	Ata, Auraiya	60	26°32.897, 79°29.675	18	8.5	17.6	80.0
04.04.23	CAFRI, Jhansi	200	25°30.729, 78°32.699	8	21.7	55.5*	95.0*
04.04.23	CAFRI, Jhansi	150	25°30.517, 78°32.923	12	24.6	20.0*	86.7*
04.04.23	IGFRI, Jhansi	120	25°31.608, 78°32.557	8	24.4	15.4*	78.0*
04.04.23	BaruaSagar, Jhansi	4	25°23.118, 76°44.356	30	4.0	0.0	85.0
20.02.24	Samamai, Hathras	4	27°31.680, 78°09.452	26	45.5	20.0	80.0
20.02.24	Sasni, Hathras	5	27°71.135, 78°08.784	30	40.0	75.0	90.0
	Average	47.5		21.8	37.9	14.4	76.2

*Cracking followed by infection

Table 2: Incidence of fruit drop of bael in fixed orchard at Rehmankhera (2021-22 to 2023-24; 3 year average)

SMW	NB5	NB9	NB17	Pant Aparna	Pant Sujata	Pant Shivani	CISH B1	CISH B2	Average
25	78.3	219.0	33.5	17.4	14.5	42.1	24.2	18.1	55.89
26	303.3	442.4	65.1	105.6	53.7	123.6	87.3	28.9	151.24
27	351.2	684.9	245.6	281.3	220.7	320.7	642.1	117.3	357.98
28	396.9	425.8	104.8	116.9	339.0	242.5	293.0	80.9	249.98
29	254.4	320.0	109.6	92.1	226.7	136.9	304.9	115.5	195.01
30	140.0	299.9	36.4	53.9	80.4	63.6	374.6	66.4	139.40
31	100.4	171.2	23.8	45.4	112.2	54.6	363.4	72.7	117.96
32	51.1	90.0	11.9	22.3	172.5	24.7	156.8	50.0	72.41
33	37.6	104.8	13.6	19.4	112.4	23.9	53.0	30.0	49.34
34	32.1	48.8	14.2	6.9	85.6	20.0	18.1	19.2	30.61
35	13.1	12.2	4.3	2.8	48.9	8.4	5.3	8.2	12.90
36	10.9	12.9	6.6	1.3	18.0	9.5	2.9	9.1	8.90
37	4.0	4.5	2.9	0.2	9.6	4.5	1.7	7.0	4.30
38	3.2	3.3	0.9	0.0	3.6	2.7	0.9	1.9	2.06
39	2.2	2.0	1.1	0.2	1.2	2.5	1.3	1.8	1.54
40	1.8	1.6	0.7	0.0	0.5	2.2	0.1	0.4	0.91
41	0.9	0.3	0.6	0.2	1.0	0.4	0.0	0.8	0.53
42	0.4	0.3	0.3	0.2	0.3	0.2	0.2	0.1	0.25
43	0.0	0.1	0.2	0.2	0.1	0.1	0.4	0.2	0.16
44	0.3	0.1	0.2	0.0	0.0	0.1	0.1	0.1	0.11
45	0.2	0.3	0.2	0.1	0.3	0.2	0.2	0.1	0.20
46	0.1	0.0	0.1	0.1	0.4	0.0	0.1	0.0	0.10
47	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.05
48	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.06
49	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.1	0.05
50	0.1	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.09
51	0.0	0.3	0.1	0.4	0.0	0.0	0.0	0.0	0.10
52	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.3	0.13
1	0.0	0.1	0.2	0.2	0.1	0.2	0.1	0.0	0.11
2	0.1	0.2	0.3	0.4	0.0	0.1	0.1	0.2	0.18
3	0.6	0.1	0.1	1.8	0.3	0.8	0.4	0.9	0.63
4	0.8	0.2	0.7	2.0	0.2	0.9	0.4	1.0	0.78
5	1.8	1.3	2.9	5.9	0.8	4.1	1.0	1.2	2.38
6	3.4	1.1	2.5	10.0	1.9	5.8	3.0	2.4	3.76
7	4.9	1.8	6.8	11.9	4.5	8.9	4.2	10.4	6.68
8	7.3	3.9	7.3	9.9	4.8	4.2	12.4	16.8	8.33
9	4.2	6.1	5.8	8.1	4.8	6.3	7.8	8.6	6.46
10	2.1	7.7	3.9	4.7	4.5	5.2	7.8	4.9	5.10
11	3.6	3.7	3.0	1.7	3.3	2.8	7.3	2.7	3.51
12	1.2	1.8	1.8	1.3	1.3	1.1	3.3	1.2	1.63
13	2.2	1.9	1.0	1.8	2.9	0.6	2.7	0.9	1.75
14	1.3	0.7	0.8	0.8	0.9	0.8	1.5	0.9	0.96
Total drop	1816.5	2875.4	714.1	827.9	1531.9	1125.2	2382.4	681.4	1494.4
Harvest	27.7	51.9	11.5	17.4	15.7	10.4	62.2	5.6	25.3
Total fruits	1844.2	2927.3	725.6	845.3	1547.6	1135.6	2444.6	687.0	1519.7
*SMW 25-14	1.53	1.81	1.61	2.10	1.03	0.92	2.61	0.82	1.69
*SMW 41-14	43.7	61.6	22.6	21.9	32.4	19.5	53.8	9.4	36.5

*Percent retention

among cultivars, reflecting the extended fruit development cycle of bael. Leaf emergence and flower bud initiation occurred during April–May, following leaf shedding in March–April. Flowering and fruit set began in the first week of June, with fruitlets becoming visible by late June. However, prolonged hot and dry weather, coupled with delayed monsoon onset in 2022, extended flower bud initiation and fruit set until August. Fruit development continued until mid-October, with physical maturity attained by late October and ripening occurring during April–May of the following year. Consequently, fruits remained on trees for nearly a year, exposing them to multiple environmental stresses, including temperature extremes, wind, low relative humidity, and pathogen attacks. Such prolonged exposure likely exacerbates fruit drop and reduces yield potential.

Fig. 1: Symptoms of infection in bael fruits.

Significant genotypic variation was observed in fruit set and retention among cultivars. NB-9 exhibited the highest fruit set per tree (2927.3), followed by CISH B-1 (2444.6) and NB-5 (1844.2), while CISH B-2 recorded the lowest (687.0). Harvested fruits per tree were highest in CISH B-1 (62.2), followed by NB-9 (51.9) and NB-5 (27.7), indicating superior yield potential in these cultivars (Table 2). Across all cultivars, an average of 1519.7 fruits set per tree, yet 98.31% dropped during developmental stages, resulting in only 1.69% reaching harvestable maturity. When retention was calculated from the stage of fully developed fruits (SMW 41), overall retention at Rehmankhera was 36.5%, with maximum retention in NB-9, followed by CISH B-1, NB-5, Pant Sujata, NB-17, Pant Aparna, Pant Shivani, and CISH B-2 (Table 2). These findings underscore that early fruit drop, predominantly during the embryo development phase, and late-stage pathogen-induced abscission jointly determine the final yield.

These results corroborate with the previous reports of Misra and Srivastava (2003), who observed that early-stage fruit drop is primarily caused by embryo abortion, sometimes accompanied by pathogenic involvement, whereas late-stage fruit drop is predominantly mediated by pathogens. In the present study, fruit abscission occurred both with and without visible external symptoms. Brown to dark brown lesions (1–12 cm diameter) were frequently observed near the stalk-end prior to abscission (Fig. 1). Dropped fruits often exhibited reddish-brown discoloration extending from the stalk-end into the pulp. Fruits that dropped during June–July generally lacked external symptoms, whereas those retained from August–April frequently developed lesions prior to abscission. Several externally healthy fallen fruits exhibited internal rot, indicating that internal pathogen invasion may precede visible symptoms. Post-monsoon and winter fruit cracking, followed by rotting and abscission, was commonly observed and often associated with soil moisture deficit and winter-induced twig desiccation (Fig. 1).

Isolation and pathogenicity studies revealed diverse fungal associations across all stages of fruit development. Pathogenicity assays identified members of the *Fusarium* species complex (*F. cassiae, F. coicis, F. lumajangense, F. nanum, F. xyrophilum*) and *Neocosmospora* species (*N. metavorans, N. falciformis*), with *F. cassiae, F. lumajangense, N. metavorans,* and *N. falciformis* demonstrating high virulence (Shukla *et al.,* 2024). Although Fusarium was previously associated primarily with stalk-end and root rot (Sharma and Gaur, 2014), the current study confirms its critical role in fruit drop throughout the developmental period, including both early-stage embryo abortion and later-stage pulp rot. These findings highlight the pervasive impact of fungal pathogens on bael productivity and the need for integrated disease management strategies.

The impact of weather variables on fruit drop was assessed across three phenological phases: SMW 25–40 (June–September), SMW 41–52 (October–December), and SMW 1–14 (January–March). The maximum fruit drop occurred during SMW 25–40, coinciding with the early fruit development phase, followed by SMW 1–14 and SMW 41–52 (Table 3). Winter conditions had a pronounced influence on fruit abscission, with chilling injury causing leaf and twig necrosis, which in turn corresponded with increased fruit drop from SMW 46 onward (Fig. 2). Correlation analyses revealed that fruit drop was

Table 3: Three years average bael fruit drop/tree/week and weather data (2021-22 to 2023-24)

SMW	Av. No. of fruits dropped	Temperature (°C)		Humidity (%)		Sunshine (hr/d)	Wind speed (km/hr)	Rainfall (mm)	No. o rainy days
		Max.	Min.	Max.	Min.				
25	55.89	36.01	26.23	73.76	49.43	6.78	3.48	27.00	1.67
26	151.24	34.94	26.60	78.81	55.30	6.05	3.72	45.40	1.33
27	357.98	35.14	26.59	93.29	68.09	6.51	2.82	62.67	1.67
28	249.98	35.29	26.81	93.61	67.80	7.33	4.28	53.17	2.00
29	195.01	34.16	26.51	93.56	62.23	5.68	3.43	40.13	2.33
30	139.40	33.40	26.17	94.04	67.53	6.08	3.73	45.80	1.00
31	117.96	32.99	25.89	94.77	74.62	4.37	3.14	60.47	1.33
32	72.41	33.19	26.32	95.59	78.86	4.43	2.89	58.67	1.33
33	49.34	34.24	25.78	95.37	71.52	7.29	3.04	35.33	1.33
34	30.61	32.75	25.48	95.77	75.72	5.32	3.26	67.87	2.33
35	12.90	33.85	25.59	95.58	74.44	7.13	2.52	9.33	0.67
36	8.90	34.65	25.52	95.60	72.85	6.52	2.87	10.00	0.33
37	4.30	32.20	25.18	95.56	69.80	4.06	5.13	134.13	1.67
38	2.06	32.72	24.83	94.66	73.40	6.48	3.18	39.33	1.00
39	1.54	32.64	23.63	94.32	75.97	7.75	1.98	33.00	1.00
40	0.91	32.93	23.10	93.99	73.52	7.08	1.99	41.20	1.33
41	0.53	33.10	21.17	94.71	68.44	6.83	2.54	31.33	0.33
42	0.25	32.21	18.70	94.34	71.19	7.31	1.85	30.67	0.67
43	0.16	31.06	20.73	93.92	78.29	8.47	1.03	0.00	0.00
44	0.11	30.52	14.03	93.62	71.37	7.26	0.88	0.00	0.00
45	0.20	29.90	13.59	92.44	66.76	5.17	0.64	0.00	0.00
46	0.10	28.37	10.96	90.61	62.81	6.12	0.78	0.00	0.00
47	0.05	26.67	9.80	88.67	64.28	6.33	0.93	0.00	0.00
48	0.06	26.28	9.73	89.47	63.62	4.89	0.52	0.00	0.00
49	0.05	25.78	10.58	89.46	63.65	6.00	0.99	10.73	0.67
50	0.09	24.54	6.13	86.48	62.28	6.86	1.27	0.00	0.00
51	0.10	22.89	4.86	86.96	61.89	5.63	1.03	0.00	0.00
52	0.13	21.82	7.19	87.54	62.60	4.16	1.17	0.00	0.00
1	0.11	18.17	7.44	85.81	62.85	2.19	1.55	0.67	0.33
2	0.18	17.58	6.66	85.63	63.01	2.87	1.56	0.00	0.00
3	0.63	16.99	4.68	84.75	63.29	3.56	1.71	0.00	0.00
4	0.78	19.86	7.25	86.23	64.13	4.14	1.98	0.67	0.33
5	2.38	23.22	7.20	83.85	63.39	5.30	2.79	0.20	0.33
6	3.76	23.45	6.95	83.05	64.18	7.13	2.38	6.00	0.33
7	6.68	25.87	7.26	83.14	64.82	7.42	2.22	0.00	0.00
8	8.33	28.47	9.34	83.42	65.28	7.78	2.64	0.00	0.00
9	6.46	28.92	10.25	81.59	63.11	7.32	2.48	1.43	0.67
10	5.10	29.71	10.60	79.58	61.03	8.20	2.67	0.00	0.00
11	3.51	32.17	13.41	78.61	59.57	7.65	2.42	0.00	0.00
12	1.63	33.04	14.08	77.30	58.00	7.56	2.42	11.53	0.67
13	1.75	35.70	15.61	74.47	55.77	8.45	2.80	26.53	0.67
14	0.96	36.68	15.71	73.13	53.79	8.82	2.30	0.00	0.00

positively associated with minimum temperature and wind velocity and negatively associated with rainy days during 2021–22 (Fig. 3). In 2022–23, the fruit drop was positively correlated with both minimum and maximum temperatures and wind velocity (Fig. 4).

Pooled three-year data indicated that fruit drop during SMW 25–45 is correlated positively with temperature, rainfall, number of rainy days, and wind velocity, and negatively with minimum relative humidity (Fig. 5). These environmental conditions favor fungal development, consistent with prior observations on sooty mould incidence (Shukla *et al.,* 2017). During SMW 46–14, the fruit drop showed positive relationships with maximum temperature, wind velocity, and sunshine hours, and a negative relationship with maximum relative humidity (Fig. 6). The minimum temperatures during late December–January were identified as a critical factor inducing chilling injury and subsequent fruit drop. Although the minimum temperature explained only 5.27–16.7% of variability, its effect was significant during SMW 25–45, but not during SMW 46–14, likely

Fig. 2: Chilled injury to trees during winter.

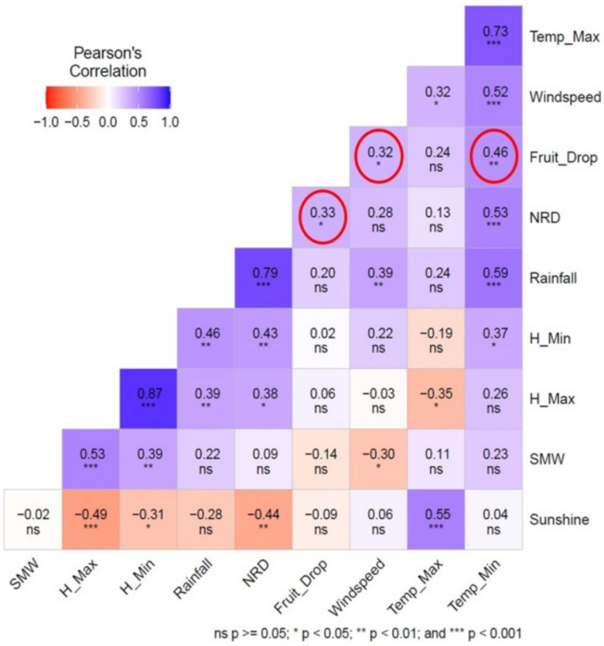


Fig. 3: Relationship of fruit drop with weather variables (2021-22).

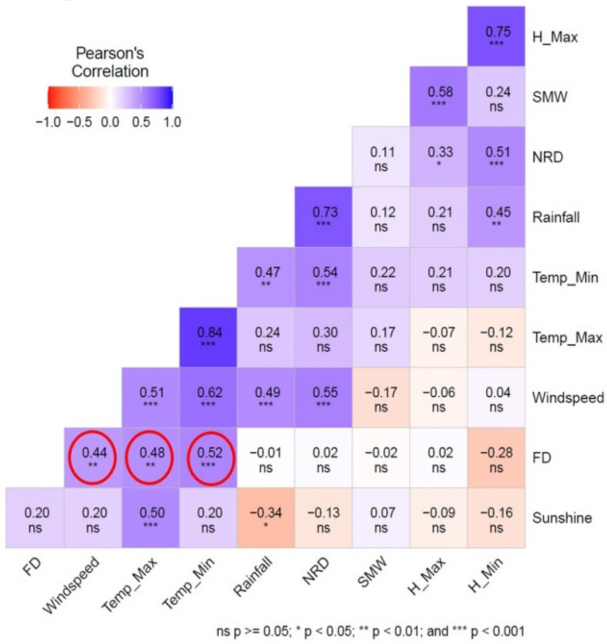


Fig. 4: Relationship of fruit drop with weather variables (2022-23).

due to delayed physiological responses following chilling stress (Fig. 7).

Genotypic variation in fruit drop was significant, whereas year-to-year variation and genotype × year interaction were non-significant, suggesting that genetic control was strong under similar environmental conditions. The minimum fruit drop occurred in CISH B-2 and Pant Aparna, whereas NB-9 and Pant Sujata exhibited the highest fruit drop (Table 4, Fig. 8). During SMW 45–15, when only physiologically mature fruits remained, environmental effects were non-significant, whereas genotypic differences remained statistically significant ($p < 0.05$) (Table 5).

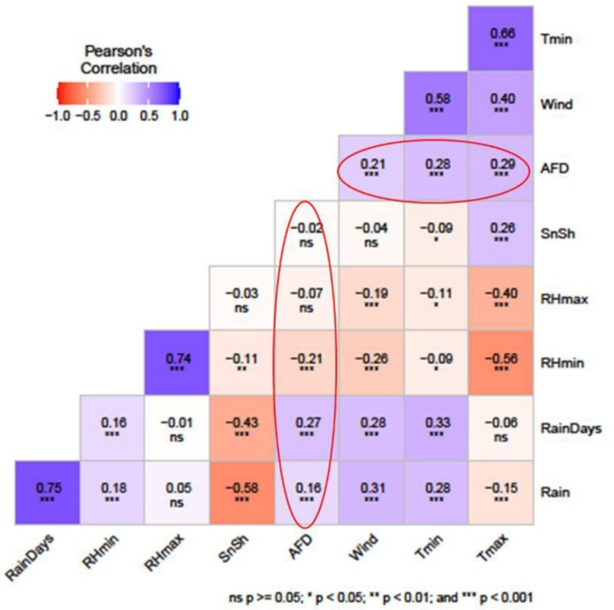


Fig. 5: Relationship of fruit drop with weather variables (25-45 SMW) in 3 year Average.

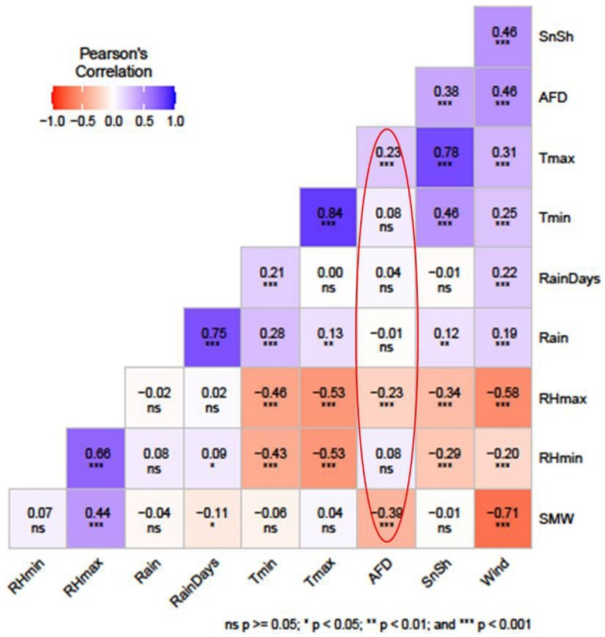


Fig. 6: Relationship of fruit drop with weather variables (46-14 SMW) in 3 year Average.

Table 4: ANOVA for testing the effects of genotype, environment and GXE interaction considering both as fixed.

	Geno
DF	7
SS	1173540
MS	167648.6
F	6.1116
P value	0.000****
Environmental Effect (p value	0.736
GXE Effects (p value)	0.9987

Table 5: ANOVA for average economic fruit drop over two years

Source of Variation	DF	SS	MS	F-value	P
Year	1	408.3333	408.3333	4.19	0.1102
Rep within Yr	4	390.0833	97.5208	0.3	0.8776
Variety	7	6769.25	967.0357	2.94	0.0193
Yr: Variety	7	2711.667	387.381	1.18	0.3464
Pooled Error	28	9204.583	328.7351		
Total	47	19483.92			

Table 6: Genetic parameter for average economic fruit drop (AEFD)

Genetic Parameters	AEFD
Phenotipic Variability	436
Genotypic Variability	106
EnvironmentalVariability	330
Heritability	24.3
GCV	21.9
ECV	38.6
PCV	60.5

Table 7: The genotypic effect contribution toward average fruit drop during 45th to 14th SMW

Genotype	Genotypic Effect (Average Fruit Drop)
CISHB1	12.04
CISHB2	6.22
NB17	-4.30
NB5	-6.39
NB9	-10.45
Pant Aparna	9.30
Pant Shivani	0.63
Pant Sujata	-7.05

Economically important fruit drop was lowest in NB-9, Pant Sujata, and NB-5, highlighting these cultivars as priority candidates for commercial orchards (Table 6).

Weekly fruit drop trends indicated substantial initial abscission until August, after which an average of 87.1 fruits per tree remained. From September to December, the fruit drop was negligible, and fruits attained full development suitable for processing (Table 7). Large-fruited genotypes (>1.25 kg), categorized as processing types (Pandey *et al.,* 2023), exhibited higher fruit drop, underscoring the need for early harvesting (October–December) for cultivars such as CISH B-2, Pant

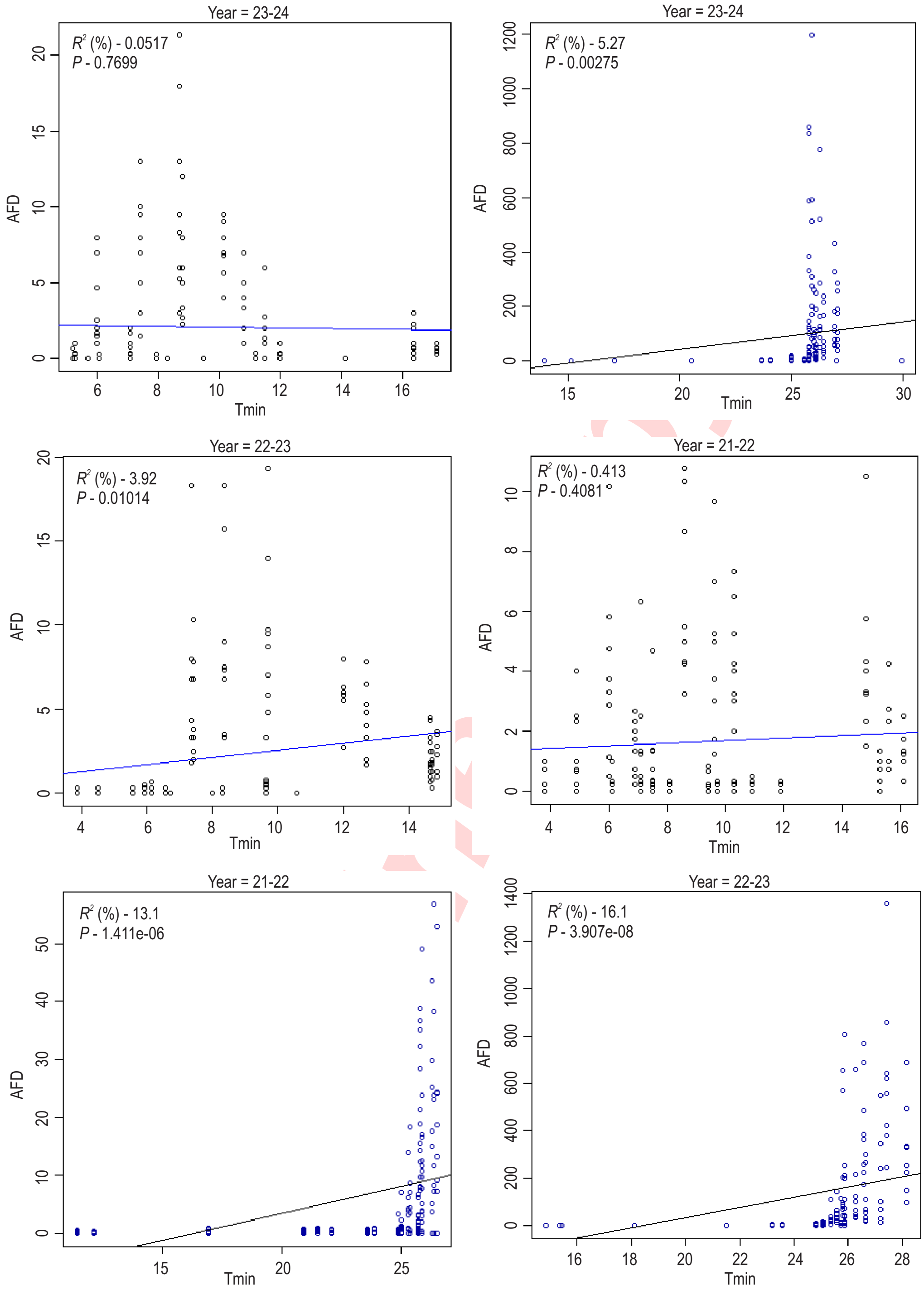


Fig. 7: Relationship of minimum temperature with average fruit drop.

Shivani, and NB-17. As most winter-dropped fruits were pathogen-infected, losses can be mitigated through timely processing and targeted fungicidal interventions. Physiological analyses revealed a decline in chlorophyll content during winter, likely attributable to suppression of chlorophyll biosynthesis under low-temperature stress. Vapour pressure deficit decreased in January, resulting in reduced transpiration, while photosynthetic activity of functional leaves declined significantly under low temperatures (Table 8). Reduced leaf functions during cold stress likely impaired assimilate availability,

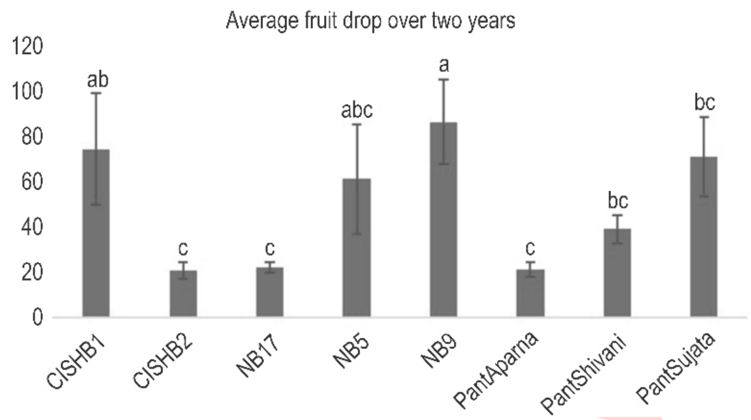


Fig. 8: Overall average fruit drop over years.

Table 8: Physiology of bael trees as influenced by weather during different months

Month	Total Chlorophyll (mg g^{-1} FW)	Stomatal conductance (mmol H_2O m^{-2} s^{-1})	Vapour pressure deficit (kPa)	Transpiration rate (mmol H_2O m^{-2} s^{-1})	Net photosynthesis rate (µmol CO_2.m-2s^{-1})
July	2.47	54.7	1.2	1.4	4.52
September	2.13	52.3	1.1	1.3	4.22
November	1.68	46.2	1.4	1.2	3.74
January	1.07	32.6	1.1	0.8	2.55
March	1.88	57.4	1.6	1.7	4.13

contributing to fruit abscission. These findings emphasize the combined effect of abiotic stress and pathogen susceptibility on fruit retention.

The present study demonstrates that fruit drop constitutes the most critical constraint to bael productivity, with near-complete losses occurring after fruit set. Significant genotypic variation emphasizes the importance of cultivar selection, with NB-9, CISH B-1, and NB-5 showing superior fruit retention and economic yield potential. Fruit drop is governed by a complex interplay of pathogen infection, physiological stress, and weather variability. Fusarium species were identified as the primary causal agents across all developmental stages, with infection severity increasing during winter. Low winter temperatures induced chilling stress, reducing chlorophyll content, transpiration, and photosynthetic activity, thereby predisposing fruits to abscission and pathogen invasion. Conditions from post-monsoon to early winter (October–December) were comparatively favorable for fruit retention, highlighting this period as optimal for harvesting and processing, particularly for large-fruited cultivars. Integrated management strategies encompassing cultivar selection, timely harvest, and effective disease management are essential to minimize fruit drop and enhance the sustainability and profitability of bael cultivation.

Acknowledgments

Authors are thankful to the Director, ICAR-Central Institute for Subtropical Horticulture, Lucknow for providing necessary facilities for the research. Thanks are also due to the Council of Science and Technology, Uttar Pradesh, Lucknow for providing financial assistance under the project, "Development of integrated package for management of fruit drop of bael (*Aegle marmelos* Correa)".

Authors' contribution: P.K. Shukla: Planning and execution of experiment, survey, compilation of data, preparation of manuscript; **A. Kushwaha:** Data analysis, establishment of correlations and preparation of manuscript; **A.K. Trivedi:** Physiological studies and preparation of manuscript, review and editing; **N. Kumari:** Identification of associated fungi on molecular basis and preparation of manuscript; **S.K. Shukla:** Execution of horticultural aspects of selected experimental orchard and preparation of manuscript; **H. Singh, A. Singh and S. Pandey:** Recording of data, isolation of fungi and pathogenicity of pure cultures of fungi.

Funding: Uttar Pradesh Council Science and Technology, Lucknow.

Research content: Certified that it is the original work of the team.

Ethical approval: The authors have followed and complied with the National/ International guidelines of relevant and appropriate authority for the use of plants or animals or humans in the experimental study.

Conflict of interest: There is no conflict of interest among the authors.

Data availability: Certified that all original data are available with the corresponding author and all the authors are in agreement to publish it through PME, ICAR-CISH, Lucknow.

Consent to publish: All authors agree to publish the paper in *Journal of Environmental Biology.*

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