



RESEARCH ARTICLE

Influence of bio-enhancers and bio-fertilisers on growth, flowering and yield of aonla (*Emblica officinalis* Gaertn.) cv. NA-7

Sarfaraj & V K Tripathi*

Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur 208 002, Uttar Pradesh, India

*Correspondence email - drvkttripathicsa@gmail.com

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Abstract

The present investigation was carried out on 22-year-old aonla (*Emblica officinalis* Gaertn.; variety NA-7) trees during the years 2023 and 2024 at Kalyanpur Nursery, Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur. The design of the experiment was randomized block design with three replications involving ten treatment combinations formed by applications of Azotobacter, PSB, Amritpani, Jeevamrit and Panchagavya. Significant improvements were recorded on the growth, flowering and yield traits, with T₉ (Azotobacter(5 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %) consistently outperforming others. Among the evaluated treatments, T₉ (Azotobacter(5 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %) exhibited the highest performance in key growth traits, recording maximum plant height (11.04, 11.42 & 11.23 m), stem girth (72.25, 74.56, 73.41 cm), plant spread in the north-south direction (7.58, 7.64, 7.61 m), plant spread in the east-west direction (7.69, 7.74, 7.72 m) and number of shoots per tree (10.54, 10.66, 10.60) during 2023, 2024 and pooled, respectively. Similarly, T₉ also recorded the highest values for flowering and yield attributes such as total number of flowers per meter shoot (562.32, 569.33, 562.82), male flowers per meter shoot (552.09, 558.90, 555.50), female flowers per meter shoot (10.23, 10.34, 10.29), male: female flower ratio (53.97, 54.06, 54.02), fruit setting percentage (74.62, 75.22, 74.92 %), fruit drop (69.35, 68.75, 69.05 %), fruit retention (30.65, 31.11, 30.88 %), number of fruits per shoot (154.23, 157.37, 155.47) and fruit yield per tree (57.56, 61.17, 59.36 kg) in 2023, 2024 and pooled, respectively.

Keywords: aonla; bio-enhancers; bio-fertilisers; correlogram; flowering and yield attributes; growth traits; principal component analysis

Introduction

Aonla (*Emblica officinalis* Gaertn.), also known as Indian gooseberry, occurs widely in tropical Southeast Asia, particularly central or southern India, Pakistan, Bangladesh, Sri Lanka, Malaya, Southern China and Mascarene Islands. Wild aonla trees are also found in China, Sri Lanka, Pakistan, USA and in Peur to Rico (1). Aonla is a subtropical plant and prefers a dry subtropical climate, but it can be successfully cultivated in a wide range of soils and climatic conditions (2). Owing to better prospects of aonla in semi-arid regions due to the hardy nature of plants, high medicinal and nutritional values, there is a possibility that it will be one of the most important fruit of the future (3). In India, it is cultivated in 107 thousand ha with a production of 1378 thousand MT (4). In India, aonla is being cultivated on a commercial scale in northern parts comprising Uttar Pradesh, Gujarat, Maharashtra (5). Uttar Pradesh is the leading State in which Pratapgarh (aonla fruit belts), Rai Bareilly, Varanasi, Jaunpur, Sultanpur, Kanpur, Bareilly, Agra and Mathura are the leading districts for aonla cultivation throughout the country (6).

The nutritional composition of aonla fruits varies with fertilization, soil fertility and availability of nutrients. Phosphorus deficiency is a serious constraint under tropical soils as almost 75 % of phosphatic fertilisers applied are immobilised in forms not

available to the plants. Bio-fertilisers, consisting of living microbial inoculants, help to overcome this problem by increasing nutrient availability through solubilisation of insoluble phosphorus and potassium and fixing atmospheric nitrogen (7).

Bio-enhancers are increasingly used in fruit crop cultivation to enhance nutrient uptake, promote plant growth and increase resistance to stress and diseases. When applied to fruit crops, bio-enhancers such as beneficial microbes (e.g., *Trichoderma*, *Azotobacter* and Mycorrhiza), plant extracts, or natural compounds like humic acid enhance the efficiency of fertilizers and other inputs. They enhance root development, improve flowering and fruit setting and ultimately increase yield and fruit quality. Additionally, bio-enhancers can reduce the need for chemical inputs, making fruit production more sustainable and eco-friendlier.

Bio-fertilisers are carrier-based treatments that contain a sufficient number of mostly efficient microorganism strains beneficial for fixing nitrogen. The anticipated yields per unit area are significantly higher when used in conjunction with macronutrients. Nitrogen is the only one of these elements that is essential for the production of amino acids, protein building blocks and chlorophyll, which is responsible for a greater source-to-sink ratio. Application of *Azotobacter* and *Azospirillum*, associative

diazotrophs residing in close associations with the roots of plants, has been generally found to sustain yield improvements in many non-leguminous crops. Further, their beneficial effects on fruit quality stem not only from biological nitrogen fixation but also from the production of physiologically active substances such as cytokinins, auxins and B-complex vitamins. The present investigation was conducted to check the effect of bio-enhancers and bio-fertilisers on the growth and flowering attributes of aonla; to check the interactive effect on fruiting and yield of all different treatment combinations.

Materials and Methods

The experiment was conducted at Kalyanpur Nursery, Department of Fruit Science, Chandra Shekhar Azad University of Agricultural and Technology, Kanpur, on 22-year-old aonla trees of variety NA-7. The Kanpur district is located at an elevation of 135 m above sea level. It is situated in a subtropical zone with coordinates between 25.26° and 26.58° N and 79.31° and 80.34° E. A total of ten treatment combinations were evaluated using a randomized block design with three replications involving applications of Azotobacter, PSB, Amritpani, Jivaamrit and Panchagavya. The treatments are detailed below:

Treatment Code	Treatment Description
T1	Control (Untreated plant)
T2	Panchagavya (5 %) + Azotobacter (50 g/tree)
T3	Panchagavya (5 %) + PSB (50 g/tree)
T4	Azotobacter (50 g/tree) + Amritpani (10 %)
T5	PSB (50 g/tree) + Amritpani (10 %)
T6	Azotobacter (50 g/tree) + Jivaamrit (20 %)
T7	PSB (50 g/tree) + Jivaamrit (20 %)
T8	Panchagavya (5 %) + Azotobacter (50 g/tree) +
T9	Azotobacter (50 g/tree) + PSB (50 g/tree) +
	Amritpani (10 %) + Panchagavya (5 %)
T10	Azotobacter (50 g/tree) + PSB (50 g/tree) +

Vermicompost at 1 kg/tree/year with organic mulching of paddy straw is commonly used in all treatments.

Application schedule

Bio-enhancers and bio-fertilisers were applied according to the specific treatment requirements. Foliar application of Panchagavya was performed on the plant canopy and drenching of Jivaamrit and Amritpani was done in the basal area of the aonla plant at flowering, fruit set (pea stage) and growth stages. To ensure thorough foliar coverage, a 10 L solution was administered using a pneumatic foot sprayer with a nozzle, targeting the entire foliage between 8:00 am and 10:00 am. A high-legged stool was used to facilitate the complete drenching of the plants, including their upper portions. Paddy straw was utilised as a mulch material around the root zone to prevent the spread of excess spray. Biofertilizers were applied according to specific treatment requirements, mixed with farmyard manure (FYM) and incorporated into the soil (Table 1).

Table 1. Method for preparation of nutrient solution

Sl. No.	Material used	Applied concentration	Quantity per litre of water	Field dose per tree
1	Panchagavya	5.00 %	50 ml	–
2	Jivamrit	20.00 %	200 ml	–
3	Amritpani	10.00 %	100 ml	–
4	Azotobacter culture	–	5 g (suspension)	50 g/tree
5	PSB culture	–	5 g (suspension)	50 g/tree

Observations recorded

The following traits were recorded during the study:

Growth attributes

Plant height (m): Using a marked bamboo stick, the height of the plants was measured from the ground to their highest point both before and after the fruit was harvested (AFH and BFA, respectively).

$$\text{Plant height} = \frac{\text{Plant height (AFH)} - \text{plant height (BFA)}}{\text{plant height (BFA)}} \times 100$$

Stem girth (cm): A measuring tape or flexible ruler

Plant spread (N-S), (E-W) (m): Plant spread was recorded for each tree before fertiliser application (BFA) and after fruit harvest (AFH) by putting the marked bamboo stick horizontally with the tree from east-west and north-south. The same was expressed as a percent increase in plant spread using the formula.

$$\text{Plant spread} = \frac{\text{Plant spread (AFH)} - \text{plant spread (BFA)}}{\text{plant spread (BFA)}} \times 100$$

Number of shoots/tree: The number of shoots per plant was counted after the last harvesting of fruits in all treatments and average value was expressed as number of shoots per plant.

Flowering attributes:

Fruit setting (%): Each treated tree's randomly chosen bearing branches were tagged and the number of blooms on each branch was counted independently. Fifteen days following foliar spray, the number of fruits was counted. The following formulas were used to determine the fruit set percentage:

$$\text{Fruit setting (\%)} = \frac{\text{Total number of fruits set per determinate shoot}}{\text{Number of flowera at initial stage}} \times 100$$

Fruit drop (%): To analyse the percentage of fruit drop, the quantity of fruits was enumerated at the starting stage and recorded at the time of fruit maturation. The percentage of fruit drop was determined using the following formula:

$$\text{Fruit drop (\%)} = \frac{\text{Number of fruits at initial stage} - \text{Numbers of fruits retained}}{\text{Number of flowera at initial stnumber of fruits at initial stage}} \times 100$$

Total number of flowers/meter shoot: For recording data on flowering, 5–10 healthy and uniform aonla plants were selected from the experimental field. Each in the batch was tagged with three to five shoots of the current season. A 1 m portion (from basal ends) of each tagged shoot was measured with the tape and the total flowers present on that portion were counted manually.

Total number of male flowers/meter shoot: The count of male flowers was recorded by selecting five to ten healthy and uniformly growing aonla plants from the experimental field. Then on each plant, three to five shoots of the present season were tagged and measured by a measuring tape from the basal end for 1 m. Within this marked portion, the total number of individual male flowers was counted by hand.

Total number of female flowers/meter shoot: In recording the number of female flowers, 5–10 healthy and uniform-growing aonla plants were selected from the experimental field. On each plant, 3–5 current-season shoots were tagged and a 1 m portion from the basal end of each shoot was measured using a measuring tape. Within the marked 1 m portion, the entire number of individual female flowers was counted manually.

Male: female ratio: Male: female ratio was calculated by using this formula:

$$\text{Male: female ratio} = \frac{\text{Total male flower}}{\text{Total female flower}} \times 100$$

Yield attributes

Fruit retention (%):

The assessment of fruit retention % on aonla trees involved recording the initial fruit set and the residual fruits after shedding for each bio-fertiliser and bio-enhancer treatment at harvest time. The percentage of fruit retention was determined using the accompanying formula:

$$\text{Fruit retention (\%)} = \frac{\text{Total number of fruits retained per determinate shoot till maturity}}{\text{Number of fruits set per determinate shoot}} \times 100$$

Number of fruit /shoots: On each selected tree, randomly select 5 –10 current season shoots (preferably similar in size and age) and mark each shoot with coloured thread or tags to avoid double -counting.

Fruit yield (kg/tree): At each harvesting under each treatment, the weight of the aonla fruits was recorded and weighed on a physical scale. The final yield per tree was calculated and expressed as kg/ tree.

Statistical analysis

The data obtained were statistically analysed using a randomised block design (RBD). The significance of treatment effects was tested using an F-test and critical differences (CD) at a 5 % probability level were calculated for comparison among treatment means. Multivariate relationships among treatments and traits

were evaluated using principal component analysis (PCA) performed with XLSTAT software.

Results and Discussion

Growth attributes

The effect of bio-enhancers and bio-fertilisers significantly influenced plant height (m), stem girth (cm), plant spread (N-S) (m), plant spread (E-W) (m) and number of shoots/trees over both seasons. The application of *Azotobacter* (50 g/tree) + PSB (50 g/ tree + Amritpani (10 %) + Panchagavya (5 %) consistently outperformed others across all traits.

Plant height (m): The perusal of data in Table 2 and Fig. 1, related to plant height revealed that the maximum plant height (11.04 m, 11.42 m and 11.23 m) was recorded in aonla plants which were treated with the application of *Azotobacter* (50 g/tree) + PSB (50 g/ tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (10.86 m, 11.24 m, 11.05 m). The minimum plant height of 7.52 m, 7.81 m, 7.67 m, was recorded with the control (Untreated plant) in 2023, 2024 and pooled, respectively (Table 2). In addition, these changes were brought in the rhizosphere microflora with the bio-enhancers and biofertilisers, thus preparing a harsher phase for solubilisation and nutrient mobilisation towards the root sides and better growth of trees. Nitrogen-fixing biofertilisers such as *Azospirillum* and *Azotobacter* specific in nitrogen supply also secrete growth-regulating substances such as indole-3-acetic acid (IAA), gibberelins and cytokinins. According to these results, plant-growth phytohormones could be absorbed via the root system and later could act as cofactors in the same processes of cell elongation, leaf initiation and canopy growth, causing enhanced vegetative growth. An increase in microbial activity may also have favoured enzymatic processes and nutrient uptake by the plant root zone, thereby favouring plant vigour. The current results align with prior reports in aonla, guava, mango and dragon fruit (8–11), where biofertilisers improved vegetative growth, nutrient uptake and overall production.

Stem girth (cm): The perusal of data related to stem girth revealed that the maximum stem girth of (72.25 cm, 74.56 cm and 73.41 cm), was recorded in aonla plants which were treated with the application of *T₉*-*Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with the application of *T₁₀*-*Azotobacter* (50 g/tree) + PSB (50 g/ tree) + Jivaamrit (20 %) having 71.32cm, 73.41cm, 72.37cm girth, respectively in 2023, 2024 and pooled (Table 2 and Fig. 1). The

Table 2. Influence of bio-enhancers and bio-fertilisers on vegetative parameters of aonla (*Emblica officinalis*) cv. NA-7

Treatment notation	Plant height (m)			Stem girth (cm)			Plant spread (N-S) (m)			Plant spread (E-W) (m)			Number of shoots/tree		
	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled
T ₁	7.52	7.81	7.67	53.72	54.92	54.32	6.67	6.72	6.70	6.75	6.79	6.77	8.41	8.62	8.52
T ₂	9.07	9.44	9.26	58.41	60.12	59.27	6.91	6.94	6.93	7.01	7.05	7.03	9.01	9.39	9.20
T ₃	8.23	8.62	8.43	56.33	57.14	56.74	6.82	6.87	6.85	6.94	6.97	6.96	8.91	9.11	9.01
T ₄	9.46	9.73	9.60	63.62	65.11	64.37	7.08	7.12	7.10	7.21	7.25	7.23	9.89	9.93	9.91
T ₅	8.64	8.95	8.80	60.16	62.12	61.14	7.01	7.05	7.03	7.18	7.22	7.20	9.45	9.57	9.51
T ₆	10.05	10.46	10.26	67.45	69.61	68.53	7.23	7.28	7.26	7.34	7.40	7.37	10.19	10.23	10.21
T ₇	9.72	10.01	9.87	65.51	67.57	66.54	7.12	7.16	7.14	7.23	7.26	7.25	10.04	10.16	10.10
T ₈	10.38	10.65	10.52	69.64	71.84	70.74	7.32	7.39	7.36	7.46	7.49	7.48	10.28	10.36	10.32
T ₉	11.04	11.42	11.23	72.25	74.56	73.41	7.58	7.64	7.61	7.69	7.74	7.72	10.54	10.66	10.60
T ₁₀	10.86	11.24	11.05	71.32	73.41	72.37	7.41	7.46	7.44	7.58	7.62	7.60	10.47	10.53	10.50
F test	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
SEm(±)	0.14	0.12	0.09	0.85	0.86	0.64	0.11	0.09	0.08	0.12	0.13	0.10	0.15	0.15	0.19
C.D.(P = 0.05)	0.44	0.37	0.27	2.56	2.60	1.92	0.32	0.28	0.24	0.37	0.40	0.30	0.46	0.44	0.57

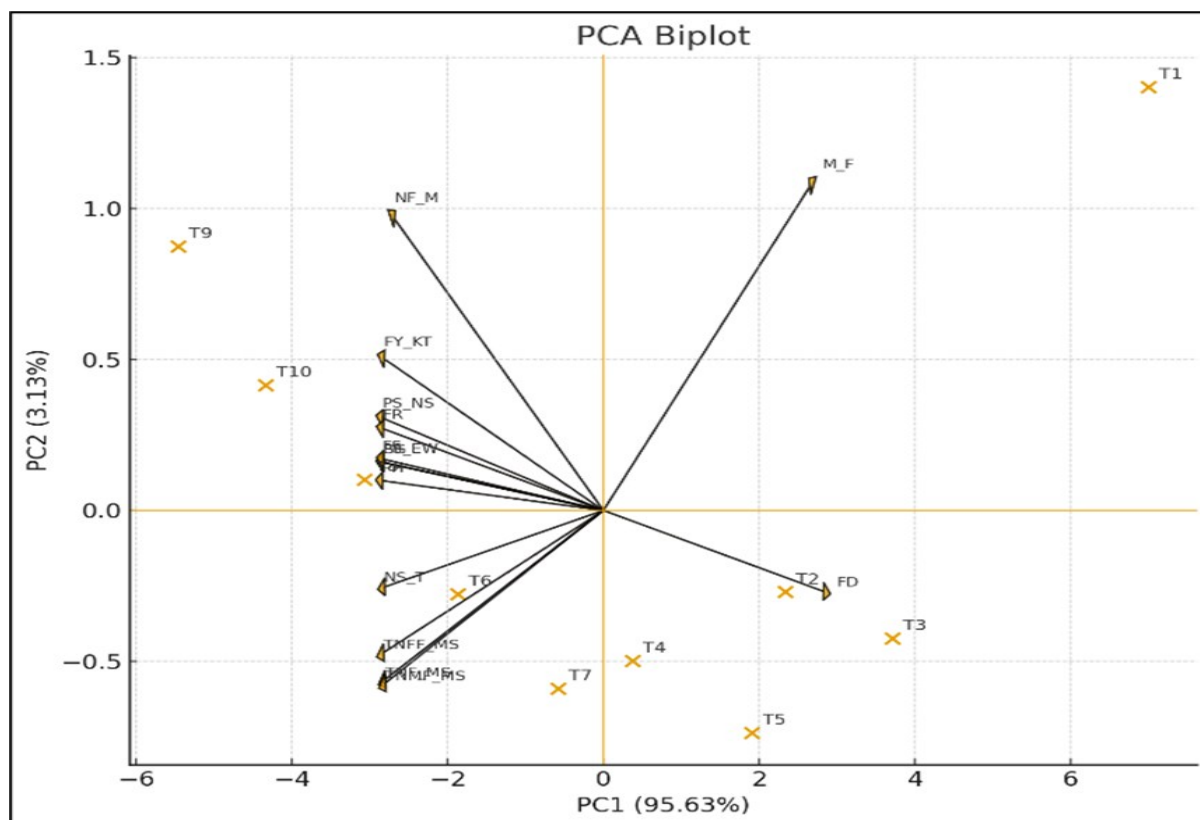


Fig. 1. Principal component biplot based on growth, flowering and yield traits of aonla (*Emblica officinalis*) cv. NA-7.

minimum stem girth was recorded (53.72 cm, 54.92 cm, 54.32 cm) with the T1-control (Untreated plant) in 2023, 2024 and pooled respectively (Table 2). In addition, the increase in stem thickness could be attributed to the combined application of vermicompost and biofertilisers, leading to increased nutrient availability and hence vigorous plant growth and diameter of stem. These observations are in line with the report in dragon fruit (9, 11) and aonla (12, 13).

Plant spread (N-S) (m): The perusal of data in Table 2 and Fig. 1, related to plant spread revealed that the maximum plant spread (7.58 m, 7.64 m and 7.61 m during 2023, 2024 and pooled, respectively) was obtained under *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Amritpani (10 %) + Panchagavya (5 %), which remained statistically on par with *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %), which recorded 7.41, 7.46 and 7.44 m. The minimum canopy spread (6.67, 6.72 and 6.70 m) was recorded in the untreated control. Improved canopy development through combined biofertiliser and bio-enhancer treatments can thus be explained by several mechanisms acting synergistically. Associative diazotrophs, *Azotobacter* and PSB fix nitrogen and solubilize phosphorus. These also play a role, wherein they are released in the environment according to the needs of the plants to carry out certain physiological activities, after which the plants initiate division of cells or formation of leaves or apical dominance of a given side of the plant. These substances further promote the growth of lateral shoots and canopy expansion. Bio-enhancers, i.e., Amritpani, Panchagavya and Jivaamrit, may act as an alternative supply of nutrients in bio-available forms, as well as organic acids, enzymes and beneficial micro-flora stimuli toward soil microbial activity to enhance the interaction of roots with the rhizosphere. Together, these promote improved nutrient-use efficiency, more extensive root proliferation and enhanced photosynthetic activity, which surface as wide canopy development and increased plant spread. These findings reflect the functional role of microbial

inoculants in modifying rhizosphere dynamics and canopy architecture and support earlier work in aonla (6, 13) and guava (14) in which biofertilisers significantly increased vegetative growth and canopy spread.

Plant spread (E-W) (m): The perusal of data in Table 2 and Fig. 1, related to plant spread revealed that the maximum plant spread (E-W) was (7.69 m, 7.74 m, 7.72 m) was recorded in aonla plants which were treated with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with (T₈ & T₁₀) the application of T₁₀-*Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (7.58 m, 7.62 m, 7.60 m) in 2023, 2024 and pooled respectively. The minimum plant spread (E-W) of (6.75 m, 6.79 m, 6.77 m) was recorded with the treatment of control (Untreated plant) in 2023, 2024 and pooled respectively (Table 2). Additionally, an increase in plant spread in all directions during the present experiment might be due to the better nutritional supply with the application of organic matter, stimulating and beneficial effect of biofertilisers solubilising and utilisation of nitrogen, which ultimately improved the soil health by improving physicochemical and biological activities of soil and biosynthesis of plant growth regulators like IAA and GA in plants. These outcomes are consistent with the findings aonla (6, 13) and guava (14).

Number of shoot/trees: The perusal of data in Table 2 and Fig. 1, related to number of shoot/trees revealed that the maximum number of shoot/trees (10.54, 10.66, 10.60) was recorded in aonla plants, which were treated with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) and the results were (10.47, 10.53, 10.50) in 2023, 2024 and pooled, respectively (Table 2). The minimum number of shoots/trees (8.41, 8.62, 8.52) was recorded with the control (Untreated plant) in 2023, 2024 and

pooled respectively. Besides, panchagavya contains natural growth hormones such as auxins, cytokinins and gibberellins, which are known to stimulate plant growth and development. These outcomes are consistent with the findings in guava (8, 15) and strawberry (16).

Flowering attributes

The effect of bio-enhancers and bio-fertilisers significantly influenced total number of flowers/meter shoot, total number of male flowers/meter shoot, total number of female flowers/meter shoot and male: female ratio, fruit setting (%), fruit drop (%) over both seasons. The application of T₉-Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %) consistently outperformed others across all traits.

Total number of flowers/meter shoot

The perusal of data related to the total number of flowers/meter shoot recorded that the maximum total number of flowers/meter shoot (562.32, 569.33, 562.82) was recorded in aonla plants which were treated with Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with the application of T₁₀-Azotobacter (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) and the results were (548.46, 552.10 and 550.28) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). The minimum total number of flowers per meter shoot (332.17, 333.24, 332.70) was observed with the T₁-control (Untreated plant) in 2023, 2024 and pooled, respectively. As well the application of Azotobacter and PSB may have encouraged the growth of inflorescence and leaf number in the autumn, which raised the levels of nutrients in the plants, increasing the number of flowers and fruits set in this treatment assimilating area of the crop due to which the rate of dry matter production was enhanced, which is positively correlated with the number of flowers and fruits in the following spring. A proper supply of nutrients and induction of growth hormones stimulated cell division and cell elongation, resulting in an increase in the number of flowers. Similar findings have been reported by guava (11, 15, 17) and aonla (18).

Total number of male flowers/meter shoot

The perusal of data related to the total number of male flower/meter shoot observed that the maximum total number of male flower/meter shoot (552.09, 558.90, 555.50) was recorded in aonla plants which were treated with the application of T₉-Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically followed by the application of T₁₀-Azotobacter (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %)

revealed the (538.50, 542.09, 540.30) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). The minimum total number of male flowers per meter shoot (327.92, 328.98, 328.45) was recorded with the T₁-control (Untreated plant) in 2023-2024 and pooled, respectively. These outcomes are consistent with the findings of aonla (3, 5, 18).

Total number of female flowers/meter shoot

The perusal of data related to the total number of female flower/meter shoot clearly revealed that the maximum total number of female flowers/meter shoot (10.23, 10.34, 10.29) was recorded in aonla plants which were treated with the application of Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically followed by the application of Azotobacter (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) and the results were (9.96, 10.01, 9.99) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). The minimum total number of female flowers per meter shoot (4.25, 4.25 and 4.25) was observed with the control (Untreated plant) in 2023, 2024 and pooled. These outcomes are consistent with the findings of aonla (3, 5 and 18).

Male: female ratio

The perusal of data related to male: female ratio revealed that the maximum male-to-female ratio of (77.15, 77.18, 77.17) was observed with the treatment control (Untreated plant) in 2023-2024 and pooled, respectively. The minimum male: female ratio (53.97, 54.06, 54.02) was recorded in aonla plants which were treated with the application of Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %) (Table 3). These outcomes are consistent with the findings of aonla (3, 5, 18).

Fruit setting (%)

The perusal of data in (Table 3 and Fig. 1) related to fruit setting revealed that the maximum fruit setting (%) of 74.62 %, 75.22 %, 74.92 % was recorded in aonla plants, which were treated with the application of T₉-Azotobacter (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with (T₈ & T₁₀) the application of T₁₀-Azotobacter (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (74.25 %, 74.75 %, 74.50 %) in 2023, 2024 and pooled respectively (Table 3). The minimum fruit setting percentage (62.26 %, 62.56 %, 62.41 %) was recorded with the T₁-control (Untreated plant) in 2023, 2024 and pooled, respectively. In addition, these results suggest that the integration of Panchagavya and biofertilisers contributed to increased inflorescence per branch by enhancing crop growth, vigour and

Table 3. Influence of bio-enhancers and bio-fertilizers on flowering parameters of aonla (*Emblca officinalis*) cv. NA-7

Treatment Notation	Total number of flowers/meter shoot			Total number of male flowers/meter shoot			Total number of female flowers/meter shoot			Male: female ratio (sex ratio)			Fruit setting (%)			Fruit drop (%)		
	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled	2023	2024	pooled
T ₁	332.17	333.24	332.70	327.92	328.98	328.45	4.25	4.25	4.25	77.15	77.18	77.17	62.26	62.56	62.41	80.72	80.32	80.52
T ₂	450.20	453.61	451.90	443.07	446.61	444.84	7.13	7.00	7.07	62.14	63.80	62.97	67.12	67.52	67.32	76.12	75.73	75.93
T ₃	431.35	433.76	432.55	424.68	427.14	425.91	6.67	6.62	6.65	63.67	64.50	64.09	65.67	66.07	65.87	78.35	77.50	77.93
T ₄	480.51	484.12	482.31	472.47	476.02	474.25	8.05	8.10	8.08	58.69	58.75	58.72	67.75	68.15	67.95	75.46	74.67	75.07
T ₅	466.77	470.05	468.41	459.16	462.40	460.78	7.61	7.65	7.63	60.34	60.44	60.39	66.34	66.74	66.54	77.72	77.22	77.47
T ₆	510.04	516.24	513.14	500.97	507.08	504.03	9.07	9.16	9.12	55.24	55.35	55.30	71.52	72.02	71.77	73.42	72.96	73.19
T ₇	498.63	502.51	500.57	490.08	498.83	494.46	8.50	8.68	8.59	57.32	57.46	57.39	69.63	70.03	69.83	74.61	74.11	74.36
T ₈	530.15	536.26	533.20	520.66	526.73	523.70	9.49	9.53	9.51	54.86	55.27	55.07	73.41	74.02	73.72	72.91	71.34	72.13
T ₉	562.32	569.33	565.82	552.09	558.90	555.50	10.23	10.34	10.29	53.97	54.06	54.02	74.62	75.22	74.92	69.35	68.75	69.05
T ₁₀	548.46	552.10	550.28	538.50	542.09	540.30	9.96	10.01	9.99	54.06	54.15	54.11	74.25	74.75	74.50	70.92	70.13	70.53
F test	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
SEm (±)	8.22	5.96	6.44	5.67	5.85	4.46	0.13	0.14	0.09	0.87	0.94	0.64	1.08	0.99	0.79	0.97	0.90	0.62
C.D. (P = 0.05)	17.42	18.98	13.64	17.00	17.54	13.36	0.38	0.44	0.28	2.63	2.81	1.93	3.23	2.96	2.37	2.92	2.72	1.86

resistance to pests and diseases, boosting growth and production. Biofertilisers such as *Azotobacter* and organic manures like FYM provide balanced nutrition by biologically fixing nitrogen, solubilizing phosphate and promoting growth with essential elements such as vitamins and hormones. These outcomes are consistent with the findings in aonla (3) and guava (14, 17).

Fruit drop (%)

The perusal of data related to fruit drop revealed that the minimum fruit drop (%) (69.35 %, 68.75 %, 69.05 %) was recorded in aonla plants which were treated with *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically followed by the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (70.92 %, 70.13 %, 70.53 %) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). The maximum fruit drop percentage (80.72 %, 80.32 %, 80.52 %) with the control (Untreated plant) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). Besides, this increase in fruit retention and reduced fruit drops with the application of a graded dose of NPK in combination with bio-fertilisers and vermicompost might be due to the result of its association with auxin synthesis, supply of nutrients and their proportion right from starting of the experimentation to the harvesting of the crop, which might have induced more flowering and retention of fruits as a result of production and supply of photosynthates at critical requirements. These outcomes are consistent with the findings of aonla (3), guava (14, 15, 17).

Yield attributes

The effects of bio-enhancers and bio-fertilizers significantly influenced fruit yield (kg/tree) across both seasons. The application of *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %) consistently outperformed others across all traits.

Fruit retention (%)

The perusal of data related to fruit retention revealed that the maximum fruit retention 30.65 %, 31.11 %, 30.88 %) was recorded in aonla plants, which were treated with the application of T₉-*Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically followed by the application of T₁₀-*Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (29.03 %, 29.52 %, 29.28 %) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). The minimum fruit retention (19.28 %, 19.48 %, 19.38 %) was observed with the treatment T1-control (Untreated plant) in 2023, 2024 and pooled respectively (Table 3 and Fig. 1). These outcomes are consistent with the findings of aonla (3), guava (14, 15, 17).

Number of fruit /shoots

The perusal of data related to number of fruits /shoots revealed that the maximum number of fruit /shoots (154.23, 157.37, 155.47) was recorded in aonla plants, which were treated with *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically at par with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (153.90, 154.90, 154.01) in 2023, 2024 and pooled respectively (Table 4 and Fig. 1). The minimum number of fruit/shoots (145.52, 147.91, 146.88) was recorded with the treatment control (Untreated plant) in 2023, 2024 and pooled (Table 4). These outcomes are consistent with the findings of aonla and potato (18–24).

Fruit yield (kg/tree)

The perusal of data related to fruit yield revealed that the maximum fruit yield (57.56 kg/tree, 61.17 kg/tree, 59.36 kg/tree) was observed in aonla plants, which were treated with the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree + Amritpani (10 %) + Panchagavya (5 %), which was statistically followed by the application of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Jivaamrit (20 %) (54.82 kg/tree, 56.63 kg/tree, 55.82 kg/tree) in 2023, 2024 and pooled respectively (Table 4). The minimum fruit yield 32.15 kg/tree, 34.17 kg/tree, 33.17 kg/tree was recorded with the treatment of control (Untreated plant) in 2023, 2024 and pooled respectively (Table 4 and Fig. 1). In addition, the results indicate that the bio-enhancers and bio-fertilisers significantly influenced the number of fruits per plant compared to the control. This might be because of the expansion in the number of leaves, which worked as an effective photosynthesis structure and produced a high quantity of carbohydrates in the plant system. Further number of blossoms, which redounded to increased fruits per plant because of the capacity of vermicompost in creating development hormones, enzymes, antifungal and antibacterial compounds, which in turn improved yield over different treatments. Similar findings were additionally revealed by aonla (13, 18–20).

Principal component biplot based on growth, flowering and yield traits of aonla (*Embllica officinalis*) cv. NA-7

Principal component analysis (PCA) reduced the multidimensional trait dataset into two PCs with eigenvalues greater than unity (Table 5 and Fig. 1). PC1 alone explained 95.63 % of total variance and PC2 accounted for an additional 3.13 % variance, making a cumulative variance of 98.76 %, which means that the two components adequately represent the variability among treatments.

Table 4. Influence of bio-enhancers and bio-fertilizers on yield parameters of aonla (*Embllica officinalis*) cv. NA-7

Treatment Notation	Fruit retention (%)			Number of fruits /shoot			Fruit yield kg/ha		
	2023	2024	Pooled	2023	2024	pooled	2023	2024	pooled
T ₁	19.28	19.48	19.38	145.52	147.91	146.88	32.15	34.17	33.170
T ₂	23.87	24.14	24.01	146.55	148.87	147.72	37.05	40.020	38.520
T ₃	21.35	21.95	21.65	146.40	147.78	147.10	35.90	37.670	36.770
T ₄	24.54	25.04	24.79	148.23	149.57	148.91	42.75	44.210	43.480
T ₅	22.26	22.67	22.47	147.34	148.66	148.01	38.71	40.260	39.480
T ₆	26.51	27.04	26.78	149.78	151.98	150.89	47.94	50.120	49.030
T ₇	25.32	25.91	25.62	148.63	149.77	149.21	45.12	46.940	46.030
T ₈	27.44	27.93	27.69	151.86	153.06	152.47	51.52	53.980	52.740
T ₉	30.65	31.11	30.88	154.23	157.37	155.47	57.56	61.17	59.36
T ₁₀	29.03	29.52	29.28	153.90	154.90	154.01	54.82	56.63	55.82
F test	S	S	S	S	S	S	S	S	S
SEm (±)	0.44	0.39	0.34	0.56	0.52	0.59	0.71	0.63	0.85
CD (P = 0.05)	1.33	1.18	1.02	1.69	1.57	1.77	2.15	1.89	2.56

Table 5. Principal component analysis loadings for growth, flowering and yield traits of aonla (*Emblia officinalis*) cv. NA-7

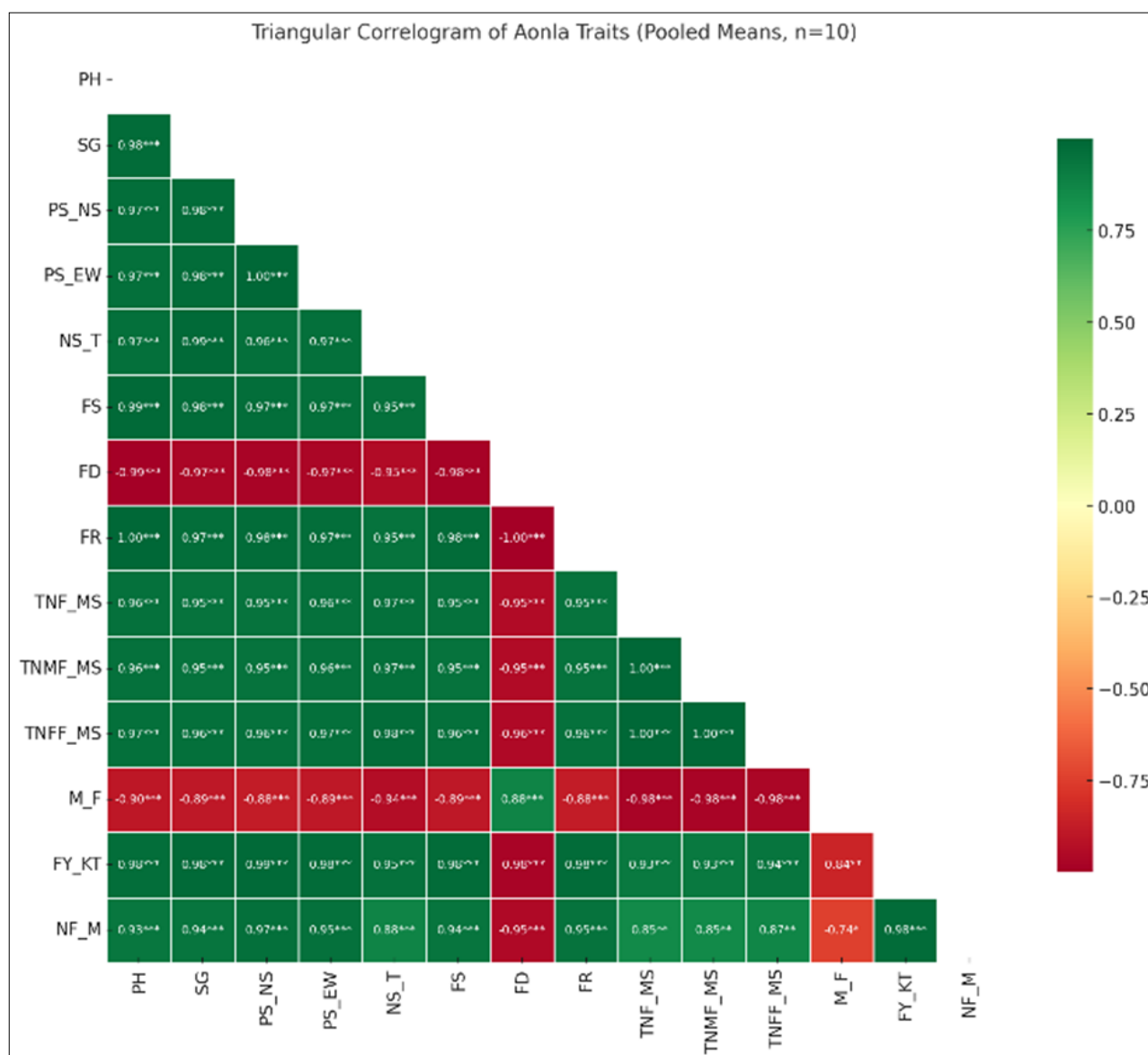
	PC1 Loading	PC2 Loading
PH (cm)	-1.0444	0.0362
PS (N-S)	-1.0427	0.1124
PS (E-W)	-1.0417	0.0585
SG	-1.0415	0.0586
FD	1.041	-0.0988
FS	-1.0409	0.0625
FR	-1.0409	0.0995
TNFF-MS	-1.0392	-0.1733
FY (Kg/T)	-1.0362	0.1848
NS-T	-1.0342	-0.0933
TNF-MS	-1.0314	-0.2058
TNMF-M	-1.0306	-0.2103
NF- M	-0.9879	0.3557
M: F	0.9761	0.3951
Eigenvalue	14.8762	0.4865
Explained Variance (%)	95.6324	3.1272
Cumulative Variance (%)	95.6324	98.7596

PH: Plant height; PS (N-S & E-W): Plant spread; SG: Stem girth; FD: Fruit drop; FS: Fruit setting; FR: Fruit retention; TNFF-MS: Total number of female flower; FY (kg/T): Fruit yield, NS-T: number of shoot; TNF-MS: Total number of flower; TNMF-MS: Total number of male flower; NF-M: Number of fruit; M:F: male: female ratio.

Most of the vegetative and reproductive traits loaded positively and strongly on PC1: plant height (PH, -1.044), stem girth (SG, -1.041), plant spread (PS_NS, -1.043; PS_EW, -1.042), number of shoot (NS_T, -1.034), fruit setting (FS, -1.041), fruit drop (FD, -1.041) and weight-related characteristics per several references (TNF_MS, -1.031; TNMF_MS, -1.031; TNFF_MS, -1.039), together with fruit yield per kilogram (FY_KT, -1.036). Therefore, PC1 stood for a broad general yield and vegetative vigour axis along which higher negative scores corresponded to high levels of vegetative and reproductive performances.

PC2 (3.13 %) represented a secondary axis where the number of fruit shoots (NF_S, 0.356) and the male: female (M: F, 0.395) ratio oppose parameters like TNF-MS (-0.206) and TNMF-MS (-0.210). This implies PC2 is associated mainly with factors concerning fruit distribution efficiency and sex ratio components, independent of the overall vigour of the plant.

To sum up, the PCA discriminated the treatments based on vigorous growth and yield performance (PC1) and fruit-to-mass efficiency traits (PC2). Treatments that lie well on the positive side of PC1 (e.g., T₉, T₁₀) can be considered for their superiority in yield-related attributes, while treatments scoring higher on PC2 have been considered to hold a more balanced profile concerning fruiting and reproductive efficiency.

**Fig. 2.** Correlogram of growth, flowering and yield attributes of aonla (*Emblia officinalis*) cv. NA-7.

Correlogram of growth, flowering and yield attributes of aonla (*Emblica officinalis*) cv. NA-7

According to the correlogram (Fig. 2), strong and significant associations among aonla growth and yield traits were observed under the pooled treatment means ($n = 10$). Plant height (PH) showed a positive correlation with stem girth (SG, $r = 0.96^*$), plant spread N-S (PS_NS, $r = 0.94^*$) and E-W (PS_EW, $r = 0.93^*$) due to treatments favouring vegetative vigour that induced uniform canopy development. Similarly, FS had a significant positive correlation with PH ($r = 0.91^*$)** and SG ($r = 0.89^*$) while FD correlated positively with FR ($r = 0.88$), all revealing the supportive role of vegetative growth to fruit development.

Conversely, the male-to-female flower ratio (M: F) showed a high negative relationship with fruit yield per tree (FY_KT, $r = -0.87$) and number of fruits per shoot (NF-S, $r = -0.91^{***}$), indicating that a bias toward males decreased actual fruit set and yield. However, a strong positive correlation was found between fruit yield per tree (FY_KT) and number of fruits per shoot (NF_S, 0.94^*), both positively correlating with fruit retention (FR, 0.89^{***}) and total number of flowers (TNF_MS, 0.92^{***} ; TNMF_MS, 0.90^{***}).

Overall, the analysis suggests that vegetative vigour and fruit retention contribute positively to yield formation, with an unfavourable male: female ratio standing as a limiting factor. The implication of this learning is that treatment balancing canopy development with reproductive allocation would contribute better to increasing aonla productivity.

Conclusion

Based on two years of field data and pooled statistical analysis, the study concluded that treatment T₉, consisting of *Azotobacter* (50 g/tree) + PSB (50 g/tree) + Amritpani (10 %) + Panchagavya (5 %), was the most effective in growth, flowering and yield parameters in aonla cv. NA-7. Specifically, T₉ improved plant height (m), stem girth (cm), plant spread (N-S) (m), plant spread (E-W) (m) and number of shoot/trees, total number of flower/meter shoot, total number of male flower /meter shoot, total number of female flower/meter shoot and male: female ratio, fruit setting (%), fruit drop (%), fruit retention (%), number of fruit/shoots and fruit yield (kg/tree). Bio-enhancers and bio-fertilisers are carrier-based preparations containing mainly effective strains of micro-organisms in sufficient numbers, which are helpful for nitrogen fixation. When used in conjunction with macronutrients, the expected yields per unit area are significantly higher. The study also highlighted that the integrated application of these components was superior to their individual use, suggesting a synergistic interaction that can be leveraged for sustainable and high-quality aonla production under the north Indian plains.

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Authors' contributions

S conducted the experiment, carried out the investigation, performed formal analysis, curated the data and drafted the original manuscript. VKT provided substantial guidance, supervised the study, facilitated the research by providing necessary laboratory facilities, assisted with data analysis, contributed to the methodology and participated in manuscript review and editing. Both S and VKT contributed to data visualisation. Both authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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