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Integrated nutrient management improves soil fertility, leading to improve the productivity and quality of aonla (*Emblica officinalis* L.)

Soustav Datta[1], *Susmita Dey*[2], *Sk Md Asif*[3], *Sarthak Bhattacharya*[4], *Suddhasuchi Das*[5], *Chinmoy Mandal*[6], *Kamal Kr. Mandal*[7], *Laila A. Al-Shuraym*[8], *Lamya Ahmed Alkeridis*[8], *Samy Sayed*[9], *Ahmed Gaber*[10], *Akbar Hossain*[11]*

[1]*Rathindra Krishi Vigyan Kendra, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati University, Sriniketan, West Bengal, India*
[2]*Faculty of Agriculture, JIS University, Agarpara, West Bengal, India*
[3]*Department of Agriculture, Brainware University, Barasat, West Bengal, India*
[4]*Department of Horticulture, Neotia University, South 24 Parganas, West Bengal, India*
[5]*Krishi Vigyan Kendra, Uttar Banga Krishi Viswavidyalaya, Malda, West Bengal, India*
[6]*Department of Pomology and Post Harvest Technology, Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal, India*
[7]*Department of Fruit Science, Bidhan Chandra Krishi Viswavidyalaya, Nadia, West Bengal, India*
[8]*Department of Biology, College of Science, Princess Nourah Bint Abdulrahman University, Riyadh, Saudi Arabia*
[9]*Department of Economic Entomology and Pesticides, Cairo University, Giza, Egypt*
[10]*Department of Biology, Faculty of Science, Taif University, Taif, Saudi Arabia*
[11]*Soil Science Division, Bangladesh Wheat and Maize Research Institute, Dinajpur, Bangladesh*

**Corresponding author: akbarhossainwrc@gmail.com*

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Abstract: Aonla (*Emblica officinalis* L.) is one of the most nutritious fruits and an excellent source of vitamin C. Chemical fertilisers and insecticides used indiscriminately have negative effects on soil fertility, yield and quality of produce. Given this background, a study was conducted from 2019 to 2021 at the Regional Research Substation, Bidhan Chandra Krishi Viswavidyalaya in Sekhampur, West Bengal, India, to examine the impacts of managing organic and inorganic nutrients for achievable production of aonla and preserving soil fertility in Red and Lateritic Regions of West Bengal, India. Treatments were: T_1: RDF (recommended dose of fertiliser): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB (phosphate solubilising bacteria) + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/ plant. All treatments were arranged in a randomised complete block design (RCBD) and repeated three times. The observations revealed that the greatest increases in plant growth

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parameters, maximum fruit physico-chemical characteristics, maximum yield/plant ratio and soil nutrient status were observed with the implementation of treatment T_6. Finally, aonla (cv. 'NA-7') orchards in Sekhampur, West Bengal, benefit from treatment T_6, which improves the soil nutrient status and increases fruit quality and yield.

Keywords: minor fruit crop; biofertiliser; physico-chemical characteristics; soil nutrient status; sustainable production

Aonla (*Emblica officinalis* L.), also recognised as Indian gooseberry, is considered a major nutritious fruit next to Barbados cherry and has a maximum vitamin-C content of 400–1 300 mg/100 g fruit pulp (Asenjo 1953). This fruit originated in the tropics of Southeast Asia, mainly central and southern India (Morton 1960). In the twenty-first century, aonla has become a significant minor fruit crop. In the western part, which covers 5 districts of West Bengal where barren as well as culturable waste land and land beneath a variety of plants and grooves not incorporated in the net region sown exist to the tune of 1.5 lakh ha, and the soil is later able to grow aonla plants (Ghosh et al. 2009), where aonla could be successfully grown in marginal, waste lands, semi-arid, coastal areas, salt-affected or ravine areas via proper technological intervention. The soil fertility, soil type and nutrient management all play a part in achieving increased growth and yields of aonla. Lateritic soil becomes exceedingly hard during the dry season because of its poor physical qualities, and crops suffer as a result of a lack of major plant nutrients. The application of organic fertilisers such as farmyard manure (FYM), vermicompost improves soil aggregation by affecting root penetration, aeration, drainage and soil infiltration (Yaganoglu, Aydin 2024).

Currently, inorganic fertiliser costs are steadily increasing. The continuous and excessive use of chemical fertilisers such as urea, muriate of potash (MOP), and other similar fertilisers may cause other essential nutrient shortages in fruit crops. The use of only chemical fertilisers has negatively affected soil fertility, production, quality of produce and water quality over the last four decades (Kalloo 2003). Because of the widespread and indiscriminate use of inorganic fertilisers, the soil has lost its biological dynamism. Under these circumstances, attention should be focused on organic nutrients to achieve improved production and better soil health in poor lateritic soils. The dynamic concept of modifying the plant nutrient supply to a supreme level to maintain the desired crop yields, as well as soil microbiological health, is known as integrated nutrient management (INM). This approach uses a well-balanced mixture of chemical fertilisers, organic manure and biofertilisers that are appropriate for improving soil by increasing the organic matter content as well as the soil quality parameters. Hazarika and Ansari (2007) reported that biofertilisers assisted in mobilising nutrients, restoring lost microflora and increasing soil health. Biofertilisers, which can be applied either through seeds or directly to soil, are formulations of active or dormant cells of effective microbe strains that assist agricultural crops in assimilating nutrients via various rhizospheric interactions (Srivastava, Ngullie 2009). In the rhizosphere of almost all crops, a free-living microorganism, *Azotobacter*, is crucial for promoting the development of plant rhizobacteria (Gomare et al. 2013). Plant growth is positively impacted by a number of growth regulators that *Azotobacter* produces, including gibberellic acid and indole acetic acid (Sharma, Kumar 2008).

Furthermore, INM assists farmers in maximising profits from nutrient sources within the farm by recycling waste and repurposing it as manure. As reported by Jat et al. (2015), when green manures and grain legumes are integrated into cropping systems, they can cover more than half of the N_2 demand of crops, lowering fertiliser costs.

The present study set out to create a schedule for managing both organic and inorganic nutrients to achieve the production of aonla as well as the maintenance of soil quality parameters in West Bengal's Red and Lateritic regions, as there is a dearth of information regarding aonla's integrated nutrient management, especially in these areas.

MATERIAL AND METHODS

Venue of the experimental site and treatment specifications. This study was conducted from 2019–2020 to 2020–2021 at the Regional

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Research Substation of Bidhan Chandra Krishi Viswavidyalaya in Sekhampur, West Bengal. This experiment was conducted at the Regional Research Substation, which is 30 m a.s.l. and is located at 23°68'N latitude and 87°69'E longitude. During the investigation period, the climate of the Regional Research Sub-Station was tropical humid with maximum temperatures ranging from 28.8 °C to 41.5 °C and minimum temperatures ranging from 7.0 °C to 27.2 °C. During the month of July, there was maximum rainfall. During the trial, the average relative air humidity ranged from 75 to 86%. Red and laterite soils with a limited water-holding capacity are found at this location. The soil is sandy with 38.4, 30.0 and 31.6% sand, silt and clay, respectively, and has a soil pH of 5.63. Before starting the investigation, the available nitrogen, phosphorus and potassium status of the soil were 160.16, 19.04 and 138.28 kg/ha, respectively, and the organic carbon content was 0.17% with a soil pH of 5.63. Aonla plants cv. 'NA-7' (Narendra Aonla-7) were 12 years old and uniformly tall, and 5 × 5 m spacing was maintained. Treatments were: T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg FYM + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-50-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g phosphate solubilising bacteria (PSB) + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/ plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/ plant. All treatments were arranged in a randomised complete block design (RCBD) and repeated three times.

Timing and technique of application of fertilisers. Two equal portions of fertiliser were applied: in January and February, before fruit set, and in September and October, following fruit harvest. Fertilisers were applied in both years according to treatments. The biofertilisers were applied 2 weeks after the application of inorganic fertilisers. The biofertilisers were mixed with organic manures (FYM/vermicompost) and applied to the rhizosphere soil around the plants at a depth of 30.00 cm below the soil surface. The biofertilisers were obtained from the Nodule Research Laboratory, BCKV. Following each treatment, a light irrigation session was consistently implemented.

Measurement of plant growth parameters. Using a measuring tape, plant height and canopy spread in the E-W and N-S directions were measured both before and after fertiliser treatment. The results were measured in metres and displayed as the percentage enhancement during the course of the study.

Measurement of fruit physical parameters. Using a measuring cylinder and the water displacement method, fruit volume was measured, fruit length and diameter were evaluated via digital slide callipers, fruit and stone weights were measured via an electronic balance, and pulp thickness was assessed via a centimetre scale.

Estimation of fruit biochemical parameters. The total soluble solids (TSS) were assessed via a digital refractometer, and the ascorbic acid level was subsequently determined via Rangana's assay process (Rangana 1977). The total sugar and titratable acidity contents were then calculated via the procedure outlined in A.O.A.C. (1980).

Estimation of the soil nutrient status. With the use of a spade, samples of soil were collected from the surface of each experimental plot (0–20 cm). The samples were then well combined, allowed to air dry in the shade, ground, sieved at a size of 0.2 mm, and then placed in polythene bags for numerous chemical analyses. A calibrated pH meter was used to measure the soil pH (Jackson 1973). The soil organic carbon content was estimated via wet digestion or quick titration procedures (Walkley, Black 1934). The alkaline potassium permanganate procedure was used to measure the amount of nitrogen in the soil (Subbiah, Asija 1956). The phosphorus content was evaluated via extraction (Bray, Kurtz 1945) via a combination of 0.03 M NH_4F and 0.025 M HCl. With the use of a flame photometer, potassium availability in the soil was evaluated via the procedure described by Page et al. (1982), and the available nitrogen, phosphorus and potassium contents were transformed to kg/ha.

Statistical analysis. Panse and Sukhatme's (1985) methodology was utilised to perform the statistical analysis, and a significance level of 0.05% for the *F* test was applied. Post-hoc comparisons among treatment means were performed using Tukey's HSD test at a 5% significance level. The Pearson correlation coefficients between yield and different plant growth parameters, as well as several physical parameters of aonla fruit and numerous

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soil nutrient parameters, as regulated by the use of several nutrient treatments, were determined via R software (version 4.4.2.).

RESULTS AND DISCUSSION

Influence of nutrient management on plant growth characteristics. An analysis of the data revealed that the implementation of multiple nutrient treatments resulted in substantial differences in the percentage increase in plant height and canopy spread in both the E-W direction and the N-S direction (Table 1).

In 2019–2020, the greatest increase in plant height (22.66%) was observed in T_6, followed by T_4 (21.04%), whereas the lowest increase (19.32%) was observed in the control. In 2020–2021, the highest percentage increase (28.55%) was again recorded in T_6, and the lowest percentage increase was recorded in the control. The percentage enhancement in the canopy spread in the E-W direction ranged from 9.99 to 12.34% from 2019–2020 and from 13.87 to 16.65% from 2020–2021. In 2019–2020, the percentage enhancement in the canopy spread in the N-S direction was 8.86–11.25%; in 2020–2021, it was 12.68–15.96%. The plants treated with T_6 performed better in both directions in both years (Table 1). Adequate availability of nitrogen, phosphorus, potassium and other essential elements is responsible for the notable improvement in growth characteristics caused by the use of chemical fertilisers, organic manures and biofertilisers. PSB is vital for making phosphorus (P) a bioavailable form of the necessary nutrient. The release of organic acids as well as enzymes from the implemented PSB

Table 1. Impact of nutrient management on the percent increase in plant height and canopy spread of aonla

Treatment	Increase in plant height		Increase in canopy spread			
			East-West (E-W)		North-South (N-S)	
	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021
T_1	19.32^{f} (26.06)	22.38^{g} (28.22)	9.99^{f} (18.42)	13.87^{e} (21.86)	8.86^{h} (17.31)	12.68^{g} (20.85)
T_2	19.63^{e} (26.29)	22.87^{f} (28.56)	10.15^{f} (18.57)	14.29^{d} (22.20)	9.24^{g} (17.69)	13.23^{f} (21.32)
T_3	19.98^{d} (26.54)	24.16^{e} (29.43)	11.37^{d} (19.70)	15.78^{b} (23.40)	10.16^{d} (18.58)	14.57^{c} (22.43)
T_4	21.04^{b} (27.29)	26.53^{b} (30.99)	11.93^{b} (20.20)	16.12^{b} (23.66)	10.94^{b} (19.31)	15.31^{b} (23.03)
T_5	20.89^{b} (27.19)	26.11^{c} (30.72)	11.01^{e} (19.37)	15.09^{c} (22.85)	9.87^{e} (18.30)	14.15^{d} (22.09)
T_6	22.66^{a} (28.42)	28.55^{a} (32.29)	12.34^{a} (20.56)	16.65^{a} (24.07)	11.25^{a} (19.59)	15.96^{a} (23.54)
T_7	20.19^{cd} (26.69)	25.34^{d} (30.21)	10.85^{e} (19.22)	14.77^{c} (22.59)	9.56^{f} (18.00)	13.76^{e} (21.77)
T_8	20.42^{c} (26.85)	25.51^{d} (30.32)	11.68^{c} (19.98)	15.94^{b} (23.52)	10.53^{c} (18.93)	15.03^{b} (22.80)
S.E.m (±)	0.042	0.047	0.042	0.061	0.056	0.057
CD (0.05)	0.128	0.143	0.129	0.186	0.171	0.174

Data in parentheses are angularly transformed values; T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g phosphate solubilising bacteria (PSB) + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; S.E.m – standard error of the mean; CD – critical difference; within a character positioned in a column, means accompanied by distinct lowercase letter(s) indicate statistically significant differences at 5% probability level (using Tukey's HSD test), whereas means sharing identical lowercase letter(s) demonstrate no statistically significant differences at 5% probability level

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biofertiliser increased P solubilisation, making it easier for crops to assimilate phosphorus. It creates amino acids as well as growth-promoting substances that enable PSB-fertilised plants to develop faster. Furthermore, *Azotobacter* is associated with the production of cytokines, antifungal components and growth-promoting chemicals, all of which may improve nutrient transfer, enhance root formation and increase growth parameters. Nutrient deficiencies for nutrient absorption led to poorer vegetative growth traits under controlled circumstances. Yadav et al. (2007), Mandal et al. (2013) and Kour et al. (2019) reported identical results in aonla.

Influence of nutrient management on fruit physical parameters. The application of different nutrient combinations resulted in notable variations in volume, length and diameter, flesh thickness and stone weight, according to the data regarding the physical properties of the aonla fruit plants shown in Table 2. During 2019–2020, the highest volume of fruit (27.23 mL) was observed in T_6, and the lowest (24.07 mL) was observed in the control. Similarly, from 2020–2021, the highest volume of fruit (31.32 mL) was recorded in T_6, and the lowest (25.70 mL) was recorded in T_1. Fruit length varied between 2.62 and 3.49 cm from 2019–2020 and between 2.77 and 3.78 cm from 2020–21. In T_6, the maximum fruit diameters were 3.51 and 3.85 cm from 2019–2020 and 2020–2021, respectively. The lowest fruit diameters of 2.94 and 2.97 cm in 2019–2020 and 2020–2021, respectively, were observed in the control plants. The flesh thickness varied from 1.09 to 1.56 cm from 2019–2020 and from 1.29 to 1.72 cm from 2020–2021. The highest stone weights (1.90 g and 2.01 g, respectively) were recorded in the plants treated with T_8 from 2019–2020 and 2020–2021, and the lowest weights (1.61 and 1.63 g, respectively) were recorded in T_6 from 2019–2020 and 2020–2021 (Table 2).

The increase in fruit length, diameter and flesh thickness caused by inorganic and organic nutrient management could be responsible for an adequate supply of essential growth hormones (e.g., auxins and cytokinins) and plant nutrients in proper amounts throughout the duration of the crop period, resulting in robust vegetative growth as well as increased photosynthetic production. This may have resulted in increased mobility of photosynthates as a result of the growth hormones that are synthesised as a result of organic nutrition

Table 2. Impact of nutrient management on the volume, length, diameter, flesh thickness and stone weight of aonla fruit

Treatment	Fruit volume (mL)		Fruit length (cm)		Fruit diameter (cm)		Flesh thickness (cm)		Stone weight (g)	
	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021
T_1	24.07^{b}	25.70^{e}	2.62^{f}	2.77^{f}	2.94^{d}	2.97^{e}	1.09^{f}	1.29^{f}	1.78^{abc}	1.80^{bc}
T_2	25.80^{ab}	27.08^{cde}	2.72^{ef}	2.85^{f}	3.00^{d}	3.03^{e}	1.18^{ef}	1.40^{ef}	1.84^{ab}	1.88^{ab}
T_3	26.45^{a}	29.40^{abc}	2.90^{de}	2.98^{ef}	3.16^{bcd}	3.38^{cd}	1.25^{de}	1.47^{de}	1.89^{a}	1.92^{ab}
T_4	27.01^{a}	30.03^{ab}	3.30^{ab}	3.61^{ab}	3.39^{ab}	3.70^{ab}	1.50^{ab}	1.65^{ab}	1.72^{bcd}	1.79^{bc}
T_5	26.27^{a}	29.72^{ab}	3.22^{bc}	3.52^{bc}	3.30^{abc}	3.58^{b}	1.44^{abc}	1.61^{abc}	1.64^{cd}	1.68^{c}
T_6	27.23^{a}	31.32^{a}	3.49^{a}	3.78^{a}	3.51^{a}	3.85^{a}	1.56^{a}	1.72^{a}	1.61^{d}	1.63^{c}
T_7	25.41^{ab}	26.29^{de}	3.04^{cd}	3.16^{de}	3.09^{cd}	3.29^{d}	1.33^{cd}	1.52^{cde}	1.85^{ab}	1.94^{ab}
T_8	26.34^{a}	28.43^{bcd}	3.13^{bc}	3.34^{cd}	3.24^{bc}	3.51^{bc}	1.39^{bc}	1.55^{bcd}	1.90^{a}	2.01^{a}
S.E.m (±)	0.423	0.530	0.043	0.052	0.051	0.042	0.027	0.028	0.032	0.035
CD (0.05)	1.296	1.624	0.132	0.160	0.156	0.128	0.081	0.084	0.097	0.108

T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; S.E.m – standard error of the mean; CD – critical difference; within a character positioned in a column, means accompanied by distinct lowercase letter(s) indicate statistically significant differences at 5% probability level (using Tukey's HSD test), whereas means sharing identical lowercase letter(s) demonstrate no statistically significant differences at 5% probability level

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sources (Sharma et al. 2013). Higher fruit weight due to fertiliser treatment may have improved the internal nutritive state of the plants, resulting in improved vigour and growth linked with photosynthesis, as well as accommodating translocation in fruits. With the induction of growth hormones, *Azotobacter* also promoted better growth and the accumulation of optimal dry matter, which induced cell elongation and cell division; activated photosynthesis; and increased nutrient translocation and energy transformation, resulting in improvements in the length, thickness and volume of fruits. The plant's metabolic processes were increased by the nutrient combinations. It works as a catalyst for the production of more complex compounds and the acceleration of enzyme activity, resulting in an improvement in the fruit's physical characteristics. Singh et al. (2012) also reported identical findings in aonla.

Influence of nutrient management on fruit chemical characteristics. The data in Table 3 clearly demonstrated that the administration of various nutrient combinations resulted in significant changes in the pulp's TSS, total sugar, titratable acidity, ascorbic acid and juice levels. During 2019–2020 and 2020–2021, there were notable differences in the fruit's TSS content between 9.19 and 10.56 °Brix and between 9.35 and 11.05 °Brix, respectively. The T_6 treatment resulted in fruits with minimal acidity contents of 1.56 and 1.45% from 2019–2020 and 2020–2021, respectively (Table 3).

The fruits of the control plants presented maximum acidity contents of 2.19 and 1.91%, respectively. As a result of various nutrient management strategies, fruit pulp ascorbic acid levels fluctuated between 458.54 and 502.31 mg/100 g in 2019–2020 and between 515.74 and 550.41 mg/100 g in 2020–2021. The plants in the T_6 treatment presented the highest total sugar content, with values of 6.02 and 6.50% from 2019–2020 and 2020–2021, respectively. The T_6 treatment caused the maximum juice percentage in both years (45.78% and 52.87% in 2019–2020 and 2020–2021, respectively). The fact that phosphorus enters the composition of phospholipids and nucleic acids, the latter combines with proteins and results in the formation of nucleoproteins, which are important constituents of the nuclei of the cells, may explain why the application of an opti-

Table 3. Impact of inorganic and organic nutrients on the TSS, titratable acidity, ascorbic acid, total sugar and juice contents of aonla fruit

Treatment	TSS (°Brix)		Titratable acidity (%)		Ascorbic acid (mg/ 100 g flesh pulp)		Total sugar (%)		Juice (%)	
	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021
T_1	9.19^{f}	9.35^{e}	2.19^{a}	1.91^{a}	458.54^{f}	515.74^{d}	5.39^{e}	5.49^{c}	42.27^{f}	47.65^{e}
T_2	9.36^{ef}	9.49^{e}	2.05^{ab}	1.85^{ab}	466.33^{ef}	521.23^{cd}	5.48^{de}	5.55^{c}	42.92^{ef}	48.00^{e}
T_3	9.58^{de}	9.73^{de}	1.99^{abc}	1.79^{ab}	474.42^{de}	526.52^{c}	5.57^{d}	5.64^{c}	43.02^{ef}	49.84^{cd}
T_4	10.37^{ab}	10.88^{a}	1.68^{de}	1.57^{de}	499.15^{ab}	545.25^{ab}	5.96^{ab}	6.44^{a}	45.00^{b}	51.75^{b}
T_5	10.00^{c}	10.24^{bc}	1.80^{bcde}	1.69^{bcd}	487.18^{bcd}	540.08^{b}	5.78^{c}	5.87^{b}	43.68^{de}	49.41^{d}
T_6	10.56^{a}	11.05^{a}	1.56^{e}	1.45^{e}	502.31^{a}	550.41^{a}	6.02^{a}	6.50^{a}	45.78^{a}	52.87^{a}
T_7	9.87^{cd}	9.97^{cd}	1.92^{bcd}	1.74^{bc}	484.81^{cd}	537.71^{b}	5.84^{bc}	5.98^{b}	44.89^{bc}	50.54^{c}
T_8	10.06^{bc}	10.65^{ab}	1.74^{cde}	1.60^{cde}	492.66^{abc}	542.76^{ab}	5.90^{abc}	6.04^{b}	44.15^{cd}	50.03^{cd}
S.E.m (±)	0.071	0.097	0.049	0.031	2.684	2.103	0.036	0.046	0.157	0.21
CD (0.05)	0.216	0.297	0.15	0.094	8.219	6.440	0.110	0.140	0.481	0.644

T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; S.E.m – standard error of the mean; CD – critical difference; within a character positioned in a column, means accompanied by distinct lowercase letter(s) indicate statistically significant differences at 5% probability level (using Tukey's HSD test), whereas means sharing identical lowercase letter(s) demonstrate no statistically significant differences at 5% probability level

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Table 4. Influence of nutrient management on the number of fruits/plant, fruit weight and yield of aonla

Treatment	Fruits/plant (No.)		Fruit weight (g)		Yield (kg/ plant)	
	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021
T_1	810^{e}	910^{e}	25.00^{e}	27.62^{c}	20.25^{d}	25.15^{d}
T_2	830^{de}	930^{de}	25.46^{e}	28.00^{bc}	21.14^{d}	26.04^{d}
T_3	860^{cde}	960^{cde}	26.09^{cde}	29.13^{abc}	22.44^{cd}	27.97^{cd}
T_4	950^{ab}	1 080^{ab}	28.15^{ab}	31.06^{ab}	26.74^{ab}	33.54^{ab}
T_5	900^{abcd}	1 010^{bcd}	27.38^{abc}	30.25^{abc}	24.65^{bc}	30.55^{bc}
T_6	980^{a}	1 150^{a}	28.66^{a}	31.74^{a}	28.09^{a}	36.50^{a}
T_7	880^{bcde}	980^{cde}	25.78^{de}	28.87^{abc}	22.72^{cd}	28.29^{cd}
T_8	920^{abc}	1040^{bc}	26.87^{bcd}	29.98^{abc}	24.72^{bc}	31.17^{bc}
S.E.m (±)	13.835	14.139	0.245	0.689	0.520	0.693
CD (0.05)	42.370	43.300	0.750	2.110	1.592	2.123

T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; S.E.m – standard error of the mean; CD – critical difference; within a character positioned in a column, means accompanied by distinct lowercase letter(s) indicate statistically significant differences at 5% probability level (using Tukey's HSD test), whereas means sharing identical lowercase letter(s) demonstrate no statistically significant differences at 5% probability level

mal dose of nutrients improves various chemical characteristics. Aonla performs better than does manure and fertiliser, so biofertilizers aid in the conversion of plant nutrients, speed up soil mineralisation and produce plant growth-promoting compounds such as gibberellic acid, indole acetic acid, cytokinin-like substances, and amino acid and vitamin contents produced by microorganisms. Another reason for the increase in biochemical characteristics could be the enhanced vegetative development of the treated plants, which resulted in higher levels of photosynthates (carbohydrates, starch), which were then transferred to aonla fruits and improved a number of fruit quality parameters. Kour et al. (2019) also reported similar findings.

Influence of nutrient management on the yield characteristics of aonla. The data in Table 4 demonstrated that variations in nutrient management caused considerable variation in the number of fruits collected per plant. At harvest, the T_6 treatment produced the most fruits per plant, with 980 in 2019–2020 and 1 150 in 2020–2021 (Table 4).

The minimal number was recorded under control, with 810 and 910 during 2019–2020 and 2020–2021, respectively. The T_6 treatment resulted in the highest average fruit content of 28.66 g from 2019–2020 and 31.74 g from 2020–2021. The lowest amounts of fruit (25.00 g and 27.62 g) were observed from 2019–2020 and 2020–2021, respectively, under the control. In 2019–2020 and 2020–2021, the yield per plant ranged from 20.25 to 28.09 kg and 25.15 to 36.50 kg, respectively (Table 1). The increase in yield due to the fact that nitrogen is a component of proteins, enzymes and chlorophyll and is involved in all photosynthetic and growth processes, an increase in weight and yield due to nitrogen treatment is clear. The addition of a suitable amount of phosphorus resulted in an increase in weight and yield, probably due to its involvement with several chemical events in the cell and its role in protoplasm formation. As a result, increased vegetative growth resulted in increased carbohydrate assimilation, which may account for the higher yields. Mustafa et al. (2013) and Kour et al. (2019) visualised identical reports in aonla (Table 4).

Influence of nutrient management on the available N, P, K and organic carbon compared to the initial soil conditions. The implementation of numerous fertiliser treatments resulted in considerable variance in the accessible nitrogen, potassium, phosphorus and organic carbon levels of the soil, according to an analysis of the data presented in Table 5. The soil available nitrogen varied between 166.07 and 169.75 kg/ha from 2019–2020 and between 166.11

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Table 5. Influence of nutrient management on the nutrient status of the available nitrogen, phosphorus, potassium and organic carbon contents of soil

Treatment	Available nitrogen		Available phosphorus		Available potassium		Organic carbon (%)	
	(kg/ha)							
	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021	2019–2020	2020–2021
T_1	166.07^{f}	166.11^{g}	20.96^{e}	22.99^{f}	143.32^{h}	146.82^{g}	0.15^{e}	0.16^{e}
T_2	166.67^{e}	166.73^{f}	21.01^{e}	23.28^{e}	143.65^{g}	147.24^{f}	0.17^{de}	0.18^{de}
T_3	166.82^{e}	166.89^{f}	21.09^{e}	23.33^{e}	144.09^{f}	147.89^{e}	0.20^{cde}	0.21^{cde}
T_4	169.24^{b}	169.41^{b}	22.12^{d}	23.41^{e}	145.38^{b}	149.01^{b}	0.24^{abc}	0.26^{abc}
T_5	168.02^{d}	168.10^{e}	22.89^{ab}	24.31^{b}	145.12^{c}	148.88^{b}	0.22^{bcd}	0.24^{bcd}
T_6	169.75^{a}	169.94^{a}	23.04^{a}	24.52^{a}	145.67^{a}	149.45^{a}	0.29^{a}	0.32^{a}
T_7	168.42^{cd}	168.53^{d}	22.49^{c}	23.83^{d}	144.43^{e}	148.35^{d}	0.26^{ab}	0.28^{ab}
T_8	168.75^{c}	168.87^{c}	22.73^{b}	24.09^{c}	144.79^{d}	148.64^{c}	0.27^{ab}	0.30^{ab}
S.E.m (±)	0.093	0.042	0.036	0.041	0.027	0.032	0.012	0.013
C.D. (0.05)	0.284	0.128	0.111	0.126	0.082	0.098	0.036	0.038

T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; S.E.m – standard error of the mean; CD – critical difference; within a character positioned in a column, means accompanied by distinct lowercase letter(s) indicate statistically significant differences at 5% probability level (using Tukey's HSD test), whereas means sharing identical lowercase letter(s) demonstrate no statistically significant differences at 5% probability level

and 169.94 kg/ha from 2020–2021. The plants treated with T_6 throughout the study period presented the highest accessible phosphorus content in the soil (23.04 and 24.52 kg/ha from 2019–2020 and 2020 to 2021, respectively). According to the experimental findings, T_6 had the highest available potassium level in the soil (145.67 and 149.45 kg/ha in 2019–2020 and 2020–2021), whereas T_1 had the lowest available potassium content in both years. The soil organic carbon content varied between 0.15% and 0.29% from 2019–2020 and between 0.16% and 0.32% from 2020–2021. *Azotobacter* fixes an adequate amount of nitrogen in the rhizosphere, thus promoting sufficient nitrogen uptake as well as available nitrogen. The available phosphorus content in postharvest soil increased successively, which may be due to the addition of biofertiliser as well as inorganic sources, because of increased microbial activity. This might be explained by the fact that biofertilisers are known to stimulate plant growth, enhance soil stability, provide biological control, biodegrade materials, recycle nutrients and encourage mycorrhiza symbiosis, which successively increases the available amount of nitrogen, potassium and phosphorus in the soil (del Carmen Rivera-Cruz et al. 2008). The soil organic carbon content increases as a result of litter formation, which increases the organic matter content through the constant input of dead and decomposed roots (Pathak 2003).

Benefit : cost ratio. All of the treatments were assessed for cost and return analysis, and the data were calculated on a per-hectare basis (Table 6). The results are interpreted using the agricultural economics notion of common spending. The costs of the various inputs used in aonla cultivation were calculated independently for each treatment. Total production per ha per treatment was multiplied by the current market price to get the gross returns. The overall cost of cultivation was subtracted from gross returns to arrive at net returns. Similarly, the benefit : cost ratio was determined by dividing net returns by total cultivation costs. Treatment comprising 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant (T8) exhibited the maximum total cost of cultivation ($ 790.60), followed by $ 732.18 obtained under treatment comprising application of 10 kg vermicompost + 400-150-450 g NPK/ plant (T_3). Lowest cost of cultivation ($ 556.79) was recorded under control (T_1). The data further revealed that net returns were

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Table 6. Influence of nutrient management on economics of cultivation of aonla

Treatment	Treatment cost	Common expenditure	Total expenditure	Gross income	Net income	B:C
			(US$)			
T_1	238.34	318.45	556.79	1 993.60	1 437.01	2.59
T_2	261.56	318.45	580.01	2 075.92	1 495.91	2.58
T_3	413.73	318.45	732.18	2 217.60	1 485.42	2.03
T_4	269.26	318.45	587.71	2 652.32	2 064.61	3.51
T_5	265.84	318.45	584.29	2 428.80	1 844.51	3.16
T_6	339.66	318.45	658.11	2 841.52	2 183.41	3.32
T_7	275.99	318.45	594.44	2 244.88	1 650.44	2.78
T_8	472.15	318.45	790.60	2 458.72	1 668.12	2.11

T_1: recommended dose of fertiliser (RDF): 600-300-600 g NPK/plant (control); T_2: 20 kg farmyard manure (FYM) + 400-200-500 g NPK/plant; T_3: 10 kg vermicompost + 400-150-450 g NPK/plant; T_4: 40 g *Azotobacter* + 550-300-600 g NPK/plant; T_5: 50 g PSB + 600-250-600 g NPK/plant; T_6: 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/plant; T_7: 10 kg FYM + 40 g *Azotobacter* + 50 g PSB + 350-150-500 g NPK/plant; T_8: 10 kg vermicompost + 40 g *Azotobacter* + 50 g PSB + 350-100-450 g NPK/plant; conversion calculated at approximately 1 US$ =£90.6; input prices: urea: $ 0.10/kg; SSP: $ 0.13/kg; muriate of potash (MOP): $ 0.22/kg; vermicompost: $0.07/kg; FYM: $ 0.01/kg; *Azotobacter* and PSB: $ 2.21/kg; labour cost: $ 3.62/man day; selling price of aonla: $ 0.22/kg; B:C – benefit:cost ratio

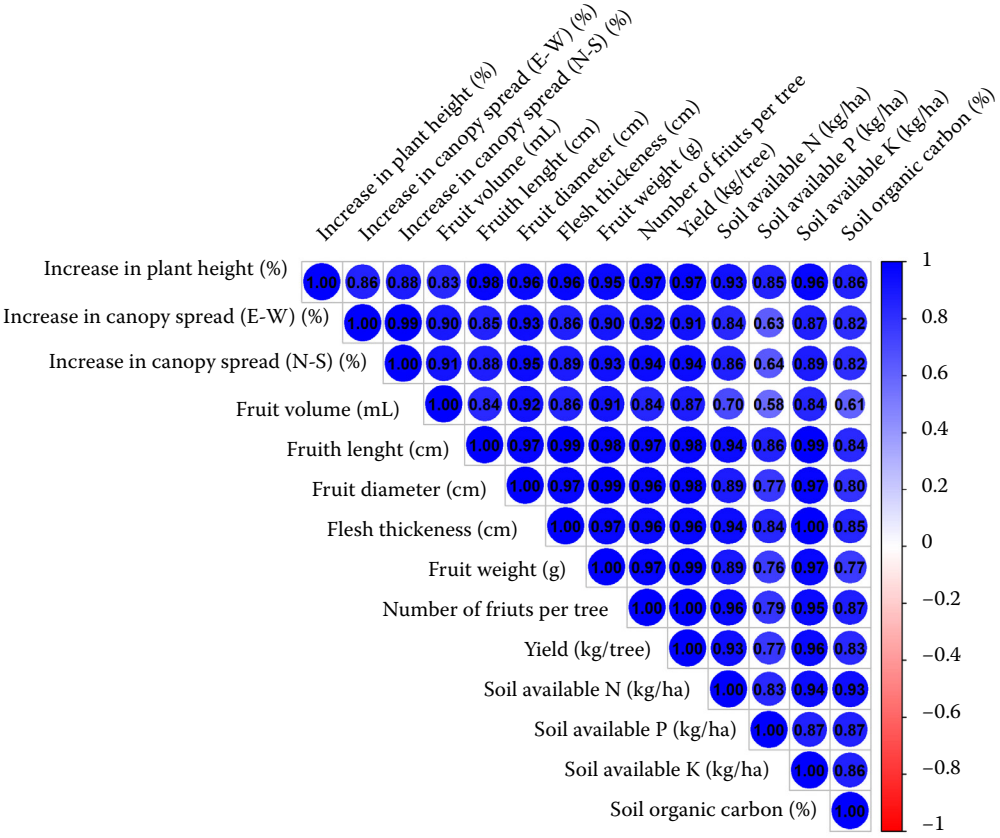

Figure 1. Correlation study between yield and plant growth parameters as well as fruit physical parameters of aonla plants along with soil nutrient parameters

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highest ($ 2183.41) under treatment where plants were applied with 40 g *Azotobacter* + 50 g PSB + 550-250-600 g NPK/ plant (T_6) followed by net returns of $ 2064.61 obtained under treatment T_4 (40 g *Azotobacter* + 550-300-600 g NPK/plant). The maximum benefit-cost ratio of 3.51 was obtained under treatment T_4, followed by the benefit-cost ratios of 3.32 and 3.16 obtained under treatments T_6 and T_5. The lowest benefit-cost ratio of 2.03 was obtained under T_3 (Table 6)

Correlation study between yield and plant growth parameters, as well as fruit physical parameters of aonla fruit, along with soil nutrient parameters. Pearson correlation coefficient analysis was conducted on the data collected from 2020–2021 to examine the relationships between yield and different plant growth parameters as well as several physical parameters of aonla fruit, along with numerous soil nutrient parameters affected by the use of several nutrient treatments (Figure 1).

It is clear from the data illustrated in Figure 1 that a significant positive correlation exists between yield and plant growth parameters such as plant height and canopy spread in the E-W and N-S directions, as well as physical parameters of fruit such as length and diameter, volume, flesh thickness and weight of aonla fruits, along with soil nutrient parameters such as soil available nitrogen, potassium, phosphorus and organic carbon. Plant height was strongly correlated with yield (r = 0.97) and fruit weight (r = 0.95), indicating that overall plant vigour plays a major role in productivity. Similarly, canopy spread demonstrated a substantial positive correlation with fruit weight (r > 0.9), highlighting that wider canopy development increases fruit weight and ultimately yield. The physical parameters of the fruit, such as the volume, length and diameter, presented high intercorrelations (r > 0.9) and were strongly associated with the weight and number of fruits per plant. The substantial positive correlation between fruit weight and yield (r = 0.99) suggests that heavier fruits directly increase yield. Furthermore, the number of fruits per plant was strongly correlated with yield, indicating that fruit quantity is an important determinant of overall yield. Nutrient availability is crucial for promoting plant growth as well as fruit development, as evidenced by the high positive correlation (r > 0.8) found between soil nutrient parameters and yield, especially soil accessible N, P and K. The substantial correlation between soil organic carbon and yield indicates that preserving soil organic matter may be advantageous for long-term sustainability as well as productivity. Therefore, correlation studies have indicated that plant growth parameters, fruit physical parameters and soil nutrient parameters contribute to the yield of aonla fruit. This positive correlation between yield and plant growth parameters, as well as the physical parameters of aonla fruit affected by several nutrient treatments, was observed in the investigations of Kour et al. (2019). A positive correlation between yield and soil nutrient parameters, as affected by the use of several nutrient treatments, was observed in an investigation by del Carmen Rivera-Cruz et al. (2008).

CONCLUSION

In the present study, various nutritional sources, *i.e.*, 600-300-600 g NPK (RDF), FYM, vermicompost, *Azotobacter* and PSB inoculants (40 and 50 g each), were provided to the plants; on the other hand, the control plants did not receive any inoculation or organic treatment. Compared with those of the control, the plant growth parameters, physicochemical characteristics of the fruits, yield parameters and soil nutrient status were substantially impacted by the inorganic and organic nutrient treatments. Finally, the aonla (cv. 'NA-7') orchards in Sekhampur, Birbhum, West Bengal, India, benefit from the application of 40 g *Azotobacter* and 50 g PSB along with NPK @ 550-250-600 g per plant, which improves the soil nutrient status and increases fruit quality and yield.

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