

# Performance and Productivity of Ocimum species under an Aonla-based Agroforestry System in the Submontane low hill zone of the North-Western Himalaya

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## Research Article

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**Performance and Productivity of *Ocimum* species under an Aonla-based Agroforestry System in the Submontane low hill zone of the North-Western Himalaya**

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**Abstract**

The present investigation, entitled “Performance and Productivity of *Ocimum* species under an Aonla-based Agroforestry System in the Submontane low hill zone of the North-Western Himalaya” was carried out from 2024 to 2025 under subtropical conditions at the Regional Horticultural Research and Training Station, Jachh, Kangra, Himachal Pradesh. The study evaluated the effects of different nutrient sources (NPK, farmyard manure (FYM), and vermicompost) and tree-crop interactions on the growth, biological yield, essential oil yield, and soil physico-chemical properties of three *Ocimum* species under an Aonla-based agroforestry system. The trial was arranged in a Randomized Block Design (RBD) featuring twelve distinct treatment combinations comprising three *Ocimum* species (*Ocimum sanctum*, *Ocimum basilicum*, and *Ocimum tenuiflorum*) and four nutrient treatments, replicated thrice. Vermicompost application (10 t ha<sup>-1</sup>) significantly enhanced growth and yield over the control. *Ocimum basilicum* (Bhabri tulsi) recorded the highest plant height (89.93 cm), number of leaves (700.43 plant<sup>-1</sup>), and biological yield (16 q ha<sup>-1</sup>), while *Ocimum tenuiflorum* (Shyam tulsi) exhibited the highest chlorophyll content at 60 and 90 days after transplanting. The maximum essential oil yield (9.06 kg ha<sup>-1</sup>) was obtained from *Ocimum sanctum* (Ram tulsi). Soil pH, and electrical conductivity remained unaffected, whereas organic carbon and available nitrogen, phosphorus, and potassium increased significantly. The highest available nitrogen (324.76 kg ha<sup>-1</sup>), phosphorus (26.58 kg ha<sup>-1</sup>), and potassium (252.44 kg ha<sup>-1</sup>) were recorded under the Aonla + vermicompost + Bhabri tulsi treatment. Vermicompost + Ram tulsi yielded the highest gross return (₹261,000 ha<sup>-1</sup>) and net return (₹183,713 ha<sup>-1</sup>), while FYM + Ram tulsi achieved the maximum benefit-cost ratio (3.92). Overall, *Ocimum basilicum* with vermicompost is recommended for maximizing productivity and soil fertility under Aonla-based agroforestry systems in subtropical Himalayan conditions.

**Key Words:** · Agri horticulture, Intercropping, Vermicompost, Soil health and Bio-economics

**Introduction**

With a population estimated at 1.42 billion, India currently ranks as the world’s most populous country representing nearly 18 % of the global population (Hertog et al. 2023). This figure is projected to increase to approximately 1.64 billion by 2050 (Gulati et al. 2023). Despite supporting such a large population, the country occupies only about 2.4% of the Earth’s total landmass. Damage to natural resources like soil, water, and air - combined with worsening climate change-puts even more strain on this limited land. Extreme weather events including tropical cyclones, torrential rainfall, floods, droughts, heatwaves, and wildfires have become more frequent, particularly across northern and northeastern India (WMO 2023). As the population continues to grow, the demand for food, livelihood opportunities and natural resources is increasing, while the availability of productive land remains limited. Moreover, Indian agriculture is predominantly characterized by small and marginal landholdings, which account for nearly 86% of all

operational holdings (Gol 2023). Under these circumstances, sustainable and integrated land-use systems are essential to enhance productivity and ensure long-term resource conservation. Agroforestry, which integrates trees with agricultural crops and /or livestock, is recognized as an ecologically sustainable land management approach that enhances farm productivity while delivering social, economic and environmental benefits (Leaky 2017). The incorporation of fruit trees into agricultural landscapes is particularly advantageous, as it improves land-use efficiency, enhances nutritional security, stabilizes crop production, and increases farmers income through diversified production systems (Jamnadass et al. 2013). Agroforestry has emerged as an important land-use system in India, covering nearly 25.31 million hectares, which account for approximately 8.20% of the total geographical area (Sen et al.2025). It involves the deliberate integration of perennial woody trees with agricultural crops and/ or livestock to create productive and sustainable farming systems. Globally, agroforestry supports the livelihoods of millions of people and contributes significantly to rural economies by enhancing farm productivity, diversifying income sources, and strengthening ecological resilience ( Food and agriculture Organization 2023; Lin et al.2021). By improving resource-use efficiency, agroforestry promotes sustainable agricultural production while mitigating the adverse effects of climate change, enhancing soil fertility , and conserving biodiversity (Ahmad et al.2019). In addition to increase crop productivity, agroforestry provides farmers with supplementary income through the production of fruits, timber, fuelwood, and non-timer forest products (Chauhan et al.2025; Sen et al.2025).

Among the various agroforestry models such as horti- medicinal and silvi-medicinal systems gained considerable attention because of their potential to recover farm profitability and livelihood security (Sarkar et al. 2024). Numerous studies have demonstrated that medicinal plants can be successfully cultivated in association with agroforestry tree species without adversely affecting their growth and productivity (Rathore et al. 2025; Octavia et al. 2024; Dash et al. 2024). Fruit based agroforestry systems integrated with medicinal plants represent an efficient and sustainable approach to land management by combining the economic returns from fruit production with the therapeutic and commercial value of medicinal herbs (Lin et al.2021). Such diversified production systems enhance biodiversity, improve ecosystem services, and generate multiple income streams for farming households (Marotti et al. 2023; Kumar et al. 2021.)

The market demand for medicinal plants has increased substantially in recent years owing to their extensive use in pharmaceutical, nutraceutical, cosmetic, and herbal industries (Singh and Kumar 2021). Therefore, including medicinal plants into fruit-based agroforestry systems presents a viable approach to satisfying this increasing need while guaranteeing sustainable land use and increased farm revenue. Additionally, by tackling a number of issues related to traditional agriculture, the use of organic agricultural methods enhances agroforestry. Organic agriculture emphasizes environmentally sound production methods and is based on the values of health, ecology, justice, and care. Health-conscious consumers are increasingly choosing organic products since they are typically higher in nutrients and have fewer synthetic additives and pesticide residues (Hammed et al. 2019).

*Emblica officinalis*, commonly known as Indian gooseberry or aonla, represents an important indigenous fruit cultivated across various agroclimatic zones in India. Historically celebrated as a sacred plant, ancient scriptures frequently referred to it as Amritphal. In Ayurvedic medicine, it is used to make Chyavanprash and Triphala. Aonla powder provides greater benefits than synthetic vitamin C as a natural source of vitamin C in addressing deficits, is also made from fruit. It produces 12,78,000 tonnes a year on an estimated 1,05,000 hectares of land. Uttar Pradesh, Uttarakhand, Gujarat, Maharashtra, Rajasthan, Tamil Nadu, Andhra Pradesh, Karnataka, Bihar, Haryana, Madhya Pradesh, and West Bengal are among the states where it is grown commercially (Pathak 2003). The country's aonla agriculture area has grown dramatically over the past 20 years, utilizing previously unutilized wasteland. Along with the restoration of wastelands, this change has resulted in more effective use of resources, higher farmer incomes, better nutritional security, and more job opportunities (Singh et al. 2014). The cultivation of aonla (*Emblica officinalis* Gaertn.) in India covers approximately 99 thousand hectares (ha), producing about 1,214 thousand metric tonnes (MT), with an average productivity of 12.3 MT ha<sup>-1</sup> (DAFW 2024). In Himachal Pradesh, aonla is cultivated on

approximately 0.73 thousand hectares (730 ha), with an annual production of about 5.10 thousand metric tonnes and an average productivity of 7.0 MT ha<sup>-1</sup> (DAFW 2024).

In the Indian subcontinent, tulsi, also referred to as the "Queen of Plants" and "The Mother Medicine of Nature," is treasured as a sacred plant with numerous therapeutic and disease-preventing qualities. There are thirty species of *Ocimum sanctum* in tropical and subtropical areas, and it is a member of the Lamiaceae family. The essential oil extracted from its leaves and flower contains five major fatty acids: stearic, linoleic, palmitic, linolenic acids and oleic. Along with volatile substances like estragole, linalool, methyl chavicol, and eugenol, as well as trace levels of methyl cinnamate, cineole, and other terpenes, tulsi is a rich source of beta carotene, calcium, and vitamin C. The leaves have long been used to cure liver, stomach, and bronchitis because of their diaphoretic and anti-periodic qualities. Cough, malaise, and colds are frequently treated with a decoction of the leaves. The majority of *Ocimum* species include essential oils that have antiviral, antifungal, and antibacterial qualities (Singh et al. 2010).

Several medicinal species have shown promising adaptation and productivity under tree-based production systems. For example, *Ocimum sanctum* has performed well when intercropped with peach and apricot (Sharma et al. 2021), whereas *Withania somnifera* has demonstrated satisfactory growth and yield under *Citrus sinensis*, *Swietenia macrophylla*, and *Mangifera indica*-based agroforestry systems (Hasan et al. 2024). The application of organic nutrient sources, particularly vermicompost, has also been reported to improve the growth, biomass production, and overall productivity of medicinal plants, including *Ocimum basilicum* (Gunda et al. 2022) and *Andrographis paniculata* (Choudhary et al. 2025). Vermicompost is produced through decomposition of organic materials by the synergistic action of earthworms and microorganisms, resulting in a nutrient-rich organic amendment that improves soil fertility, stimulates microbial activity, and promotes sustainable agricultural production (Pilli et al. 2019). Therefore, the present study was conducted to evaluate the performance and Productivity of *Ocimum* species under an Aonla-based Agroforestry System using organic and inorganic nutrient applications. Considering the economic significance of aonla (*Emblia officinalis*) and tulsi, the present study was conducted to (i) effect of inorganic and organic fertilizers on growth and yield of tulsi under aonla, (ii) evaluate the productivity of essential oil yield in different species of tulsi under aonla, (iii) to assess the bioeconomic performance of the system under aonla-based agri-horticultural system in the north-western Himalayas.

## Material and Methods

### Experimental location and climate

The field experiment was carried out during the period from 2024-2025 in an established 11-year-old aonla (*Emblia officinalis* Gaertn.) orchard at the Regional Horticultural Research and Training Station, Jachh, Kangra, Himachal Pradesh, India. The experimental site is located in the sub-mountain and low hill sub-tropical agroclimatic zone (zone 1) of Himachal Pradesh, India (Fig.1). The region experiences distinct seasonal and diurnal temperatures variations, with May-June as the hottest months and December-January as the coldest. The area receives an average annual rainfall of approximately 1500 mm, about 75% of which occurs during the southwest monsoon (July-September). Temperature ranges from -0.1 °C in winter to 43.5 °C in summer, with mean winter and summer temperatures of 13.6 °C and 29.3 °C, respectively.

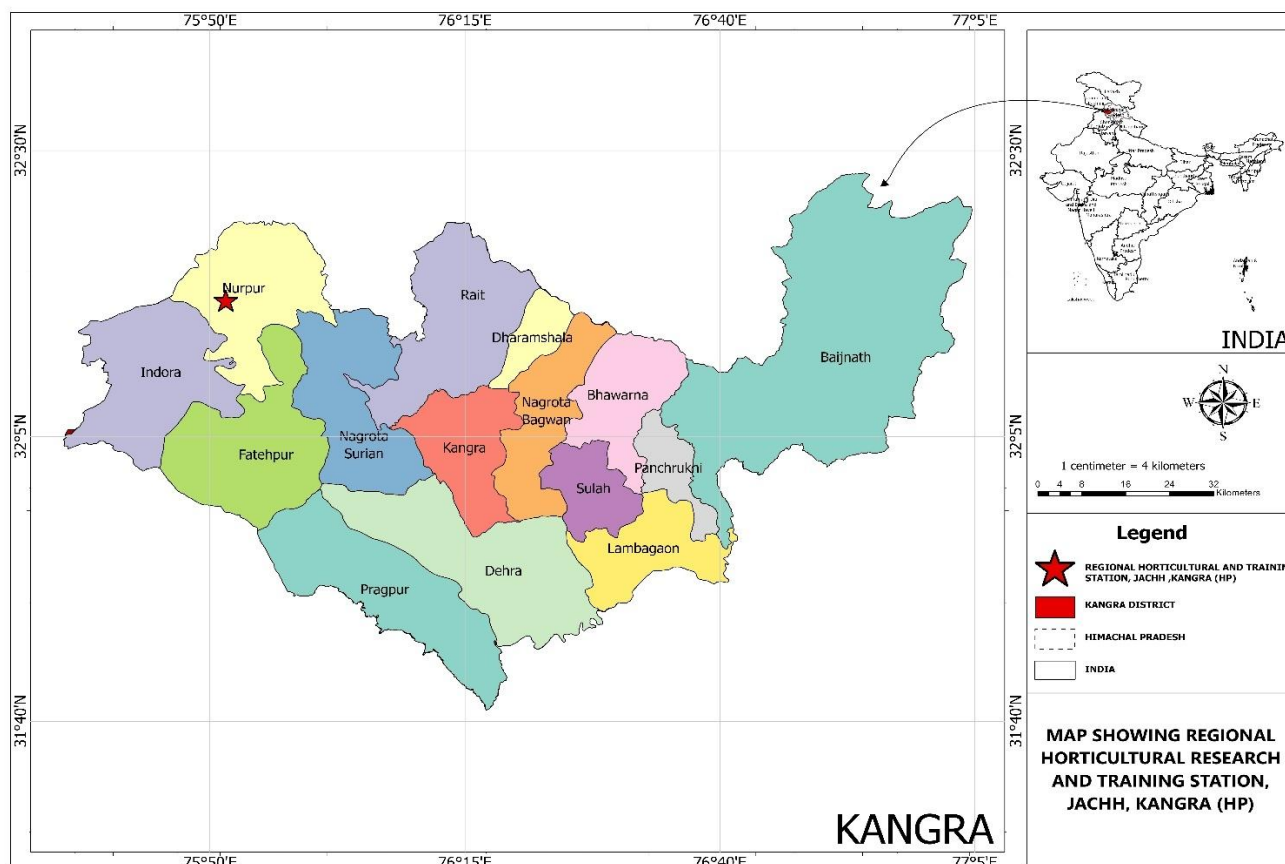


Fig 1- Study area map

### Initial Soil Properties

The soil at the study area is clayey loam in texture with neutral to slightly high pH and medium to rich organic matter content. Before starting the experimental study, soil samples (0-15 cm) were collected from different tree proximities and the open field. The nutrient status of soil characteristics of study site was estimated and shown in the Table 1.

Table 1: Initial Physicochemical Properties of the Experimental Soil.

| S. No. | Parameters                                  | With trees | Sole cropping |
|--------|---------------------------------------------|------------|---------------|
| 1.     | Soil pH                                     | 7.16       | 7.4           |
| 2.     | EC soil (dS m <sup>-1</sup> )               | 0.31       | 0.33          |
| 3.     | Organic carbon (%)                          | 1.13       | 0.92          |
| 5.     | Available Nitrogen (kg ha <sup>-1</sup> )   | 318.62     | 255.82        |
| 6.     | Available Phosphorus (kg ha <sup>-1</sup> ) | 24.46      | 22.08         |
| 7.     | Available Potassium (kg ha <sup>-1</sup> )  | 246.71     | 230.15        |

### Experimental details

The experiment was established under an aonla-based agroforestry system comprising two principal components: aonla (*Emblica officinalis* Gaertn.) as the woody perennial component and tulsi (*Ocimum* spp.) as the medicinal and aromatic intercrop. It assessed (i) effect of inorganic and organic fertilizers on growth and yield of tulsi under aonla,

(ii) evaluate the productivity of essential oil yield in different species of tulsi under aonla, (iii) to assess the bioeconomic performance of the system under aonla-based agri-horticultural system in the north-western Himalayas.

Three *Ocimum* species were evaluated and coded as follow: V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*). Four nutrient management treatments were imposed and coded as T<sub>1</sub> to T<sub>4</sub> such as T<sub>1</sub>: NPK, T<sub>2</sub>: FYM, T<sub>3</sub>: Vermicompost and T<sub>4</sub>: control (open conditions and without fertilizers).

Treatment Details:

Treatment combination:

T<sub>1</sub>V<sub>1</sub>: Aonla + NPK + Ram tulsi

T<sub>1</sub>V<sub>2</sub>: Aonla + NPK + Shyam tulsi

T<sub>1</sub>V<sub>3</sub>: Aonla + NPK + Bhabri

T<sub>2</sub>V<sub>1</sub>: Aonla + FYM + Ram tulsi

T<sub>2</sub>V<sub>2</sub>: Aonla + FYM+ Shyam tulsi

T<sub>2</sub>V<sub>3</sub>: Aonla + FYM+ Bhabri

T<sub>3</sub>V<sub>1</sub>: Aonla + Vermicompost+ Ram tulsi

T<sub>3</sub>V<sub>2</sub>: Aonla + Vermicompost+ Shyam tulsi

T<sub>3</sub>V<sub>3</sub>: Aonla + Vermicompost+ Bhabri

T<sub>4</sub>V<sub>1</sub>: Control Ram tulsi

T<sub>4</sub>V<sub>2</sub>: Control Shyam tulsi

T<sub>4</sub>V<sub>3</sub>: Control Bhabri

To determine yield performance, soil physicochemical changes, and bio-economic outcomes, both planting setups were evaluated using a factorial randomized block design (RBD) with three replications. Uniform applications of organic amendments (FYM and vermicompost) and inorganic fertilizers (NPK) were maintained across all crop treatments, except for T<sub>4</sub>. Nutrients were applied per plot, with nitrogen fertilizer applied in three distinct doses: during planting, throughout vegetative growth and during reproductive stage. Manures were applied uniformly and fully incorporated into the soil. The quantity of FYM and vermicompost was determined based on nitrogen equivalency. Manure and fertilizer quantities estimated per hectare are converted to per plot and applied accordingly.

Table 2: Doses of fertilizers applied (kg ha<sup>-1</sup>)

| Crop                     | Nitrogen* | Phosphorus** | Potassium*** | FYM                   | Vermicompost          |
|--------------------------|-----------|--------------|--------------|-----------------------|-----------------------|
| <i>Ocimum</i><br>Species | 120       | 60           | 60           | 10 t ha <sup>-1</sup> | 10 t ha <sup>-1</sup> |

Nitrogen\*- through urea (as split dose- during planting and then after 30 days of planting)

P\*\*- through SSP (as basal dose)

K\*\*\*- through MOP (as basal dose)

#### Cultural Practices

Field preparation involved clearing and plowing to establish 36 plots (1.6 m × 4 m each). In December 2024, *Ocimum* species was sown at a 40 cm × 40 cm grid (25plants/plot) under an *Emblica officinalis* (aonla) agroforestry canopy (10 m × 10 m tree spacing). Basal applications of organic manures and inorganic fertilizers were applied following the recommended package of practices of CSKHPKV, Palampur (CSKHPKV 2009). Stand maintenance included thinning at 20 (DAS) days after sowing and manual weeding at 45 and 90 DAS. All harvesting and post-harvest operations were conducted by hand.

#### Growth and yield traits

Plant height and the number of leaves were recorded from five randomly selected plants per treatment at 30, 60, and 90 (DAS) days after sowing and at harvest. Chlorophyll content was estimated at 60 and 90 DAS from 100 mg fresh leaf tissue using 80% acetone, with absorbance measured at 645 and 663 nm. At harvest, root and shoot fresh and dry

weights, agronomic efficiency, and essential oil yield were recorded. Essential oil was obtained from fresh leaves by steam distillation using a Clevenger apparatus and expressed as kg ha<sup>-1</sup>.

#### Soil physical and chemical properties

Surface soil samples (0-15 cm depth) were composited from each experimental plot before sowing and after crop harvest under dry field conditions. After shade-drying, the soil samples were sieved through a 2 mm mesh following standard protocols and analyzed for key physicochemical properties. Soil pH was measured in a 1:2 soil-to-water suspension with a combined glass electrode (Jackson, 1973). Soil organic carbon was quantified using the Walkley and Black (1934) rapid titration method. Available nitrogen, phosphorus, and potassium were estimated via the alkaline permanganate (Subbiah and Asija, 1956), Olsen et al. (1954), and ammonium acetate extraction (Merwin and Peech, 1951) methods, respectively.

#### Bio-economics analysis

To evaluate the bio-economic performance of both agroforestry and sole cropping systems on a per-hectare basis, the establishment and maintenance expenditures for aonla plantation were amortized into equivalent annual costs using the annuity method. The total cost of tulsī cultivation was estimated by accounting for all input expenses, including seeds, manures and labor charges based on prevailing local market rates, for both production systems. Economic indicators were calculated by estimating gross returns based on the market value of the harvested produce. Net returns were obtained by deducting the total cost of cultivation from the gross returns, while the benefit-cost (B:C) ratio was computed as the ratio of gross returns to the total cost of cultivation.

#### Statistical analysis

Statistical analyses were conducted using RStudio (version 2026.04.0). Data were subjected to analysis of variance (ANOVA) following the procedure described by Gomez and Gomez (1984), and treatment means were compared using the Least Significant Difference (LSD) test at the 5% level of significance ( $p < 0.05$ ). Data visualization and graph representation were carried out in Microsoft Excel and Origin Pro 2024. The location map of the experimental site was developed using ArcMap version 10.8.1

## Results

#### Agro-morphological traits of tulsī

The data presented in Table 3 showed that fertilizers significantly influenced plant height of tulsī at 30,60,90 days after sowing (DAS) and at harvest under the aonla-based agroforestry system. Significant variation was observed among species, fertilizer treatments, and their interaction. At 30 DAS, the highest plant height (34.30 cm) was recorded in T<sub>3</sub>V<sub>3</sub> (Aonla + Vermicompost + Bhabri), while the lowest (12.93 cm) was observed in T<sub>4</sub>V<sub>1</sub> (Control + Ram tulsī). Among species, V<sub>3</sub> (*Ocimum basilicum*) recorded the highest mean height (24.58 cm), followed by V<sub>2</sub> (*Ocimum tenuiflorum*, 22.38 cm) and V<sub>1</sub> (*Ocimum sanctum*, 18.33 cm). Vermicompost produced the highest mean plant height (27.01 cm), whereas the control recorded the lowest (15.21 cm). A similar trend was observed at 60,90 DAS and at harvest, where T<sub>3</sub>V<sub>3</sub> consistently recorded the maximum plant heights (79.67, 84.67 and 89.83 cm, respectively), while T<sub>4</sub>V<sub>1</sub> recorded the minimum (23.33, 29.33 and 34.03 cm, respectively). Across all growth stages, *Ocimum basilicum* remained the tallest species (51.34, 59.02 and 64.23 cm at 60, 90 DAS and harvest, respectively), and vermicompost consistently produced the highest mean plant height ( 57.54, 64.47 and 69.01 cm), whereas the control recorded the lowest values ( 28.92, 35.84 and 39.86 cm). Overall, *Ocimum basilicum* grown with vermicompost (T<sub>3</sub>V<sub>3</sub>) exhibited superior plant height throughout the study.

The data presented in Table 4 revealed that fertilizer application significantly influenced the number of leaves of tulsī at 30,60,90 DAS and at harvest under the aonla-based agroforestry system. Significant variation was observed among species, fertilizer treatments and their interaction. At 30 DAS, the highest number of leaves (35.60) was recorded in T<sub>3</sub>V<sub>3</sub> (Aonla + Vermicompost + Bhabri), while the lowest (19.33) was observed in T<sub>4</sub>V<sub>2</sub> (control + Shyam tulsī). Among species, V<sub>3</sub> (*Ocimum basilicum*) recorded the highest mean number of leaves (29.55), followed by V<sub>2</sub>

(*Ocimum tenuiflorum*, 23.78) and V<sub>1</sub> (*Ocimum sanctum*, 23.73). Vermicompost produced the highest mean leaf number (30.98), whereas the control recorded the lowest (19.94). A similar trend was observed at 60, 90 DAS and at harvest, where T<sub>3</sub>V<sub>3</sub> consistently recorded the highest number of leaves (383.30, 701.37 and 700.43, respectively), while the minimum values were recorded in T<sub>4</sub>V<sub>1</sub> (218.13) at 60 DAS, T<sub>4</sub>V<sub>2</sub> (517.67) at 90 DAS, and T<sub>4</sub>V<sub>1</sub> (518.57) at harvest. Across all growth stages, *Ocimum basilicum* remained superior, recording the highest mean leaf numbers (335.48, 640.19 and 639.80 at 60, 90 DAS and at harvest, respectively), while vermicompost consistently produced the highest mean values (311.51, 618.67 and 618.17), compared with the control (227.45, 526.70 and 526.99). Overall, *Ocimum basilicum* grown with vermicompost (T<sub>3</sub>V<sub>3</sub>) produced the maximum number of leaves.

Table 5 shows the Total leaf chlorophyll was measured at 60 and 90 days after transplanting (DAS); results are presented in Table 5. Chlorophyll content differed significantly among tulsi species, fertilizer treatments and their interaction in the aonla-based agroforestry system. At 60 DAS, the highest chlorophyll (2.017 mg g<sup>-1</sup>) was recorded in T<sub>3</sub>V<sub>2</sub> (Aonla + vermicompost + Shyam tulsi) and the lowest (0.938 mg g<sup>-1</sup>) in T<sub>4</sub>V<sub>1</sub> (control Ram tulsi). Species means at 60 DAS were highest for V<sub>2</sub> (*Ocimum tenuiflorum*, 1.684 mg g<sup>-1</sup>), followed by V<sub>3</sub> (*Ocimum basilicum*, 1.540 mg g<sup>-1</sup>) and V<sub>1</sub> (*Ocimum sanctum*, 1.401 mg g<sup>-1</sup>). Among fertilizers, vermicompost produced the highest mean chlorophyll, while the control produced the lowest. At 90 DAS, T<sub>3</sub>V<sub>2</sub> again showed the maximum chlorophyll (1.690 mg g<sup>-1</sup>) and T<sub>4</sub>V<sub>1</sub> the minimum (0.911 mg g<sup>-1</sup>). Species means at 90 DAS were highest in V<sub>2</sub> (*Ocimum tenuiflorum*) (1.410 mg g<sup>-1</sup>), followed by V<sub>3</sub> (*Ocimum basilicum*) (1.198 mg g<sup>-1</sup>) and V<sub>1</sub> (*Ocimum sanctum*) (1.109 mg g<sup>-1</sup>). Vermicompost remained the most effective fertilizer for enhancing leaf chlorophyll, whereas the control consistently showed the lowest values.

Root fresh and dry weight were significantly affected by the application of organic fertilizers (Table 5). The highest root fresh weight (0.852 q ha<sup>-1</sup>) and dry weight (0.563 q ha<sup>-1</sup>) were recorded in T<sub>3</sub>V<sub>3</sub> (Aonla + Bhabri + vermicompost), while the lowest fresh (0.287 q ha<sup>-1</sup>) and dry (0.144 q ha<sup>-1</sup>) weights occurred in T<sub>4</sub>V<sub>1</sub> (control Ram tulsi). Among species, V<sub>3</sub> (*Ocimum basilicum*) produced the greatest fresh (0.627 q ha<sup>-1</sup>) and dry (0.368 q ha<sup>-1</sup>) root weights, followed by V<sub>2</sub> (*Ocimum tenuiflorum*; fresh 0.442, dry 0.262 q ha<sup>-1</sup>) and V<sub>1</sub> (*Ocimum sanctum*; fresh 0.401, dry 0.207 q ha<sup>-1</sup>). By fertilizer, vermicompost increased root fresh weight (0.685 q ha<sup>-1</sup>) relative to the control (0.326 q ha<sup>-1</sup>). Overall, vermicompost and the combined T<sub>3</sub>V<sub>3</sub> treatment markedly enhanced root biomass.

Table 3- Effect of different fertilizers and organic manures on the plant height of *Ocimum* species grown under an Aonla-based agroforestry system at different days after transplanting (DAS).

|                               | Plant height (30 DAS) |                |                |                    | Plant height (60 DAS) |                |                |                    | Plant height (90 DAS) |                |                |                    | Plant height (At Harvest)) |                |                |                    |
|-------------------------------|-----------------------|----------------|----------------|--------------------|-----------------------|----------------|----------------|--------------------|-----------------------|----------------|----------------|--------------------|----------------------------|----------------|----------------|--------------------|
| Treatments                    | Species               |                |                | Mean               | Species               |                |                | Mean               | Species               |                |                | Mean               | Species                    |                |                |                    |
|                               | V <sub>1</sub>        | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>        | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>        | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>             | V <sub>2</sub> | V <sub>3</sub> |                    |
| T <sub>1</sub> (NPK)          | 21.37                 | 21.83          | 18.07          | 20.42 <sup>c</sup> | 37.07                 | 37.50          | 36.70          | 37.09 <sup>c</sup> | 42.23                 | 46.60          | 49.07          | 45.97 <sup>c</sup> | 46.83                      | 51.80          | 53.93          | 50.86 <sup>c</sup> |
| T <sub>2</sub> (FYM)          | 20.27                 | 24.93          | 28.00          | 24.40 <sup>b</sup> | 38.90                 | 44.87          | 54.77          | 46.18 <sup>b</sup> | 46.47                 | 55.93          | 61.67          | 54.69 <sup>b</sup> | 51.37                      | 59.63          | 67.53          | 59.51 <sup>b</sup> |
| T <sub>3</sub> (Vermicompost) | 18.73                 | 28.00          | 34.30          | 27.01 <sup>a</sup> | 44.47                 | 48.50          | 79.67          | 57.54 <sup>a</sup> | 50.30                 | 58.43          | 84.67          | 64.47 <sup>a</sup> | 55.50                      | 61.70          | 89.83          | 69.01 <sup>a</sup> |
| T <sub>4</sub> (Control)      | 12.93                 | 14.73          | 17.97          | 15.21 <sup>d</sup> | 23.33                 | 29.20          | 34.23          | 28.92 <sup>d</sup> | 29.33                 | 35.97          | 40.67          | 35.32 <sup>d</sup> | 34.03                      | 39.93          | 45.60          | 39.86 <sup>d</sup> |
| Mean                          | 18.33                 | 22.38          | 24.58          |                    | 35.94                 | 40.02          | 51.34          |                    | 42.08                 | 49.23          | 59.02          |                    | 46.93                      | 53.27          | 64.23          |                    |
| Factors                       | CD (5%)               | SE(d)±         | SE(m)±         |                    | CD (5%)               | SE(d)±         | SE(m)±         |                    | CD (5%)               | SE(d)±         | SE(m)±         |                    | CD (5%)                    | SE(d)±         | SE(m)±         |                    |
| Species (V)                   | 1.82                  | 0.87           | 0.62           |                    | 3.11                  | 1.49           | 1.05           |                    | 3.76                  | 1.80           | 1.27           |                    | 3.85                       | 1.85           | 1.30           |                    |
| Fertilizers (T)               | 2.10                  | 1.01           | 0.71           |                    | 3.59                  | 1.72           | 1.22           |                    | 4.34                  | 2.08           | 1.47           |                    | 4.45                       | 2.13           | 1.51           |                    |
| Interaction                   | 3.64                  | 1.74           | 1.23           |                    | 6.21                  | 2.98           | 2.11           |                    | 7.52                  | 3.61           | 2.55           |                    | 7.70                       | 3.69           | 2.61           |                    |

Means followed by different alphabets (a, b, c, ...) are significantly different at  $p \leq 0.05$ ; V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*); DAS: Days after Sowing

Table 4 – Effect of different fertilizers and organic manures on the number of leaves of *Ocimum* species grown under an Aonla-based agroforestry system at different days after transplanting (DAS).

|                               | No. of leaves (30 DAS) |                |                |                    | No. of leaves (60 DAS) |                |                |                     | No. of leaves (90 DAS) |                |                |                     | No. of leaves (At Harvest) |                |                |                     |
|-------------------------------|------------------------|----------------|----------------|--------------------|------------------------|----------------|----------------|---------------------|------------------------|----------------|----------------|---------------------|----------------------------|----------------|----------------|---------------------|
| Treatments                    | Species                |                |                | Mean               | Species                |                |                | Mean                | Species                |                |                | Mean                | Species                    |                |                |                     |
|                               | V <sub>1</sub>         | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>         | V <sub>2</sub> | V <sub>3</sub> |                     | V <sub>1</sub>         | V <sub>2</sub> | V <sub>3</sub> |                     | V <sub>1</sub>             | V <sub>2</sub> | V <sub>3</sub> |                     |
| T <sub>1</sub> (NPK)          | 22.47                  | 21.77          | 28.53          | 24.26 <sup>c</sup> | 244.67                 | 259.57         | 357.30         | 287.18 <sup>c</sup> | 539.77                 | 548.17         | 656.80         | 581.57 <sup>c</sup> | 539.23                     | 549.47         | 656.37         | 581.69 <sup>c</sup> |
| T <sub>2</sub> (FYM)          | 26.10                  | 31.03          | 35.60          | 27.57 <sup>b</sup> | 255.87                 | 274.17         | 355.67         | 295.23 <sup>b</sup> | 553.40                 | 569.10         | 658.20         | 593.57 <sup>b</sup> | 552.33                     | 568.30         | 658.77         | 593.13 <sup>b</sup> |
| T <sub>3</sub> (Vermicompost) | 26.30                  | 31.03          | 35.60          | 30.98 <sup>a</sup> | 262.33                 | 288.90         | 383.30         | 311.51 <sup>a</sup> | 563.43                 | 591.20         | 701.37         | 618.67 <sup>a</sup> | 564.43                     | 589.63         | 700.43         | 618.17 <sup>a</sup> |
| T <sub>4</sub> (Control)      | 20.07                  | 19.33          | 20.43          | 19.94 <sup>d</sup> | 218.13                 | 218.57         | 245.63         | 227.45 <sup>d</sup> | 518.17                 | 517.67         | 544.27         | 526.70 <sup>d</sup> | 518.57                     | 518.77         | 543.63         | 526.99 <sup>d</sup> |
| Mean                          | 23.73                  | 23.78          | 29.55          |                    | 245.25                 | 260.30         | 335.48         |                     | 543.69                 | 556.53         | 640.16         |                     | 543.64                     | 556.54         | 639.80         |                     |
| Factors                       | CD (5%)                | SE(d)±         | SE(m)±         |                    | CD (5%)                | SE(d)±         | SE(m)±         |                     | CD (5%)                | SE(d)±         | SE(m)±         |                     | CD (5%)                    | SE(d)±         | SE(m)±         |                     |
| Species (V)                   | 3.02                   | 1.45           | 1.02           |                    | 12.60                  | 6.04           | 4.27           |                     | 12.966                 | 6.212          | 4.393          |                     | 14.27                      | 6.837          | 4.834          |                     |
| Fertilizers (T)               | 3.49                   | 1.67           | 1.18           |                    | 14.55                  | 6.97           | 4.93           |                     | 14.972                 | 7.173          | 5.072          |                     | 16.477                     | 7.894          | 5.582          |                     |
| Interaction                   | NS                     | 2.90           | 2.05           |                    | 25.20                  | 12.07          | 8.54           |                     | 25.932                 | 12.424         | 8.785          |                     | 28.539                     | 13.673         | 9.668          |                     |

Means followed by different alphabets (a, b, c, ...) are significantly different at  $p \leq 0.05$ ; V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*); DAS: Days after Sowing

Table 5. Effect of different Fertilizers and Organic Manures on Chlorophyll Content and Root Fresh and Dry Weight of *Ocimum* Species grown under an Aonla-based Agroforestry System.

|                               | Chlorophyll content<br>(60 DAS) |                |                |                   | Chlorophyll content<br>(90 DAS) |                |                |                   | Root fresh weight<br>(q ha <sup>-1</sup> ) |                |                |                    | Root dry weight<br>(q ha <sup>-1</sup> ) |                |                |                    |
|-------------------------------|---------------------------------|----------------|----------------|-------------------|---------------------------------|----------------|----------------|-------------------|--------------------------------------------|----------------|----------------|--------------------|------------------------------------------|----------------|----------------|--------------------|
| Treatments                    | Species                         |                |                | Mean              | Species                         |                |                | Mean              | Species                                    |                |                | Mean               | Species                                  |                |                | Mean               |
|                               | V <sub>1</sub>                  | V <sub>2</sub> | V <sub>3</sub> |                   | V <sub>1</sub>                  | V <sub>2</sub> | V <sub>3</sub> |                   | V <sub>1</sub>                             | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>                           | V <sub>2</sub> | V <sub>3</sub> |                    |
| T <sub>1</sub> (NPK)          | 1.40                            | 1.76           | 1.51           | 1.55 <sup>c</sup> | 1.07                            | 1.47           | 1.20           | 1.25 <sup>c</sup> | 0.321                                      | 0.35           | 0.519          | 0.397 <sup>c</sup> | 0.156                                    | 0.178          | 0.26           | 0.198 <sup>c</sup> |
| T <sub>2</sub> (FYM)          | 1.50                            | 1.98           | 1.71           | 1.73 <sup>b</sup> | 1.19                            | 1.54           | 1.32           | 1.35 <sup>b</sup> | 0.424                                      | 0.472          | 0.759          | 0.552 <sup>b</sup> | 0.234                                    | 0.314          | 0.442          | 0.330 <sup>b</sup> |
| T <sub>3</sub> (Vermicompost) | 1.76                            | 2.01           | 1.98           | 1.92 <sup>a</sup> | 1.25                            | 1.69           | 1.34           | 1.43 <sup>a</sup> | 0.570                                      | 0.633          | 0.852          | 0.685 <sup>a</sup> | 0.295                                    | 0.381          | 0.536          | 0.413 <sup>a</sup> |
| T <sub>4</sub> (Control)      | 0.93                            | 0.97           | 0.95           | 0.95 <sup>d</sup> | 0.91                            | 0.93           | 0.92           | 0.92 <sup>d</sup> | 0.287                                      | 0.311          | 0.379          | 0.326 <sup>d</sup> | 0.144                                    | 0.175          | 0.209          | 0.176 <sup>d</sup> |
| Mean                          | 1.40                            | 1.68           | 1.54           |                   | 1.10                            | 1.41           | 1.19           |                   | 0.401                                      | 0.442          | 0.627          |                    | 0.207                                    | 0.262          | 0.368          |                    |
| Factors                       | CD<br>(5%)                      | SE(d)±         | SE(m)±         |                   | CD<br>(5%)                      | SE(d)±         | SE(m)±         |                   | CD<br>(5%)                                 | SE(d)±         | SE(m)±         |                    | CD<br>(5%)                               | SE(d)±         | SE(m)±         |                    |
| Species (V)                   | 0.03                            | 0.01           | 0.01           |                   | 0.02                            | 0.01           | 0.01           |                   | 0.004                                      | 0.002          | 0.001          |                    | 0.006                                    | 0.003          | 0.002          |                    |
| Fertilizers (T)               | 0.03                            | 0.01           | 0.01           |                   | 0.03                            | 0.01           | 0.01           |                   | 0.005                                      | 0.002          | 0.002          |                    | 0.007                                    | 0.003          | 0.002          |                    |
| Interaction                   | 0.06                            | 0.03           | 0.02           |                   | 0.05                            | 0.02           | 0.02           |                   | 0.08                                       | 0.004          | 0.003          |                    | 0.012                                    | 0.006          | 0.004          |                    |

Means followed by different alphabets (a, b, c, ...) are significantly different at  $p \leq 0.05$ ; V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*) ; DAS: Days after Sowing

The data in Table 6 show that organic fertilizers significantly increased shoot fresh and dry weight of tulsi in the aonla-based agroforestry system. The highest shoot fresh weight (15.15 q ha<sup>-1</sup>) and dry weight (5.747 q ha<sup>-1</sup>) were recorded in T<sub>3</sub>V<sub>3</sub> (Aonla + vermicompost + Bhabri), while the lowest fresh (7.353 q ha<sup>-1</sup>) and dry (2.533 q ha<sup>-1</sup>) weights occurred in T<sub>4</sub>V<sub>1</sub> (control Ram tulsi). Among species, V<sub>3</sub> (*Ocimum basilicum*) produced the greatest shoot fresh (11.458 q ha<sup>-1</sup>) and dry (4.251 q ha<sup>-1</sup>) weights, followed by V<sub>2</sub> (*Ocimum tenuiflorum*; fresh 10.713, dry 3.873 q ha<sup>-1</sup>) and V<sub>1</sub> (*Ocimum sanctum*; fresh 10.071, dry 3.605 q ha<sup>-1</sup>). By fertilizer, vermicompost enhanced shoot fresh weight (13.871 q ha<sup>-1</sup>) relative to the control (7.611 q ha<sup>-1</sup>). Overall, vermicompost and the combined treatment T<sub>3</sub>V<sub>3</sub> markedly improved shoot biomass.

The data in Table 6 show that organic fertilizers significantly increased total plant fresh and dry weight of tulsi in the aonla-based agroforestry system. The highest total fresh weight (16.00 q ha<sup>-1</sup>) and total dry weight (6.31 q ha<sup>-1</sup>) were recorded in T<sub>3</sub>V<sub>3</sub> (Aonla + vermicompost + Bhabri), whereas the lowest fresh (7.64 q ha<sup>-1</sup>) and dry (2.68 q ha<sup>-1</sup>) weights occurred in T<sub>4</sub>V<sub>1</sub> (control Ram tulsi). Among species, V<sub>3</sub> (*Ocimum basilicum*) produced the greatest total fresh (12.09 q ha<sup>-1</sup>) and dry (4.62 q ha<sup>-1</sup>) weights, followed by V<sub>2</sub> (*Ocimum tenuiflorum*; fresh 11.16, dry 4.14 q ha<sup>-1</sup>) and V<sub>1</sub> (*Ocimum sanctum*; fresh 10.47, dry 3.81 q ha<sup>-1</sup>). By fertilizer, vermicompost increased total fresh weight (14.56 q ha<sup>-1</sup>) relative to the control (7.94 q ha<sup>-1</sup>). Overall, vermicompost and the combined treatment T<sub>3</sub>V<sub>3</sub> markedly enhanced total biomass.

The Agronomic efficiency (AE)-an important indicator of crop production per unit nutrient applied and influenced by fertilizer management and soil-plant water relations was evaluated for *Ocimum* species (Table 7). Fertilizer application significantly affected AE. The highest AE (0.70 kg grain kg<sup>-1</sup>) was observed in T<sub>2</sub>V<sub>3</sub> (Aonla + FYM + Bhabri), while the lowest (0.17 kg grain kg<sup>-1</sup>) occurred in T<sub>1</sub>V<sub>1</sub> (Aonla + NPK + Ram tulsi). By fertilizer source, FYM (T<sub>2</sub>) produced the greatest mean AE (0.62 kg grain kg<sup>-1</sup>), followed by vermicompost (T<sub>3</sub>, 0.42 kg grain kg<sup>-1</sup>), whereas NPK (T<sub>1</sub>) showed the lowest mean AE (0.32 kg grain kg<sup>-1</sup>). These results indicate that organic manures, particularly FYM, improved nutrient use efficiency relative to mineral NPK in this system.

The essential oil yield of tulsi varied significantly with species and fertilizer application, and the significant species × fertilizer interaction demonstrated that fertilizer effects differed among the tulsi species (Table 7). The highest oil yield (9.06 kg ha<sup>-1</sup>) was recorded in T<sub>3</sub>V<sub>1</sub> (Aonla + vermicompost + Ram tulsi) and the lowest (1.46 kg ha<sup>-1</sup>) in T<sub>4</sub>V<sub>2</sub> (control Shyam tulsi). Species means were highest for V<sub>1</sub> (Ram tulsi, 6.13 kg ha<sup>-1</sup>), followed by V<sub>3</sub> (*Ocimum basilicum*, 2.87 kg ha<sup>-1</sup>) and V<sub>2</sub> (*Ocimum tenuiflorum*, 2.05 kg ha<sup>-1</sup>). Among fertilizer sources, vermicompost produced the greatest mean oil yield (5.79 kg ha<sup>-1</sup>) compared with the control (1.88 kg ha<sup>-1</sup>). Overall, vermicompost and the combined T<sub>3</sub>V<sub>1</sub> treatment markedly enhanced essential oil productivity.

328 Table 6. Effect of different fertilizers and organic manures on shoot fresh weight, shoot dry weight, Total fresh weight and total dry weight of *Ocimum* species  
 329 grown under an Aonla based agroforestry system.

|                               | Shoot fresh weight (q ha <sup>-1</sup> ) |                |                |         | Shoot dry weight (q ha <sup>-1</sup> ) |                |                |                   | Total fresh weight (q ha <sup>-1</sup> ) |                |                |                    | Total dry weight (q ha <sup>-1</sup> ) |                |                |                   |
|-------------------------------|------------------------------------------|----------------|----------------|---------|----------------------------------------|----------------|----------------|-------------------|------------------------------------------|----------------|----------------|--------------------|----------------------------------------|----------------|----------------|-------------------|
| Treatments                    | Species                                  |                |                | Mean    | Species                                |                |                | Mean              | Species                                  |                |                | Mean               | Species                                |                |                | Mean              |
|                               | V <sub>1</sub>                           | V <sub>2</sub> | V <sub>3</sub> |         | V <sub>1</sub>                         | V <sub>2</sub> | V <sub>3</sub> |                   | V <sub>1</sub>                           | V <sub>2</sub> | V <sub>3</sub> |                    | V <sub>1</sub>                         | V <sub>2</sub> | V <sub>3</sub> |                   |
| T <sub>1</sub> (NPK)          | 9.213                                    | 9.493          | 10.44          | 9.716c  | 2.92                                   | 3.41           | 3.9            | 3.41 <sup>c</sup> | 9.54                                     | 9.84           | 10.96          | 10.11 <sup>c</sup> | 3.08                                   | 3.59           | 4.16           | 3.61 <sup>c</sup> |
| T <sub>2</sub> (FYM)          | 11.157                                   | 11.823         | 12.393         | 11.791b | 4.06                                   | 4.307          | 4.577          | 4.31 <sup>b</sup> | 11.58                                    | 12.30          | 13.15          | 12.34 <sup>b</sup> | 4.29                                   | 4.62           | 5.02           | 4.64 <sup>b</sup> |
| T <sub>3</sub> (Vermicompost) | 12.56                                    | 13.903         | 15.15          | 13.871a | 4.907                                  | 5.097          | 5.747          | 5.25 <sup>a</sup> | 13.13                                    | 14.54          | 16.00          | 14.56 <sup>a</sup> | 5.20                                   | 5.48           | 6.31           | 5.66 <sup>a</sup> |
| T <sub>4</sub> (Control)      | 7.353                                    | 7.63           | 7.85           | 7.611d  | 2.533                                  | 2.68           | 2.78           | 2.66 <sup>d</sup> | 7.64                                     | 7.94           | 8.23           | 7.94 <sup>d</sup>  | 2.68                                   | 2.86           | 2.99           | 2.84 <sup>d</sup> |
| Mean                          | 10.071                                   | 10.713         | 11.458         |         | 3.605                                  | 3.873          | 4.251          |                   | 10.47                                    | 11.16          | 12.09          |                    | 3.81                                   | 4.14           | 4.62           |                   |
| Factors                       | CD (5%)                                  | SE(d)±         | SE(m)±         |         | CD (5%)                                | SE(d)±         | SE(m)±         |                   | CD (5%)                                  | SE(d)±         | SE(m)±         |                    | CD (5%)                                | SE(d)±         | SE(m)±         |                   |
| Species (V)                   | 0.052                                    | 0.025          | 0.018          |         | 0.057                                  | 0.027          | 0.019          |                   | 0.052                                    | 0.025          | 0.017          |                    | 0.06                                   | 0.029          | 0.02           |                   |
| Fertilizers (T)               | 0.060                                    | 0.029          | 0.020          |         | 0.066                                  | 0.032          | 0.022          |                   | 0.059                                    | 0.028          | 0.02           |                    | 0.07                                   | 0.033          | 0.024          |                   |
| Interaction                   | 0.104                                    | 0.05           | 0.035          |         | 0.115                                  | 0.055          | 0.039          |                   | 0.103                                    | 0.049          | 0.035          |                    | 0.121                                  | 0.058          | 0.041          |                   |

330 Means followed by different alphabets (a, b, c, ...) are significantly different at  $p \leq 0.05$ ; V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and  
 331 V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*)

Table 7: Effect of different fertilizers and organic manures on nutrient use efficiency and essential oil yield of *Ocimum* species grown under an Aonla-based agroforestry system.

|                               | Agronomic efficiency (kg grain kg <sup>-1</sup> ) |                |                |                   | Essential oil yield (kg ha <sup>-1</sup> ) |                |                |                   |
|-------------------------------|---------------------------------------------------|----------------|----------------|-------------------|--------------------------------------------|----------------|----------------|-------------------|
| Treatments                    | Species                                           |                |                | Mean              | Species                                    |                |                | Mean              |
|                               | V <sub>1</sub>                                    | V <sub>2</sub> | V <sub>3</sub> |                   | V <sub>1</sub>                             | V <sub>2</sub> | V <sub>3</sub> |                   |
| T <sub>1</sub> (NPK)          | 0.17                                              | 0.30           | 0.49           | 0.32 <sup>c</sup> | 5.25                                       | 1.18           | 1.97           | 2.80 <sup>c</sup> |
| T <sub>2</sub> (FYM)          | 0.55                                              | 0.60           | 0.70           | 0.62 <sup>a</sup> | 7.30                                       | 2.21           | 3.29           | 4.27 <sup>b</sup> |
| T <sub>3</sub> (Vermicompost) | 0.38                                              | 0.39           | 0.49           | 0.42 <sup>b</sup> | 9.06                                       | 3.34           | 4.96           | 5.79 <sup>a</sup> |
| T <sub>4</sub> (Control)      | -                                                 | -              | -              | -                 | 2.90                                       | 1.46           | 1.27           | 1.88 <sup>d</sup> |
| Mean                          | 0.32                                              | 0.43           | 0.56           |                   | 6.13                                       | 2.05           | 2.87           |                   |
| Factors                       | CD (5%)                                           | SE(d)±         | SE(m)±         |                   | CD (5%)                                    | SE(d)±         | SE(m)±         |                   |
| Species (V)                   | 0.012                                             | 0.006          | 0.004          |                   | 0.208                                      | 0.099          | 0.07           |                   |
| Fertilizers (T)               | 0.010                                             | 0.005          | 0.003          |                   | 0.24                                       | 0.115          | 0.081          |                   |
| Interaction                   | 0.021                                             | 0.010          | 0.007          |                   | 0.415                                      | 0.199          | 0.141          |                   |

Means followed by different alphabets (a, b, c, ...) are significantly different at  $p \leq 0.05$ ; V<sub>1</sub>: Ram tulsi (*Ocimum sanctum*), V<sub>2</sub>: Shyam tulsi (*Ocimum tenuiflorum*) and V<sub>3</sub>: Bhabri tulsi (*Ocimum basilicum*)

Table 8 – Growth and Yield Parameter of Aonla tree.

| Growth and Yield Parameters                           | Aonla Tree |
|-------------------------------------------------------|------------|
| Tree height (m)                                       | 6.4        |
| Tree diameter (cm)                                    | 19.45      |
| Crown spread (m <sup>2</sup> )                        | 4.77       |
| Number of branches tree <sup>-1</sup>                 | 13.27      |
| Fruit yield Tree <sup>-1</sup> (kg ha <sup>-1</sup> ) | 35         |

#### Growth and yield parameters of Aonla tree (*Emblica officinalis*)

The data pertaining to the growth and yield parameters of Aonla (*Emblica officinalis*) are presented in table 8.

**Tree height (m):** The height of aonla trees ranged from 5.5 m to 7.35 m. The average height of Aonla (*Emblica officinalis*) trees was 6.44 m.

**Tree diameter (cm):** The diameter of aonla trees ranged from 15.5 cm to 21.5 cm. The average tree diameter at the breast height of Aonla (*Emblica officinalis*) at 1.37m above the ground level was recorded as 19.45 cm.

**Crown spread (m<sup>2</sup>):** The crown spread of aonla trees varied from 3.5 m to 6.2 m. The average crown spread of Aonla (*Emblica officinalis*) trees was recorded to be 4.77 m<sup>2</sup>.

**Number of branches:** The aonla trees recorded an average of 13.27 branches per tree.

**Fruit yield (kg tree<sup>-1</sup>):** The average fruit yield per tree of Aonla (*Emblica officinalis*) was 35 kg.

#### Soil properties under agroforestry system compared to control

**Soil pH:** The soil pH data after tulsi harvest (Fig. 2) indicated no significant differences between pre-sowing and post-harvest values. Likewise, tulsi species fertilizer application, and their interaction (species × fertilizer) had no significant effect on soil pH.

**Electrical conductivity (dS m<sup>-1</sup>):** The soil electrical conductivity data after tulsi harvest (Fig.2) showed no significant differences between pre-sowing and post-harvest values. Similarly, tulsi species, fertilizer application, and their interaction (species × fertilizer) had no significant effect on soil EC.

Soil organic carbon (%): The soil organic carbon data presented in Fig.2 showed significant variation among tulsi species, fertilizers treatments, and their interaction (species  $\times$  fertilizer) under the aonla-based agroforestry system. Soil organic carbon increased slightly after crop harvest, ranging from 0.92-1.13% before sowing to 0.98-1.22% after harvesting. The highest soil organic carbon (1.22 %) was recorded in T<sub>3</sub>V<sub>2</sub> (Aonla + Vermicompost + Shyam tulsi) and T<sub>1</sub>V<sub>1</sub> (Aonla + NPK + Ram tulsi), while the lowest (0.98%) was observed in T<sub>4</sub>V<sub>1</sub> (Control + Ram tulsi)

Available Nitrogen (kg ha<sup>-1</sup>): Among the species, *Ocimum sanctum* (V<sub>1</sub>) recorded the highest available nitrogen (316.51 kg ha<sup>-1</sup>), followed by *Ocimum basilium* (V<sub>3</sub>) (310.86 kg ha<sup>-1</sup>), while the lowest was observed in *Ocimum tenuiflorum* (V<sub>2</sub>) (310.15 kg ha<sup>-1</sup>). Among fertilizer treatments, FYM significantly increased available nitrogen (341.55 kg ha<sup>-1</sup>), followed by vermicompost (336.31 kg ha<sup>-1</sup>), whereas the control recorded the lowest value (244.66 kg ha<sup>-1</sup>). The interaction effect revealed that T<sub>1</sub>V<sub>1</sub> (Aonla + NPK + Ram tulsi) produced the highest available nitrogen (347.46 kg ha<sup>-1</sup>), followed by T<sub>3</sub>V<sub>2</sub> (Aonla + FYM + Shyam tulsi ) (343.88 kg ha<sup>-1</sup>), while T<sub>4</sub>V<sub>1</sub> (Control + Ram tulsi ) recorded the lowest value (240.58 kg ha<sup>-1</sup>)

Available Phosphorus (kg ha<sup>-1</sup>): The available phosphorus differed significantly among species, fertilizer treatments and their interaction. Among the species, *Ocimum tenuiflorum* (V<sub>2</sub>) recorded the highest available phosphorus (31.47 kg ha<sup>-1</sup>), followed by *Ocimum sanctum* (V<sub>1</sub>) (30.93 kg ha<sup>-1</sup>) and *Ocimum basilium* (V<sub>3</sub>) (29.95 Kg ha<sup>-1</sup>). Among fertilizer treatments, FYM resulted in the highest available phosphorus (33.82 kg ha<sup>-1</sup>), followed by vermicompost (32.88 kg ha<sup>-1</sup>), while the control recorded the lowest value (24.04 kg ha<sup>-1</sup>). The interaction effect showed that T<sub>3</sub>V<sub>2</sub> (Aonla + FYM + Shyam tulsi) recorded the highest available phosphorus (3534 kg ha<sup>-1</sup>), followed by T<sub>3</sub>V<sub>1</sub> (Aonla + FYM + Ram tulsi) (34.50 kg ha<sup>-1</sup>), whereas T<sub>4</sub>V<sub>3</sub> (control + Bhabri) recorded the lowest value (23.06 kg ha<sup>-1</sup>).

Available Potassium (kg ha<sup>-1</sup>): The data on available potassium in the soil after tulsi harvest are presented in Fig.2. Available potassium varied significantly with fertilizer application and the species  $\times$  Fertilizer interaction, whereas species alone had no significant effect. The highest available potassium (259.52 kg ha<sup>-1</sup>) was recorded in T<sub>3</sub>V<sub>1</sub> (Aonla + Vermicompost + Ram tulsi), followed by T<sub>3</sub>V<sub>2</sub> (Aonla + Vermicompost + Shyam tulsi) with 258.00 kg ha<sup>-1</sup>, while the lowest (212.76 kg ha<sup>-1</sup>) was observed in T<sub>4</sub>V<sub>3</sub> (Control + Bhabri). Among fertilizer treatments, vermicompost resulted in significantly higher available potassium (257.16 kg ha<sup>-1</sup>), followed by FYM (254.38 kg ha<sup>-1</sup>), whereas the control recorded the lowest value (213.97 kg ha<sup>-1</sup>).

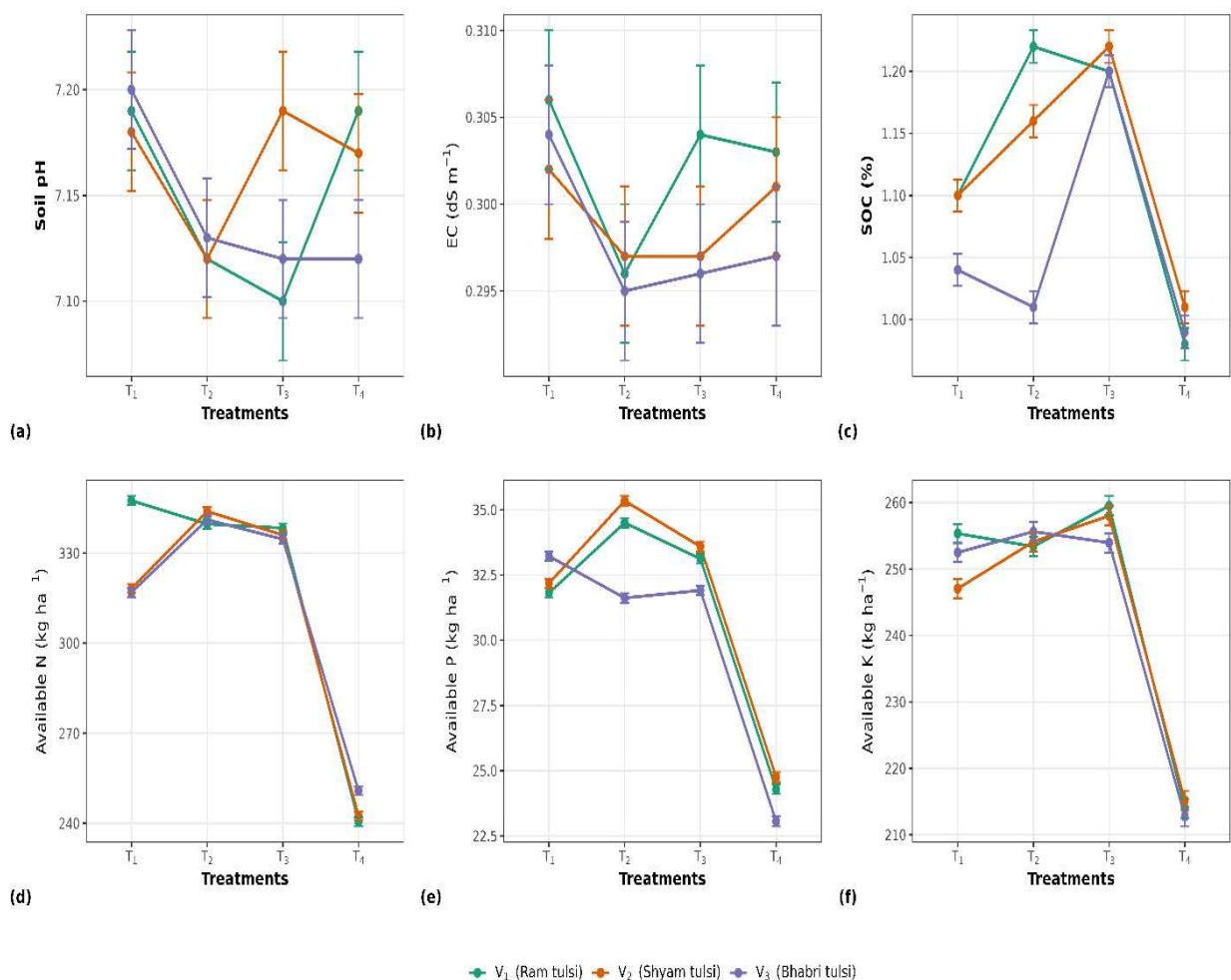


Fig. 2 Effect of different fertilizers and organic manures on soil pH, EC, OC, N, P, K under an Aonla-based agroforestry system

Table 9 - Bio-economic appraisal of Aonla-based agroforestry system

| Treatments                                                        | Cost of cultivation<br>(₹ ha <sup>-1</sup> ) | Total gross returns<br>(₹ ha <sup>-1</sup> ) | Total net returns<br>(₹ ha <sup>-1</sup> ) | B:C Ratio |
|-------------------------------------------------------------------|----------------------------------------------|----------------------------------------------|--------------------------------------------|-----------|
| T <sub>1</sub> V <sub>1</sub> (Aonla + NPK + Ram tulsi)           | 60619.1                                      | 197400                                       | 136781                                     | 3.26      |
| T <sub>1</sub> V <sub>2</sub> (Aonla + NPK + Shyam tulsi)         | 60298.4                                      | 183980                                       | 123682                                     | 3.05      |
| T <sub>1</sub> V <sub>3</sub> (Aonla + NPK + Bhabri)              | 60084.4                                      | 177800                                       | 117716                                     | 2.96      |
| T <sub>2</sub> V <sub>1</sub> (Aonla + FYM+ Ram tulsi)            | 59587.1                                      | 233700                                       | 174113                                     | 3.92      |
| T <sub>2</sub> V <sub>2</sub> (Aonla+ FYM+ Shyam tulsi)           | 59466.4                                      | 206640                                       | 147174                                     | 3.47      |
| T <sub>2</sub> V <sub>3</sub> (Aonla + FYM+ Bhabri)               | 59252.4                                      | 192850                                       | 133598                                     | 3.25      |
| T <sub>3</sub> V <sub>1</sub> (Aonla + Vermicompost+ Ram tulsi)   | 77287.1                                      | 261000                                       | 183713                                     | 3.38      |
| T <sub>3</sub> V <sub>2</sub> (Aonla + Vermicompost+ Shyam tulsi) | 76966.4                                      | 225560                                       | 148594                                     | 2.93      |
| T <sub>3</sub> V <sub>3</sub> (Aonla + Vermicompost+ Bhabri)      | 76752.4                                      | 215425                                       | 138673                                     | 2.81      |
| T <sub>4</sub> V <sub>1</sub> (Control Ram tulsi)                 | 37544.3                                      | 80400                                        | 42855.7                                    | 2.14      |
| T <sub>4</sub> V <sub>2</sub> (Control Shyam tulsi)               | 37223.3                                      | 62920                                        | 25696.7                                    | 1.69      |
| T <sub>4</sub> V <sub>3</sub> (Control Bhabri)                    | 37009.3                                      | 52325                                        | 15315.7                                    | 1.41      |

An economic evaluation of the aonla-based agroforestry system involving *Ocimum* species was conducted. Table 9 summarizes the cost of cultivation, gross returns, net returns, and benefit–cost ratio of tulsi under the different treatment combinations.

#### **Cost of cultivation**

The expenditure of growing three different systems was calculated on the basis of per hectare. The examination of costs revealed a wide range of significant disparities between the various treatments. Estimates of the benefit cost ratio in relation to the variable cost were made in order to arrive at a decision regarding the most appropriate economic treatment and the findings are provided in Table 9. Amongst the different treatments given, the maximum cost of cultivation (₹77287.1) was observed in T<sub>3</sub>V<sub>1</sub> (Aonla + Vermicompost+ Ram tulsi), while the minimum cost of cultivation (₹ 37009.3) was observed for the treatment, T<sub>4</sub>V<sub>3</sub> (Control Bhabri).

#### **Total gross returns**

The maximum gross returns (₹ 261000) were observed for treatment T<sub>3</sub>V<sub>1</sub> (Aonla + Vermicompost+ Ram tulsi), while the minimum (₹ 52325), for T<sub>4</sub>V<sub>3</sub> (Control Bhabri). Optimal gross returns were achieved under the aonla based agroforestry system, which can be attributed to the supplementary revenue produced by fruit trees in contrast to monoculture agriculture.

#### **Total net returns**

The findings obtained for the net return revealed that the maximum net returns (₹183713) were gained from T<sub>3</sub>V<sub>1</sub> (Aonla + Vermicompost+ Ram tulsi) and the minimum (₹15315.7) from T<sub>4</sub>V<sub>3</sub> (control Bhabri).

#### **Benefit-cost ratio**

The table 9 interprets, that the maximum B:C was recorded in Aonla + Ram tulsi +FYM (3.92), while the minimum was recorded in Control Bhabri (1.41). Highest gross (₹ 261000) and net returns (₹183713) were obtained from T<sub>3</sub>V<sub>1</sub> (Aonla + Vermicompost+ Ram tulsi).

#### **Discussion**

##### **Agro-morphological traits**

The use of various fertilizers under the aonla-based agroforestry system had a substantial impact on the agro-morphological characteristics of tulsi, specifically plant height and number of leaves (Tables 3 and 4). Significant differences between the *Ocimum* species and fertilizer treatments were found in observations made at 30, 60, and 90 DAS and at harvest. Both parameters differed significantly across species, and their interaction with fertilizer application. Vermicompost application with Bhabri tulsi was the most effective combination for promoting vegetative growth under the aonla-based agroforestry system, as evidenced by T<sub>3</sub>V<sub>3</sub> (Aonla + Vermicompost + Bhabri), which consistently recorded the highest plant height and number of leaves among all treatment combinations. According to Dhakad et al. (2024) observed that the application of organic nutrient management practices significantly promotes plant growth and leaf production in *Ocimum basilicum*. Similarly, Thakur et al.2025; Lhaj et al. (2025) found that compost application enhanced soil fertility and basil growth. These findings are consistent with the present study, where vermicompost significantly improved the agro-morphological traits of tulsi under the aonla based agroforestry system.

The total chlorophyll concentration varied significantly between *Ocimum* species and fertilizer treatments at 60 and 90 DAS under the aonla-based agroforestry system (Table 5). Chlorophyll content was highest in vermicompost and lowest in the control. Improved nutrient availability and photosynthetic activity could be the cause of the increased chlorophyll content under vermicompost. Similar findings were reported by Nagbanshi and Mishra (2024) and Mishra

et al. (2022), who noted higher levels of chlorophyll under better fertilizer management and notable heterogeneity in chlorophyll content among *Ocimum* species.

Root fresh and dry weight were significantly higher under vermicompost application than under the other fertilizer treatment. The increased root biomass may be attributed to the sustained availability of nutrients, improved soil aggregation, enhanced microbial abundance and activity, and the presence of humic substances, which collectively stimulate root growth, nutrient uptake, and water absorption. Similar findings have been reported by Raj et al. (2022); Biswas et al. (2025), who demonstrated that organic nutrient management significantly enhances root growth and biomass accumulation in *Ocimum* species.

Vermicompost application significantly enhanced shoot fresh weight, shoot dry weight, and total (fresh and dry) compared to all other fertilizer treatments. This pronounced biomass accumulation reflects the superior physiological environment fostered by vermicompost. Unlike conventional inorganic fertilizers, vermicompost provides a balanced, synchronized release of macro-and micronutrients aligned with crop demand. The continuous nutrient supply enhances photosynthetic pigments and enzymatic activity, thereby driving higher carbon assimilation and optimizing source-to-sink photossimilate translocation. Furthermore, the bioactive humic substances and plant growth -promoting microorganism inherent to vermicompost improve root architecture, optimizing nutrient uptake efficiency and stimulating cellular expansion. Similar study by Wang et al. (2021) observed a 56% increase in cucumber yield after applying vermicompost. According to Devi et al. 2026 and Munnu (2011) also reports similar important results, where a combination of vermicompost at 5 t ha<sup>-1</sup> and 50% of the recommended NPK fertilizer (100:25:25 kg ha<sup>-1</sup>) led to much better growth and a higher yield of fresh herbage than the full dose of fertilizer NPK (200:50:50 kg ha<sup>-1</sup>) in geranium (*Pelargonium graveolens*). Accordingly, Maheshwari et al. (2023), observed that the maximum fresh herb yield, maximum dry weight yield was observed by the application of vermicompost with recommended dose of fertilizers in sweet basil.

The higher agronomic efficiency (AE) recorded with FYM and vermicompost compared with NPK may be attributed to their slow and synchronized nutrient release, improved soil organic matter, enhanced microbial activity, and better root development, which collectively increase nutrient uptake and utilization. In contrast, sole application of inorganic fertilizers is often associated with greater nutrient losses, resulting in lower nutrient use efficiency. Similar findings have been reported by Rehman et al. (2023), who demonstrated that vermicompost enhances nutrient uptake and fertilizer use efficiency, and by Biswas et al. (2025), who observed improved growth, yield, and nutrient use of efficiency of *Ocimum* under organic nutrient management.

The significant increase in essential oil yield under vermicompost application likely stems from greater nutrient uptake, enhanced rhizosphere bioactivity, robust root development, and stimulated biosynthesis of target secondary metabolites. Vermicompost also improves soil physical and biological properties, thereby enhancing plant growth and oil accumulation. Similar findings were reported by Biswas et al. (2025), who observed that vermicompost significantly increased fresh herbage yield, essential oil content, and eugenol concentration in holy basil (*Ocimum* species) compared with the control. Singh et al. (2014) in the case of Indian basil, Singh and Guleria (2012) in the case of rosemary, Bistagani et al. (2018) in the case of Denaian thyme (*Thymus daenensi*), Singh and Wasnik (2013) in the case of rosemary and Verma (2016) in the case of *Mentha piperita*.

Growth and yield parameters of trees

The growth and yield attributes of aonla, including tree height, stem diameter, crown spread, number of branches, and fruit yield (Table 8) were improved under organic nutrient management, particularly with vermicompost. This improvement may be attributed to the sustained release of nutrients, enhanced soil physical properties, improved microbial activity, and better root development, which collectively promoted vegetative growth, canopy expansion, and fruit production. The higher fruit yield under organic treatments is likely due to improved photosynthetic efficiency, better flowering and fruit retention, and balanced nutrient availability throughout the growing season.

Similar findings have been reported by recent studies, where vermicompost and integrated nutrient management significantly improved tree growth and fruit yield in aonla (Dhakar et al. 2025; Pandey et al.2025).

#### Soil properties

Agroforestry systems generally improve organic carbon, and the availability of nitrogen, phosphorus and potassium compared with monocropping, thereby enhancing overall soil health. Several studies have demonstrated that agroforestry systems improve soil fertility and nutrients status. Verma et al. (2023) and Bhatia et al. (2024) reported enhanced soil fertility and nutrient availability under agroforestry systems, while Rana et al. (2026); Dori et al. (2022) observed significant improvements in soil properties across different agroforestry systems and topographical gradients. Vermicompost serves as a valuable organic nutrient source that enhances soil fertility while stimulating plant growth Guerrero (2010); Rehman et al. (2023). In the present study, vermicompost improved soil productivity by enhancing its physical, chemical, and biological properties. Similar findings were reported by Kumar et al. (2023), who observed significantly higher available nitrogen, phosphorus and potassium with vermicompost application. Likewise, Tripathi et al. (2020) reported that integrating agroforestry with organic manures improves soil physicochemical properties. The beneficial effects of vermicompost on soil structure, nutrient availability, microbial activity, and sustainable crop production have also been well documented by Xue et al. (2022) and Toor et al. (2024), who reported that vermicompost significantly improved soil health and crop performance.

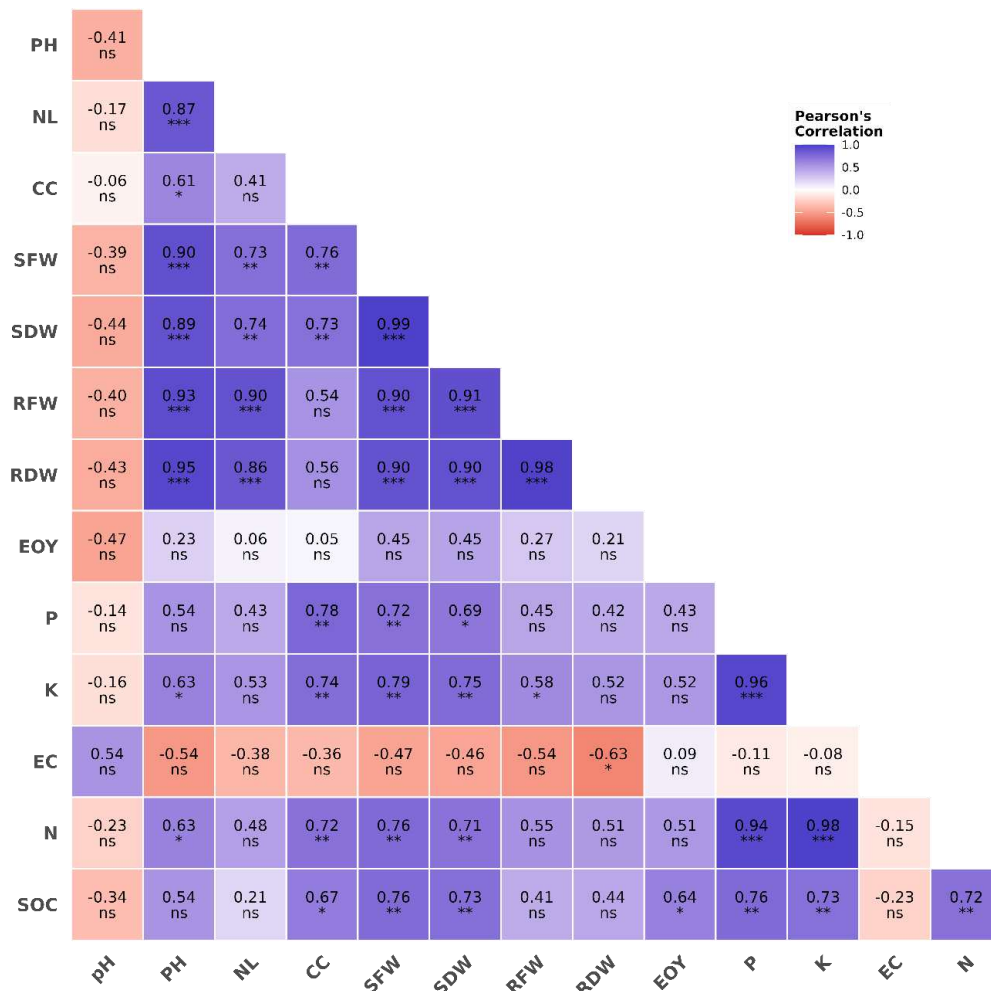


Fig. 3 - Correlation between Agro-morphological traits and soil parameters of tulsi. Whereas pH, Soil pH; PH, Plant Height; NL, Number of Leaves; CC, Chlorophyll Content; SFW, Shoot Fresh Weight; SDW, Shoot Dry Weight; RFW, Root Fresh Weight; RDW, Root Dry Weight; EOY, Essential oil Yield; SOC, Soil Organic Carbon; EC, Electric Conductivity; N, Available Nitrogen; P, Available Phosphorus; K, Available Potassium

Correlation between Agro-morphological traits and soil parameters of tulsi

Pearsons's correlation analysis revealed strong positive associations between most plant growth attributes and soil physicochemical properties (Fig. 3). Among the growth parameters, shoot fresh weight, shoot dry weight, and root dry weight exhibited positive correlations with the measured soil properties. Shoot fresh weight showed particularly strong correlations with available nitrogen (N;  $r = 0.76$ ), available potassium (K;  $r = 0.79$ ), and soil organic carbon (SOC;  $r = 0.76$ ). Similarly, shoot dry weight was strongly correlated with available nitrogen ( $r = 0.71$ ). Essential oil yield (EOY) also displayed a positive association with soil organic carbon, with a correlation coefficient of  $r = 0.64$ , indicating the importance of soil organic matter in enhancing essential oil production.

Conversely, electrical conductivity (EC) negative relationships with nearly all the studied variables, with the strongest negative correlations observed for root dry weight (RDW;  $r = -0.63$ ) and root fresh weight (RFW;  $r = -0.54$ ). The observed negative correlation between electrical conductivity (salinity) and root biomass can be attributed to osmotic stress, which alters morphological development in *Ocimum* plants Pandey et al. (2021). The continuous turnover and decomposition of aonla leaf litter enhance soil organic carbon; however, a healthy rhizosphere without high salinity

constraints is a prerequisite for the optimal development of *Ocimum* roots and overall plant biomass. Furthermore, improved nutrient availability, such as nitrogen and potassium, enhances root absorption and the translocation of resources, contributing to localized improvements in crop quality in nutrient-rich plots. Consequently, plots with higher electrical conductivity have lower root biomass. These results are aligned with the findings of Jadczyk et al. (2022) and Moradzadeh et al. (2021) who reported a strong correlation between crop growth parameters and soil characteristics such as organic carbon, N, P, K, and salinity status.

## Bio economics

Cultivating medicinal plants under multistorey agroforestry systems is a viable strategy for increasing farm profitability and generating sustainable income. Among agroforestry systems, horti-medicinal systems are particularly effective in enhancing farmers livelihood by increasing farm income Sarkar et al. (2024). In the present study, the tulsi-based aonla agroforestry system generated higher net returns than sole tulsi cultivation, primarily due to the additional income from aonla trees. Moreover, the application of organic manures, especially vermicompost, further increased net returns by improving tulsi productivity. These finding are consistent with those reported in previous studies, which informed that integrating medicinal crops fruit trees and adopting organic nutrient management enhances systems productivity, profitability and economic sustainability. Kumar et al. (2023) reported greater economic returns and B:C ratio in *Grewia-bhringraj* intercropping than in sole bhringraj cultivation. Similarly, Thakur et al. (2019) observed net returns and B:C ratio in a *Pongamia pinnata-Ocimum* Silvi-medicinal system, while Chauhan et al. (2024) reported a significantly higher B:C ratio (5.34) in a marigold-*Mangifera indica* agroforestry system, highlighting the economic superiority of agroforestry over monocropping.

## Conclusion

The present study demonstrated that integrating tulsi with aonla under organic nutrient management is a promising agroforestry strategy for enhancing productivity, soil fertility, and farm profitability in the subtropical low hill zone of the north-western Himalayas. Among the nutrient management practices, vermicompost @ 10t ha<sup>-1</sup> consistently produced superior growth, chlorophyll content, biomass accumulation and nutrient- use efficiency across the tulsi species. *Ocimum basilicum* exhibited the highest vegetative growth and biomass production, whereas *Ocimum sanctum* recorded the maximum essential oil yield (9.06 kg ha<sup>-1</sup>). Organic nutrient sources, particularly vermicompost and FYM, also improved soil organic carbon and the availability of N, P, and K, thereby supporting long-term soil health and sustainable production. The aonla-tulsi agroforestry system proved economically viable, with vermicompost-based treatments generating the highest gross and net returns, while FYM-based treatments recorded the maximum benefit-cost ratio (3.92). Therefore, integrating *Ocimum basilicum* and *Ocimum sanctum* with aonla using organic nutrient sources, especially vermicompost and FYM, is recommended as a productive, sustainable, and economically viable land-use option for similar agro-ecological regions. Further long-term and multi-location studies are essential to confirm the wider applicability and consistency of this agroforestry system across different environments.

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## Author contributions

Saakshi: Written original draft, Methodology, Investigation, Formal analysis, Data collection, analysis. Vipin Guleria: Conceptualizing, Supervision, Methodology Validation, review and editing. Renu Kapoor: Supervision,

547 methodology, Sahil Chauhan: Visualization, reviewed & Data Analysis, Prashant Rana: Data collection, Writing,  
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552 **Declarations**

553 **Competing interests** The authors declare no competing interests

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