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Research article

Response of aonla-based horti-pastoral systems to foliar application of micronutrients

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Abstract

A field experiment was conducted in a ten-year-old aonla (*Emblica officinalis* Gaertn.) based horti-pastoral system under semi-arid conditions to evaluate the effect of foliar application of boron and zinc on tree growth, fruit yield and quality, pasture productivity, and biomass carbon sequestration. Foliar sprays were applied twice annually, at flowering and after fruit set, for five consecutive years (2018-2023). Micronutrient application significantly improved growth parameters, fruit retention, yield, and fruit quality of aonla trees. Among the treatments, the combined application of borax @ 0.5% + $ZnSO_4$ @ 0.25% consistently recorded superior performance, resulting in the highest fruit yield and improved quality attributes. Pasture yield and quality were not significantly influenced by micronutrient application to trees. Biomass carbon stock at the system level was enhanced under micronutrient treatments, indicating that targeted foliar nutrition is an effective strategy for improving productivity and carbon sequestration in mature Aonla-based horti-pastoral systems under semi-arid agro-climatic conditions.

Keywords: Aonla, Carbon storage potential, Foliar application, Fruit yield, Hortipastoral system, Micronutrients

Introduction

Hortipastoral systems, which integrate fruit trees with pasture crops, have been recognized as sustainable land-use models, particularly in rainfed regions. These systems provide multiple benefits, viz. diversified farm income, enhanced soil fertility, enhanced biodiversity, soil and water conservation, and carbon sequestration (Jinger *et al*., 2024; Ghasal *et al*., 2024). The integration of fruit-bearing trees like aonla (*Emblica officinalis* Gaertn.) with pasture crops not only improves land-use efficiency but also contributes to long-term ecological and economic sustainability (Malik *et al*., 2021). The presence of deep-rooted perennial species enhances water infiltration and retention, making these systems suitable for drought-prone areas. Moreover, the coexistence of trees and pasture crops fosters biodiversity, supporting pollinators, beneficial insects, and soil microbes. Economically, these systems offer stability by diversifying farm income through both fruit and fodder production, thereby providing financial resilience against market and climate fluctuations. Despite these advantages, the long-term sustainability of horti-pastoral systems hinges on effective nutrient management (Kumar *et al*., 2020). As trees age, their ability to absorb and utilize soil nutrients diminishes and intensive crop (tree and pasture) cultivation also leads to rapid removal of micronutrients from soils, necessitating external supplementation through targeted interventions like foliar sprays of essential micronutrients. As a result, old (10 years) established Aonla trees in hortipasture showed deficiency symptoms of boron and zinc by visual observation, like necrosis, fruit cracking and declining trend of yield as well as quality of fruits. Thus, a sufficient supply of micronutrients is important for optimal plant development, better blooming and higher fruit set, leading to higher yield (Ram and Bose, 2000; Shekhar *et al*., 2010; El-Motaium *et al*., 2024). Significant improvement in fruit quality because of the catalytic impact of micronutrients, especially when they are present in higher concentrations, ensuring fruit quality and productivity, particularly the micronutrients zinc and

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boron, are crucial in orchard plant nutrition programmes. Zinc and boron significantly play role in nitrogen metabolism; synthesis of tryptophan a prerequisite for auxin synthesis; enhancing photosynthetic capacity; essential hormone transport as well as cell division thus their application can significantly enhance the fruit set, fruit retention, fruit yield as well as physico-chemical characteristics (Babu and Singh, 2001; Kumar and Shukla, 2016, Chawala and Sharma, 2025). Since very scanty information is available regarding micro-nutrient management of aonla-based Hortipastoral system in a grown-up established system, particularly under rain-fed conditions of central India. In the context of mature Aonla orchards, deficiencies of key micronutrients like boron (B) and zinc (Zn) can have detrimental effects on tree health and productivity (Tripathi and Nand, 2022). Addressing these deficiencies through foliar application ensures rapid nutrient uptake and immediate physiological response, thereby improving overall orchard performance.

Several studies have demonstrated the efficacy of micronutrient foliar applications in enhancing fruit set, fruit yield and quality in fruit trees, including aonla, mango, and cashew. Singh *et al.* (2007) and Tripathi *et al.* (2023) have also reported that foliar application of 0.5% $ZnSO_4$ combined with 10 ppm NAA and 25 ppm GA_3 significantly improved fruit size, weight, and biochemical composition in aonla cv. NA-10. Similarly, other research studies have highlighted the role of micronutrient applications in enhancing shoot growth, fruit set, and yield across various fruit crops. Given the above considerations, the current research was conducted with an aim to rejuvenate the existing aonla-based hortipasture system by implementing targeted foliar applications of boron and zinc. The specific objectives of the present study were to: (i) evaluate the effect of foliar application of boron and zinc on growth, fruit yield and quality of mature aonla trees; (ii) assess the influence of micronutrient application on pasture yield and quality under an aonla-based hortipastoral system; and (iii) quantify the impact of micronutrient management on biomass carbon sequestration at the system level under semi-arid conditions. A comprehensive evaluation of foliar interventions presents a crucial opportunity to develop effective micronutrient management strategies for mature orchard rejuvenation. Given the increasing interest in sustainable fruit production systems, the findings of this study are expected to have far-reaching implications, aiding in the expansion and refinement of hortipastoral models across diverse agro-climatic zones. Through improved micronutrient supplementation, this research aspires to enhance orchard resilience, optimize yield potential, and ensure long-term sustainability of aonla-based hortipastoral systems.

Materials and Methods

Description of study location: The trial was established in 2007 at the Central Research Farm of ICAR-IGFRI (25°26′08″N, 78°30′21″E, 216 m AMSL) in the Bundelkhand region, which is characterized by a semi-arid climate with frequent droughts, poor soil fertility, and high climatic variability (Fig 1).

Weather and soil characteristics: During the study period, the average annual maximum temperature ranged from 32 to 33°C, while the average annual minimum temperature varied between 20 and 21°C. The mean relative humidity was recorded at 47–54%. Geologically, the region is composed of gneissic and granitic rock formations, featuring gneiss beds and igneous intrusions. The soil at the experimental site is clay loam, classified under the Typic Haplustepts hypothermic family. These soils are dark brown, shallow, and well-drained but possess low moisture retention and nutrient-holding capacity. Additionally, poor soil aggregation, low soil organic carbon (SOC) content, and minimal microbial activity further limit soil fertility. These constraints, coupled with limited moisture availability, present significant challenges for agriculture in this region.

Experimental setup and crop management: In a 10-year-old aonla (cv. NA-7) orchard, four uniform trees per treatment were selected for foliar application of micronutrients. The experiment included five treatment combinations: T_1 (Borax 0.25% + $ZnSO_4$ 0.25%), T_2 (Borax 0.25% + $ZnSO_4$ 0.5%), T_3 (Borax 0.5% + $ZnSO_4$ 0.25%), T_4 (Borax 0.5% + $ZnSO_4$ 0.5%), and T_5 (Control- Water spray). Foliar sprays were applied twice: at flowering and after fruit set (1st Week of April and 1st week of September). The experiment followed a randomized block design (RBD) with four replications, selecting a total of 80 trees from the orchard. Four trees per treatment were assessed for plant growth, reproductive parameters, and yield attributes. Additionally, five fruits were randomly sampled from each treatment to evaluate

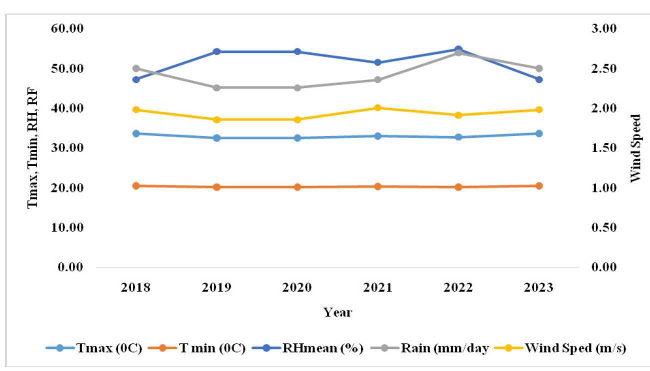

Fig 1. Meteorological data of the experimental site during the period of experimentation from 2018 to 2023

physicochemical characteristics. The same set of mature Aonla trees was maintained and evaluated throughout the five-year experimental period to ensure consistency of observations.

***Description about the aonla orchard*:** A 10-year-old aonla-based hortipastoral system was established using grafted aonla (*Emblica officinalis* Gaertn.) cv. NA-7, planted during August 2007 at a spacing of 8 × 8 m. The saplings were planted in 1 m^3 pits filled with a mixture of soil, 30 kg farmyard manure (FYM), and a recommended termiticide to ensure healthy root establishment. To utilize interspaces effectively, a pasture combination of *Cenchrus ciliaris* and *Stylosanthes seabrana* was introduced as an understorey intercrop. In 2007, *S. seabrana* was sown in rows spaced 50 cm apart at a seed rate of 4 kg/ha, ensuring that one row of *S. seabrana* was positioned between two rows of *C. ciliaris* under aonla trees. The following year, in July 2008, *C. ciliaris* seedlings were transplanted at a spacing of 100 cm (row-to-row) and 50 cm (plant-to-plant). Nutrient management practices were carefully implemented to support both pasture growth and aonla tree development. For pasture, nitrogen was applied in two split doses at monthly intervals during the rainy season through broadcasting, while 20 kg phosphorus (P) and 30 kg potassium (K) per hectare were applied as basal fertilizers. Aonla trees received 10 kg of FYM, 100 g of nitrogen (N), 50 g of phosphorus (P), and 100 g of potassium (K) per plant during the first year, with the dose gradually increasing each year until the trees reached eight years of age. From the eighth year onwards, each aonla tree was supplied with 80 kg FYM, 800 g N, 400 g P, and 800 g K annually, with nitrogen applied in two split doses, one in mid-July and another in mid-September, to enhance nutrient uptake and utilization. These management practices ensured sustainable growth, improved soil fertility, and optimized pasture utilization within the aonla-based hortipastoral system. The schematic representation of the aonla-based hortipasture system is shown in Fig 2.

Observations on tree growth and fruit traits: Tree height, collar diameter, and canopy spread were measured using a measuring tape and digital callipers in the month of 2nd week of November in each consecutive year of experiments (2018-2023). Fruit drop and fruit retention were recorded by counting the number of fruits retained and shed from tagged branches at different developmental stages at weekly intervals. Fruit yield was determined on a per-tree basis (kg/tree) and Mg/ha basis by harvesting mature fruits/tree and weighing them using a digital balance. Fruit length and width were measured using Vernier callipers, while fruit weight was recorded using an electronic weighing scale. Dry matter content was estimated by oven-drying fruit samples at 70°C until a constant weight was achieved. Ascorbic acid content was quantified using the 2, 6-dichlorophenol-indophenol (DCPIP) titration method. Fruit quality analysis was carried out using randomly selected representative fruit samples per treatment, following standard horticultural quality assessment protocols. Fruit samples of 20 to 30 fruits per tree were randomly collected from different canopy positions and from five trees per treatment. This sample size ensures representative and statistically reliable estimates for fruit quality parameters such as ascorbic acid content, total soluble solids, and fruit weight.

***Yield and quality attributes of pasture*:** Fresh pasture yield from each plot was recorded immediately after harvesting pasture biomass during the growing season from a 1 × 1 m quadrat. Dry weight was recorded randomly by selecting five plants from each plot, followed by drying at 80 ± 5°C for 24 hours until constant weight was achieved. From this value, dry matter yield in Mg/ha was calculated. The nitrogen content of the whole plant was estimated by the modified micro kjeldhal method (Banerjee, 1978) and expressed in percentage. The crude protein (CP) content of forage was worked out by multiplying the nitrogen percentage by 6.25 (Doubetz and Wells, 1968). The NDF and ADF contents were estimated through a reflux apparatus using fibre bags and neutral detergent and acid detergent solutions (AOAC, 2005).

Biomass carbon stock potential: Biomass carbon stock of the aonla trees under each treatment was calculated

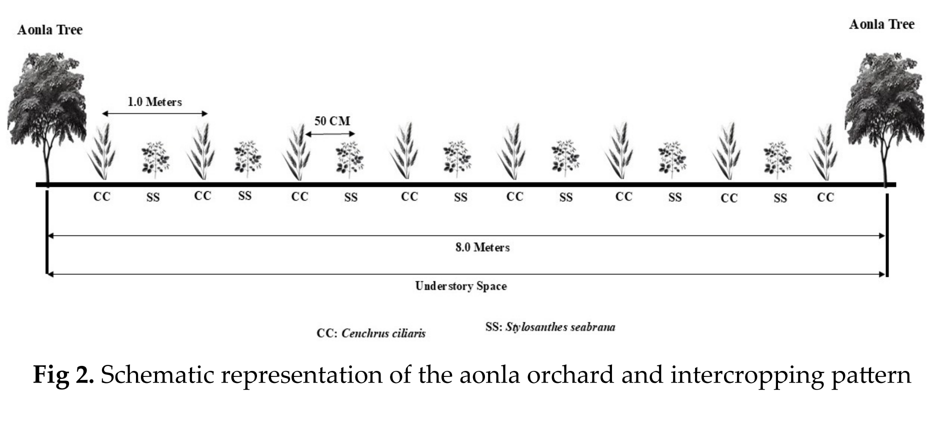

Fig 2. Schematic representation of the aonla orchard and intercropping pattern

for the various parts of the tree, viz., bole, branches, leaves, fruits and roots using allometric equations based on the collar diameter of trees and carbon content given as per Rathore *et al.* (2018). Total biomass carbon stock of the aonla trees under each treatment was calculated by adding the bole, branches, leaves, fruits and roots carbon stock. The biomass carbon stock was calculated on a per-hectare basis (Mg C ha^{-1}) based on the number of stems per hectare. Biomass carbon stock was estimated using standard allometric equations for woody perennials, and carbon content was calculated by applying a carbon fraction of 0.45, as commonly adopted in agroforestry and perennial horticultural systems. System-level carbon stock was computed by summing above-ground biomass carbon of aonla trees and associated pasture biomass, providing a comprehensive estimate of carbon sequestration under the horti-pastoral system. In the case of pasture, the total biomass carbon stock was calculated by adding the above and below-ground biomass carbon stocks. The above-ground carbon stock of pasture was calculated by multiplying per hectare dry biomass of pasture by 0.5 (IPCC, 2006). The total below-ground dry biomass of grasses was determined from their root shoot ratio and below-ground carbon stock by multiplying dry biomass per hectare by 0.5. Thereafter, the total biomass carbon stock potential of the hortipasture system was calculated by adding the total biomass carbon stock of trees and the pasture component.

Statistical analysis: The data recorded on various growth and yield parameters were subjected to analysis of variance as detailed by Gomez and Gomez (1984). Statistical analysis of pooled data was performed using standard statistical software. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% level of significance.

Results and Discussion

Growth attributes of aonla tree: Growth parameters of aonla trees, including tree height, collar diameter, and canopy spread, were significantly influenced by foliar application of boron and zinc in the aonla-based hortipastoral system (Table 1). Micronutrient application markedly improved tree growth compared to the control, highlighting the importance of boron and zinc in sustaining vegetative development of mature aonla orchards. Among the treatments, the combined application of borax and zinc sulphate resulted in superior growth performance. Treatments receiving higher boron levels along with moderate zinc exhibited greater improvement in tree height, collar diameter, and canopy spread, indicating a synergistic effect of these micronutrients. Boron plays a critical role in cell division, cell elongation, and meristematic activity, which directly influence shoot growth and canopy expansion (Abhijith *et al.*, 2017). Zinc contributes to enzyme activation, protein synthesis, and auxin metabolism, thereby enhancing overall tree vigor and trunk girth development (Singh *et al.*, 2023). Tree canopy development followed a similar trend, with micronutrient-treated trees exhibiting wider canopy spread than the control. Enhanced canopy expansion under foliar application of boron and zinc reflects improved lateral branching and leaf development, which are essential for efficient light interception and higher fruit-bearing potential (Kumar *et al.*, 2009). In contrast, reduced growth in the control treatment highlights the adverse effects of micronutrient deficiency on tree architecture. The observed improvements in growth attributes are consistent with earlier studies reporting the beneficial role of boron in cell division and reproductive tissue development, and zinc in improving photosynthetic efficiency and carbohydrate metabolism in perennial fruit crops (Saroj and Jatav, 2021). Overall, the results demonstrate that combined foliar application of borax @ 0.5% with $ZnSO_4$ @ 0.25% is the most effective treatment for promoting vegetative growth of mature aonla trees under horti-pastoral systems.

Fruit drop, fruit retention and fruit yield: Foliar application of boron and zinc significantly influenced fruit drop, fruit retention, and fruit yield of aonla

Table 1. Height, collar diameter and canopy spread of aonla trees as influenced by foliar application of micronutrients under aonla based hortipasture system

Treatment	Treatment details	Tree height (m)	Tree CD (cm)	Tree CP (m)
T_1	Borax @ 0.25% + Zn SO_4 @ 0.25%	5.8^{ab}	20.02^{bc}	5.7^{c}
T_2	Borax @0.25% + Zn SO_4@ 0.5%	5.8^{ab}	21.09^{ab}	6.0^{bc}
T_3	Borax @ 0.5% + Zn SO_4 @ 0.25%	6.2^{a}	21.35^{a}	6.8^{a}
T_4	Borax @ 0.5% + Zn SO_4@ 0.5%	6.2^{a}	20.83^{ab}	6.6^{ab}
T_5	Water spray	5.3^{b}	19.24^{c}	5.4^{c}
	S.Em±	0.27	0.51	0.23

CD: Collar diameter; CP: Canopy spread; *Values followed by the same letter(s) within a column indicate no significant difference according to Duncan's Multiple Range Test (p <0.05) under the horti-pastoral system (Table 2). Micronutrient supplementation effectively reduced fruit drop and enhanced fruit retention compared to the control, resulting in improved fruit yield at both tree and hectare levels. Fruit drop was considerably lower in micronutrient-treated trees, with the minimum fruit drop recorded under the combined application of borax and zinc sulphate. Treatments T_4 (Borax @ 0.5% + $ZnSO_4$ @ 0.5%) and T_3 (Borax @ 0.5% + $ZnSO_4$ @ 0.25%) recorded fruit drop values of about 72-73%, whereas the control treatment showed substantially higher fruit drop (83.35%). Reduced fruit drop under micronutrient application may be attributed to the role of boron and zinc in improving pollen viability, fruit set, and strengthening the fruit pedicel, thereby reducing premature fruit abscission. Correspondingly, fruit retention was significantly enhanced by foliar application of micronutrients. The highest fruit retention (22.17%) was observed in T_3, followed by T_4 (21.81%), while the control recorded the lowest retention (16.85%). Improved fruit retention can be attributed to enhanced auxin synthesis, better pollen tube growth, and improved assimilate translocation under adequate boron and zinc availability, which collectively strengthen fruit attachment to the tree (Abhijith *et al.*, 2017). Improved fruit retention translated into significantly higher fruit yield. The combined application of borax @ 0.5% and $ZnSO_4$ @ 0.25% (T3) produced the highest fruit yield (81.2 kg tree^{-1} and 12.7 Mg ha^{-1}), followed by T4, whereas the control recorded markedly lower yield (59.1 kg tree^{-1} and 9.2 Mg ha^{-1}). The increase in fruit yield under micronutrient treatments can be attributed to improved physiological efficiency, reduced fruit drop, and enhanced metabolic activity regulated by boron and zinc (Bhandari *et al.*, 2014). The findings indicate that foliar application of boron and zinc effectively reduces fruit drop, enhances fruit retention, and improves fruit yield in mature aonla trees. Among the treatments, combined application of borax @ 0.5% with $ZnSO_4$ @ 0.25% proved to be the most effective nutrient management practice under the aonla-based horti-pastoral system.

Fruit length, fruit width, fruit weight, fruit dry matter, and ascorbic acid content: The results indicate that foliar supplementation of boron and zinc had a significant impact on fruit length, fruit width, fruit weight, fruit dry matter, and ascorbic acid content in aonla (Table 3). The highest fruit length (2.722 cm) and fruit width (2.710 cm) were recorded in T_3 (Borax @ 0.5% + $ZnSO_4$ @ 0.25%), followed by T_2 and T_4, whereas the

Table 2. Fruit drop, fruit retention and fruit yield of aonla trees as influenced by foliar application of micronutrients under aonla based hortipasture system

Treatment	Fruit drop (%)	Fruit retention (%)	Fruit yield (kg/tree)	Fruit yield (t/ha)
T_1	75.80^{b}	18.95^{c}	65.70^{c}	10.20^{bc}
T_2	76.45^{b}	20.61^{b}	72.38^{b}	11.40^{ab}
T_3	73.26^{c}	22.18^{a}	81.20^{a}	12.70^{a}
T_4	72.06^{c}	21.81^{ab}	78.40^{a}	12.20^{a}
T_5	83.35^{a}	16.86^{d}	59.10^{d}	9.20^{c}
S.Em±	0.62	0.61	3.69	0.72

*Values followed by the same letter(s) within a column indicate no significant difference according to Duncan's Multiple Range Test (p <0.05); **Please see table 1 for treatment details

Table 3. Fruit length, fruit width, fruit weight, fruit dry matter and ascorbic acid content of aonla as influenced by foliar application of micronutrients under aonla based hortipasture system

Treatment	Fruit length (cm)	Fruit width (cm)	Fruit weight (g)	Fruit dry matter (%)	Ascorbic acid (mg/100 g fresh pulp)
T_1	2.51^{a}	2.40^{ab}	39.29^{c}	13.04^{a}	961^{d}
T_2	2.64^{a}	2.57^{ab}	39.80^{c}	13.07^{a}	974^{c}
T_3	2.72^{a}	2.71^{a}	44.34^{a}	13.33^{a}	1029^{b}
T_4	2.63^{a}	2.55^{ab}	41.59^{b}	12.62^{a}	1090^{a}
T_5	2.31^{a}	2.18^{b}	35.96^{d}	13.16^{a}	879^{e}
S.Em±	0.09	0.07	0.88	0.33	44.87

*Values followed by the same letter(s) within a column indicate no significant difference according to Duncan's Multiple Range Test (p <0.05); **Please see table 1 for treatment details smallest fruits were observed in the control (T_5) with 2.31 cm length and 2.18 cm width. The improvement in fruit size due to Boron and Zinc application can be attributed to their role in cell elongation, division, and overall fruit development. A similar trend was observed for fruit weight, where the highest value (44.35 g) was recorded in T_3, followed by T_4 (41.589 g), while the lowest fruit weight (35.96 g) was observed in the control (T_5). The increased fruit weight in micronutrient-treated trees may be due to improved nutrient translocation, enhanced carbohydrate metabolism, and better physiological efficiency of the plant.

Fruit dry matter content did not show a significant variation among treatments, although slight differences were recorded. The highest dry matter content (13.33%) was observed in T_3, followed closely by T_5 (13.16%), while the lowest (12.62%) was recorded in T_4. The relatively stable dry matter content suggests that micronutrient supplementation primarily influences fruit size and weight rather than altering the proportion of dry matter in the fruit.

Ascorbic acid content, a key quality parameter in aonla, was significantly influenced by micronutrient application. The highest ascorbic acid content (1090.78 mg/100 g) was recorded in T_4 (Borax @ 0.5% + $ZnSO_4$ @ 0.5%), followed by T_3 (1029.70 mg/100 g), while the lowest content (879.50 mg/100 g) was recorded in T_5. The increased ascorbic acid content in treated trees indicates the role of boron and zinc in enhancing biochemical processes responsible for vitamin C synthesis. The positive effect of foliar micronutrient application on fruit quality parameters suggests that these nutrients play a vital role in improving both the nutritional and commercial value of aonla. Among the treatments, T_3 (Borax @ 0.5% + $ZnSO_4$ @ 0.25%) was found to be most effective in improving fruit size and weight, while T_4 showed the highest ascorbic acid content.

Fodder yield and quality: Pasture yield and quality were not significantly affected by micronutrient application to the tree component. This suggests that foliar application of boron and zinc to aonla trees did not exert competitive or adverse effects on the associated pasture. Maintenance of pasture productivity alongside improved tree performance highlights the compatibility of micronutrient management with the horti-pastoral system (Table 4). The numerically highest dry fodder yield (5.64 Mg/ha) was observed in T_1 (Borax @ 0.25% + $ZnSO_4$ @ 0.25%), followed closely by T_3 (5.52 Mg/ha) and T_4 (5.54 Mg/ha). The lowest yield (5.08 Mg/ha) was recorded in T_2 (Borax @ 0.25% + $ZnSO_4$ @ 0.5%), which was even lower than the control treatment (T_5: 5.26 Mg/ha). Crude protein content, a crucial determinant of forage quality, showed an increasing trend with micronutrient supplementation on trees. The highest crude protein content (13.10%) in pasture biomass was recorded in T_4 (Borax @ 0.5% + $ZnSO_4$ @ 0.5%), followed by T_3 (13.05%) and T_2 (13.01%), whereas the lowest crude protein content (12.85%) was recorded in the control (T_5). The increase in crude protein percentage was attributed to enhanced tree attributes like canopy, which will provide shade to the understory and improve nitrogen metabolism and protein synthesis, which is otherwise impacted by harsh climates in semi-arid regions (Gutmanis *et al.*, 2001; Ghosh *et al.*, 2021). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) content, which are important indicators of fodder digestibility, exhibited variations across the treatments. The highest NDF content (59.51%) was recorded in T_4, the lowest NDF (56.00%) was observed in the control (T_5), while ADF values ranged from 36.71% (T2) to 37.31% (T_5). Higher NDF content generally reduces voluntary intake in ruminants, whereas lower ADF values indicate improved digestibility. The slight increase in NDF suggests structural enhancement of plant cell walls, which may be beneficial for plant resilience but could slightly reduce palatability (Patidar *et al.*, 2023; Rather *et al.*, 2025). However, the relatively stable ADF values indicate that digestibility was not significantly compromised, ensuring that the fodder remained nutritionally rich.

Table 4. Dry fodder yield and quality of grasses (understorey grass *i.e. Cenchrus ciliaris* and legume *i.e. Stylosanthes seabrana* in the ratio of 1:1) as influenced by foliar application of micronutrients under aonla based hortipasture system

Treatment	Dry fodder yield (t/ha)	Crude protein (%)	NDF	ADF
T_1	5.64^{a}	12.91^{a}	57.91^{b}	36.88^{a}
T_2	5.08^{a}	13.01^{a}	58.65^{ab}	36.71^{a}
T_3	5.52^{a}	13.05^{a}	58.71^{ab}	36.98^{a}
T_4	5.54^{a}	13.10^{a}	59.51^{a}	37.01^{a}
T_5	5.26^{a}	12.85^{a}	56.00^{c}	37.31^{a}
S.Em±	0.15	0.07	0.35	0.41

*Values followed by the same letter(s) within a column indicate no significant difference according to Duncan's Multiple Range Test (P<0.05); **Please see table 1 for treatment details

Table 5. Carbon storage (Mg/ha) in different parts aonla trees, pasture and system as influenced by foliar application of micronutrients under aonla based hortipasture system

Treatment	Aonla						Pasture	Aonla + Pasture
	Bole	Branches	Leaves	Fruits	Roots	Total	Above and below ground	System C stock
T_1	1.99	5.75	1.53	0.79	2.62	12.68	4.26	16.94
T_2	2.20	6.04	1.66	0.90	2.80	13.60	4.25	17.85
T_3	2.24	6.09	1.68	1.00	2.83	13.84	4.12	17.96
T_4	2.15	5.96	1.63	0.97	2.76	13.47	4.06	17.52
T_5	1.78	5.47	1.41	0.72	2.44	11.82	4.25	16.07
S.Em±	0.09	0.12	0.06	0.45	0.08	0.57	0.39	0.74

**Please see table 1 for treatment details

Carbon storage (Mg/ha) in different parts of aonla and pasture: The results indicate that foliar application of boron and zinc significantly influenced carbon storage in aonla trees and the associated pasture under the hortipasture system. The highest total carbon storage in Aonla trees was recorded in T_3 (13.84 Mg/ha), followed by T_2 (13.60 Mg/ha) and T_4 (13.45 Mg/ha), while the lowest (12.68 Mg/ha) was observed in T_1 (Table 5). The control (T_5: Water Spray) exhibited a slightly higher value (12.82 Mg/ha) than T_1, possibly due to a greater allocation of biomass to fruit production rather than structural growth. The increased carbon storage in Aonla trees under micronutrient treatments can be attributed to enhanced physiological activity, improved biomass accumulation, and increased efficiency of carbon assimilation, which are promoted by the synergistic effects of zinc and boron (Raj and Jhariya, 2023). Among the tree components, branches accounted for the highest carbon stock, with values ranging from 5.47 Mg/ha (T_5) to 6.09 Mg/ha (T_3). This suggests that micronutrient application improved vegetative growth, leading to better canopy development and greater carbon sequestration. Bole carbon storage was also highest in T_3 (2.24 Mg/ha), indicating increased secondary growth and long-term carbon accumulation in woody biomass. Root carbon storage followed a similar pattern, with T_3 (2.83 Mg/ha) showing the highest values, highlighting the role of zinc and boron in root development, which enhances nutrient and water uptake (Tanwar *et al.*, 2019; Mohanasundari *et al.*, 2025). Fruit carbon storage exhibited notable variation across treatments, with T_3 recording the highest value (1.00 Mg/ha) and T_5 the lowest (0.72 Mg/ha). The contribution of the pasture component to total system carbon storage was also significant. The highest pasture carbon storage was recorded in T_1 (4.26 Mg/ha), followed closely by T_5 (4.25 Mg/ha) and T_2 (4.25 Mg/ha), while the lowest was in T4 (4.06 Mg/ha). Despite variations in pasture biomass, the total system carbon stock (Aonla + pasture) was highest in T_3 (17.96 Mg/ha), followed by T_2 (17.85 Mg/ha) and T_4 (17.52 Mg/ha). The lowest system carbon stock was observed in T5 (16.07 Mg/ha), indicating that the combination of boron and zinc at higher concentrations contributed to better carbon sequestration at the system level (Shekara *et al.*, 2025; Paramesh *et al.*, 2025).

The improved carbon storage in micronutrient-treated plots aligns with previous studies indicating that zinc plays a critical role in carbohydrate metabolism, enzyme activation, and auxin biosynthesis, which contribute to plant growth and biomass accumulation (Baradwal *et al.*, 2023). Similarly, boron is essential for cell wall synthesis, lignification, and enhanced photosynthetic efficiency, which positively impact structural biomass and carbon sequestration (Baradwal *et al.*, 2022). The presence of a pasture component further enhances soil organic carbon storage and improves ecosystem stability, making the hortipasture system a sustainable land-use model for carbon sequestration (Ghosh *et al.*, 2020). The results of this study are particularly relevant for semi-arid agro-climatic regions, such as the Bundelkhand region, characterized by low rainfall and nutrient-limited soils. The observed improvements in growth, fruit yield, and quality under foliar application of boron and zinc indicate that targeted micronutrient management can effectively address common nutrient deficiencies in such conditions. These findings are consistent with other studies in semi-arid perennial horticultural systems, demonstrating enhanced tree performance and fruit quality. While these results are directly applicable to similar mature Aonla orchards, caution should be exercised when extrapolating to regions with markedly different soil fertility, rainfall patterns, or tree age.

Conclusion

The results clearly indicate that foliar application of boron and zinc significantly enhances growth, fruit yield, fruit quality and biomass carbon sequestration in mature aonla-based hortipastoral systems. Among the treatments, borax @ 0.5% combined with $ZnSO_4$ @ 0.25% proved most effective, consistently improving fruit retention, yield and system-level carbon stock without adversely affecting pasture productivity. These findings suggest that targeted foliar micronutrient management is a practical and sustainable strategy for rejuvenating grown-up Aonla-based hortipastoral systems in semi-arid regions.

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