InternationalJournalofEnvironmentalSciences
ISSN:2229-7359
Vol.11No.22s,2025
https://www.theaspd.com/ijes.php

Impact OfTraditionalVrikshayurveda FormulationsOn GrowthAndPhytochemicalProfilesOfIntercropped Ocimum Sanctum

[1]AnjuKumariThakur,[2]Dr.DeepNarayanPandeyRetdIFS,[3]Dr.GulshanKumar
[1]ResearchScholar,SchoolofBasic&AppliedSciences,CareerPointUniversity,Bhoranj(Tikker-Kharwarian), Hamirpur, Himachal Pradesh 176041, India
[2]NIAJaipur,SchoolofBasic&AppliedSciences,CareerPointUniversity,Bhoranj(Tikker-Kharwarian), Hamirpur, Himachal Pradesh 176041, India
[3]AssistantProfessor(Botany)SchoolofBasic&AppliedSciences,CareerPointUniversity,Bhoranj (Tikker-Kharwarian), Hamirpur, Himachal Pradesh 176041, India

*CorrespondenceforAuthor:anjusai9omthakur999@gmail.com

Abstract
Therevivalofancientagroecologicalknowledge,particularlyVrikshayurveda,offerspromisingsolutionsforsustainable agriculture and conservation of medicinal plants. This study investigates the impact of two traditional bioformulations—Kunapajala and Panchagavya—on the growth performance, physiological health, and phytochemical enrichmentof Ocimumsanctum (Tulsi)intercroppedwith Solanumtuberosum (Potato)intheHamirpurregionof HimachalPradesh,India.Arandomizedblockdesignwithsixtreatments(Control,FYM,RDF,Kunapajala, Panchagavya, and Kunapajala + Panchagavya) was implemented under field conditions. Growth attributes such as plantheight,leafarea,biomass,androotarchitectureshowedsubstantialimprovementintheKunapajala+ Panchagavyatreatment.Phytochemicalanalysisrevealedelevatedchlorophylla(1.45mg/g),chlorophyllb(0.64 mg/g), total carotenoids (0.38 mg/g), anthocyanins (0.37 mg/g), and total pigment concentration (3.1 mg/g). The treatment also enhanced ascorbic acid (24.5 mg/100g), total soluble proteins (1.91 mg/g), and essential oil yield (0.61%). Moisturecontentandashcontentwererecorded at80.5%and2.9%, respectively. Soilnutrientuptakewas significantlyhigher,withN(2.7%),P(0.37%),K(2.1%),andmicronutrientssuchasFeandZnreaching148ppm. Total acid concentration in Tulsi leaf extracts reached 4.3, reflecting enhanced biosynthetic activity. These findings demonstrate the efficacy of Vrikshayurveda bioformulations in promoting phytochemical richness, nutrient density, andsustainablecultivationofmedicinalplants.Thisintegrativeeco-centricfarmingapproachnotonlyalignswith SDG goals on health, biodiversity, and sustainable agriculture but also reinforces the relevance of traditional knowledge systems in climate-resilient, low-input, organic crop production.
Keywords:*Eco-centricfarming,essentialoil,intercropping,Kunapajala,medicinalplantconservation,Ocimum sanctum,Panchagavya,phytonutrients,rootbiomass,Vrikshayurveda.*

1. Introduction:

Theintensificationofmodernagriculturehasundoubtedlyincreasedfoodproductionbutatthecostof long-termecologicalstabilityandhumanwell-being.Overrelianceonsyntheticfertilizers,pesticides,and monocropping systems has led to alarming consequences such as soil degradation, nutrient depletion, biodiversity loss, and residual toxicity in crops (Tilman et al., 2002; Pretty & Bharucha, 2014; FAO, 2021). These trends are particularly concerning for medicinal and aromatic plants (MAPs), which are highly sensitive to soil and environmental conditions and have shown a notable decline in therapeutic qualitywhencultivatedunderconventionalregimes(Yadav et al.,2012).

Oneofthemostreveredmedicinalplants,*Ocimumsanctum*L.(commonlyknownasTulsiorHolyBasil), holds a sacred status in Indian households and is a cornerstone of the Ayurvedic pharmacopeia. It is widely valued for its antioxidant, antimicrobial, immunomodulatory, and adaptogenic properties (Yadav et al.,2012). The bioefficacy of Tulsi depends heavily on the soil microbiome,root-zonehealth,andnatureofinputapplication(Mishra,2007).Unfortunately, chemical-based cultivation practices have been shown to degrade not only plant quality but also compromisesoilfertilityandlong-termecologicalfunctions(Chakraborty et al., 2019;Mishra, 2007).

1.1ReclaimingTraditionalWisdomthroughVrikshayurveda

The growing awareness of climate resilience and the limitations of chemical agriculture has led to a renewed interest in indigenous plant sciences,particularly *Vrikshayurveda*, an ancient Sanskrit treatise on plant life. Rooted in holistic, ecosystem-based thinking, *Vrikshayurveda* provides a comprehensive system of plant health management, soil fertility restoration, and disease prevention using natural inputs (Sadhale, 1996; Surapala,1000 CE; Nene, 2006).

Keyformulationsprescribedin*Vrikshayurveda*include:

Kunapajala: Kunapajala is a traditional organic formulation described in Vrikshayurveda, prepared by fermenting a mixture of animal and plant materials. It is rich in beneficial microorganisms, growth-promoting hormones, enzymes, vitamins, and bio-pesticidal compounds, which play key roles in crop growth and development (Chakraborty et al., 2019; Mishra, 2007). Kunapajala has been shown to enhance soil fertility, improve plant health, and increase crop yields. It is particularly effective when applied as a foliar spray or soil drenching (Mishra, 2007; Nene, 2018).

Panchagavya: A Probiotic mixture of five cow-derived products—dung, urine, milk, curd, and ghee with demonstrated benefits on plant immunity, growth hormones, and soil micro biota (Ghosh et al., 2020; Rengasamy, 2006; Thakur et al., 2025).

In this study, considering the sacred and ritual significance of Tulsi, we adopted an ethical adaptation of *Kunapajala*, eliminating animal parts and instead using plant-based ingredients, fruit and vegetable peels, and kitchen waste. This aligns with the principles of non-violence, sanctity, and sustainability in sacred plant cultivation (Chakraborty et al., 2019; Khan, 2009; Sadhale, 1996).

Ethical Adaptation of Kunapajala

In this study, considering the sacred and ritual significance of Tulsi, we adopted an ethical adaptation of Kunapajala, eliminating animal parts and instead using plant-based ingredients, fruit and vegetable peels, and kitchen waste. This aligns with the principles of non-violence, sanctity, and sustainability in sacred plant cultivation (Chakraborty et al., 2019).

1.2 Intercropping as a Strategy for Land Optimization and Soil Health

Intercropping is an agricultural practice where two or more crops are cultivated simultaneously on the same piece of land. This system is increasingly recognized as a key strategy for sustainable intensification of agriculture, particularly in regions facing land constraints or challenging terrains (Altieri & Nicholls, 2020; Brooker et al., 2015). By combining crops with complementary growth patterns and nutrient requirements, intercropping maximizes the efficient use of land, sunlight, and soil resources.

In the context of Himachal Pradesh, integrating *Ocimum sanctum* (Tulsi) with a staple crop like *Solanum tuberosum* (potato) offers multiple advantages. Tulsi, a medicinal herb with high economic and ecological value, grows well alongside potato, a nutrient-demanding tuber crop. This combination not only improves land-use efficiency but also enhances on-farm biodiversity, which is critical for ecosystem resilience in hilly terrains (Thakur et al., 2025)

Functional diversity in intercropping systems promotes ecological benefits such as improved nutrient cycling, enhanced soil structure, better water retention, and natural suppression of pests and diseases. In addition, intercropping contributes to increased overall farm productivity by enabling multiple harvests and reducing the risk of total crop failure. Traditional bioformulations of Vrikshayurveda, such as Panchagavya and Kunapajala, have demonstrated growth-promoting and yield-enhancing effects in monocrops, including mustard (*Brassica juncea*), tomato (*Solanum lycopersicum*), and rice (*Oryza sativa*) (Debnath et al., 2015; Dwivedi et al., 2022). However, there remains a significant research gap in evaluating these formulations under intercropping conditions, especially involving medicinal plants like Tulsi. Systematic field studies are required to validate the potential of these organic formulations for enhancing crop growth, soil fertility, and ecological sustainability in intercropping systems (Thakur et al., 2025).

1.3 Literature Review and Research Gaps

Traditional bio-inputs such as *Panchagavya* and *Kunapajala* have garnered attention for their roles in promoting plant growth, enhancing microbial activity, and improving crop resilience. Studies have

InternationalJournalofEnvironmentalSciences
ISSN:2229-7359
Vol.11No.22s,2025
https://www.theaspd.com/ijes.php

demonstrated their efficacy in various crops, including rice, basil, mustard, and tomatoes, leading to increased chlorophyll content, yield, root biomass, and stress resistance (Ghosh et al., 2020; Chakraborty et al., 2019; Bhardwaj et al., 2020; Sundaramoorthy et al., 2021). Additionally, these formulations have been shown to enhance soil health by increasing organic carbon content and microbial enzyme activities (Chakraborty et al., 2019; Bhardwaj et al., 2020).

Identified Research Gaps: Despite these promising outcomes, several critical gaps persist:

1. **Limited Exploration of Medicinal Plant Intercropping Systems**: While intercropping systems involving food crops have been extensively studied, there is a paucity of research focusing on medicinal plants like *Tulsi* (*Ocimum sanctum*) when intercropped with food crops. Studies suggest that intercropping Tulsi with crops such as potato can improve soil health and crop yield under Vrikshayurveda practices (Sundaramoorthy et al., 2021).
2. **Underutilization of Kitchen Waste in Kunapajala Preparation**: Traditional *Kunapajala* formulations typically utilize animal and plant residues. However, limited data exists on the preparation and efficacy of herbal *Kunapajala* using kitchen waste and plant residues, particularly under sacred cultivation constraints. Recent explorations indicate potential benefits from utilizing such waste materials for sustainable nutrient cycling (Ghosh et al., 2020; Chakraborty et al., 2019).
3. **Insufficient Evaluation of Phytonutrient Biosynthesis**: While the impact of traditional bio-inputs on plant growth is well-documented, minimal studies have evaluated their effects on phytonutrient biosynthesis, including chlorophyll, carotenoids, anthocyanins, total acids, ascorbic acid, and essential oils (Ghosh et al., 2020; Sundaramoorthy et al., 2021). This represents a significant knowledge gap in understanding the Nutraceuticals benefits of these inputs.
4. **Absence of Comparative Analysis in Himalayan Agroecological Zones**: There is a notable absence of comparative studies evaluating the efficacy of traditional bio-inputs against chemical inputs such as RDF and FYM in Himalayan agroecological zones. Thakur et al. (2024) emphasize the need for such studies to understand the relative advantages and limitations of these inputs under region-specific conditions.

Addressing these research gaps is crucial as India strives to develop scalable, culturally rooted, and climate-resilient organic farming systems that contribute to both food security and medicinal biodiversity conservation. Future research should focus on medicinal plant intercropping, the use of kitchen waste in bio-input preparation, evaluation of phytonutrient biosynthesis, and comparative analyses across diverse agroecological zones (Pretty & Hine, 2001; Tilman et al., 2011; United Nations, 2015).

1.4 Objectives of the Study

1. To evaluate the effect of Vrikshayurveda-based bioformulations (*Kunapajala* and *Panchagavya*) on the morphological traits of *Ocimum sanctum*, including leaf, stem, inflorescence, and flower characteristics, when intercropped with *Solanum tuberosum*.
2. To quantify physiological and biochemical changes in Tulsi, including chlorophyll, carotenoids, total acids, ascorbic acid, phenolics, flavonoids, and essential oil content in leaves, stems, and flowers, under different treatments.

2. Methodology

2.1 Site Description: The field experiment was conducted during the *Rabi* season in the agricultural fields of Hamirpur district, Himachal Pradesh (Latitude 31.7°N, Longitude 76.5°E, altitude ~780 m above sea level). This region falls under the sub-tropical lower Himalayan agro-climatic zone characterized by moderate rainfall (800–1100 mm annually) and average temperatures ranging from 9°C (winter) to 34°C (summer). The soil texture is sandy loam, slightly acidic to neutral in nature (pH 6.2–6.8), and has moderate fertility with low nitrogen and organic carbon levels prior to experimentation (Thakur et al., 2024). Figure1 depict the map the experimental site where *Ocimum sanctum* (Tulsi) was intercropped with *Solanum tuberosum* (potato). The red square indicates the precise experimental site.

The surrounding districts and major towns are marked for geographic reference.

Figure1. Experimental site location in Hamirpur, Himachal Pradesh, India. Source: Adapted from Survey of India topographic maps and local district maps (Choudhary et al., 2023).

2.2 Experimental Design: A Randomized Complete Block Design (RCBD) was used to assess the impact of *Vṛkṣāyurveda* bioformulations on the growth, physiology, and phytochemical content of *Ocimum sanctum* (Tulsi) intercropped with *Solanum tuberosum* (potato). The experiment included six treatments: T_0: Control (no input), T_1: Recommended Dose of Fertilizers (RDF), T_2: Farmyard Manure (FYM), T_3: *Kunapajala* (herbal formulation), T_4: *Panchagavya*, T_5: *Kunapajala* + *Panchagavya* (50:50 mix)

Each treatment was replicated three times, with each plot measuring 1.8×1.8 m^2 and intercropping carried out at a 1:1 ratio (Tulsi: Potato). Spacing between Tulsi plants was maintained at 30 cm, while potato was sown at 15 cm spacing to ensure balanced inter-specific competition and land-use optimization. Row-to-row spacing was 45 cm (Choudhary et al., 2023; Sadhale, 1996).

2.2 Crop and Intercropping: **Main crop:** *Ocimum sanctum* (Tulsi); **Intercrop:** *Solanum tuberosum* (Potato); Standard spacing and agronomic practices will be followed. **In figure 2.** Experimental layout of Tulsi (***Ocimum sanctum***) intercropped with potato (***Solanum tuberosum***) under field conditions in Barsar, Himachal Pradesh, India has been shown. The image shows labeled plots with seedlings and shading arrangements, illustrating the randomized block design (RBD) setup used for evaluating the effects of Vrikshayurveda formulations (Kunapajala and Panchagavya) on plant growth and biomass allocation.

InternationalJournalofEnvironmentalSciences
ISSN:2229-7359
Vol.11No.22s,2025
https://www.theaspd.com/ijes.php

Figure2. Experimental layout of Tulsi (***Ocimum sanctum***) intercropped with potato (***Solanum tuberosum***) under field conditions in Barsar, Himachal Pradesh, India.

Source: Field photograph taken at Barsar, Himachal Pradesh, India (Lat 31.496411°, Long 76.459505°) on 08 June 2024 at 02:14 PM GMT+05:30 using GPS Map Camera.

2.3 Bioformulation Preparation

2.3.1 *Kunapajala* (Herbal Variant)

As the focal crop, *Ocimum sanctum*, holds sacred and religious significance, a strictly herbal version of *Kunapajala* was used in this study in accordance with Ayurvedic and *Vṛkṣāyurveda* ethical considerations. Following guidelines from Surapala's *Vṛkṣāyurveda* (9th–10th century CE) and interpretations by **Sadhale (1996)**, animal-derived substances were omitted. Instead, the fermented concoction was prepared using: Vegetable and fruit peels (banana, papaya, citrus, apple, cucumber, etc.), Kitchen wastes (biodegradable leftovers), Weed biomass and green leaves (*Calotropis*, *Azadirachta indica*, *Cassia tora*), Residues of pulses and legumes, Cow dung and urine (in small proportion) as microbial starters. The mixture was fermented for 30 days in earthen pots, stirred daily, and kept in the shade to facilitate microbial activity. The final product was filtered and applied weekly as a foliar spray and soil drench (**Chakraborty et al., 2019**; **Thakur et al., 2024**).

2.3.2 *Panchagavya*

Panchagavya was prepared as per traditional protocols mentioned in classical texts and supported by modern studies (**Patil et al., 2020**; **Somasundaram et al., 2007**). The formulation included: Fresh cow dung (7 kg), Cow urine (3 L), Cow milk (2 L), Curd (2 L), Ghee (0.5 kg). Fermentation occurred over 15 days with daily stirring. Jaggery and mashed bananas were added to enhance microbial activity (**Bharadwaj et al., 2020**).

2.4 Parameters Studied

2.4.1 Morphological Observations (Objective 1)

Morphological parameters were recorded to assess plant growth, biomass allocation, and structural development under different treatments. The parameters included:

Leaves – Leaf area (cm^2) was measured using the graph paper method (Montgomery, 1911). The number of leaves per plant was counted manually, and fresh and dry leaf biomass (g/plant) was measured after oven-drying at 65°C until constant weight (AOAC, 2016).

Stem – Plant height (cm) was measured from the base to the apical bud using a measuring scale, and the number of branches per plant was counted manually.

Inflorescence/Flowers – The number of flower branches per plant was counted at full bloom, and flower biomass (g/plant) was measured for fresh and dry weight to assess reproductive allocation.

2.4.2 Physiological Measurements (Objective 2)

Physiological traits were evaluated to assess photosynthetic potential, pigment composition, and leaf water status:

- **Chlorophyll content (mg/g FW)** – chlorophyll a, b, and total chlorophyll were extracted in

80% acetone and quantified using UV-Vis spectrophotometry following Arnon (1949) and Lichtenthaler & Wellburn (1983).

- **Carotenoids (mg/g FW)** – quantified spectrophotometrically using standard protocols (Lichtenthaler & Wellburn, 1983).
- **Leaf moisture content (%)** – determined by oven-drying at 65°C until constant weight (AOAC, 2016).

2.5 Biochemical and Phytochemical Analysis (Objective 2)

Leaf biochemical constituents and bioactive compounds were analyzed using standard analytical methods: **Total acids (%)** – determined by titration with NaOH (AOAC, 2016).

Ascorbic acid (mg/100 g FW) – quantified using 2,6-dichlorophenolindophenol (DCPIP) titration method (Ranganna, 2001). **Total soluble proteins (mg/g FW)** – estimated using Lowry et al. (1951) method. **Moisture content (%)** – oven-drying at 65°C until constant weight (AOAC, 2016). **Ash content (%)** – incineration in a muffle furnace at 550°C (AOAC, 2016). **Essential oil content (% v/w)** – extracted from leaves, stems, and flowers using Soxhlet extraction or hydro-distillation (Clevenger, 1928) and, if available, analyzed using GC-MS. **Phenolics and flavonoids** – quantified using Folin–Ciocalteu and aluminum chloride methods, respectively (Singleton & Rossi, 1965; Chang et al., 2002).

2.6 Nutrient Analysis

Post-harvest leaf samples were analyzed to assess plant nutrient uptake: **Total Nitrogen (%)** – determined using the Kjeldahl method (AOAC, 2016). **Available Phosphorus (%)** – quantified following Olsen's method adapted for plant tissue (Olsen et al., 1954). **Available Potassium (%)** – measured using flame photometry (AOAC, 2016). **Micronutrients (Fe, Zn in ppm)** – analyzed using Atomic Absorption Spectroscopy (AAS) (AOAC, 2016). All analyses were performed according to standard AOAC (2016) protocols.

2.7 Statistical Analysis: Data were analyzed using **one-way ANOVA** at $p < 0.05$ significance level, and post-hoc comparisons were performed using **Tukey's HSD test** (Sharma & Mishra, 2024). Results are expressed as **mean ± standard error (SE)** for three replications. Correlation analyses were performed to assess relationships between morphological, physiological, and biochemical traits.

3. Results and Observations

3.1 Morphological Growth Performance

Significant morphological differences were observed among treatments. The combination of *Kunapajala* and *Panchagavya* led to the maximum plant height (48.3 cm) and highest leaf area (94.2 cm²) in *Ocimum sanctum* when intercropped with *Solanum tuberosum*. This treatment also exhibited a robust root system (length 19.1 cm) and enhanced shoot biomass (18.9 g plant^{-1}), outperforming both chemical fertilizer (NPK) and farmyard manure (FYM) applications (Table 1).

Table1. Effect of treatments on morphological traits of *Ocimum sanctum*

Treatment	Plant Height (cm)	Leaf Area (cm²)	Root Length (cm)	Shoot Biomass (g)
Control	**24.6**	**48.2**	**12.5**	**10.2**
FYM	**32.7**	**58.3**	**14.1**	**11.7**
NPK	**39.2**	**71.6**	**15.4**	**13.6**
Kunapajala	**42.8**	**79.3**	**17.2**	**16.1**
Panchagavya	**44.1**	**82.6**	**17.8**	**16.9**
Kunapajala* + *Panchagavya	**48.3**	**94.2**	**19.1**	**18.9**

Source: These findings align with the results of Chakraborty et al. (2019) and Tilman et al. (2011), who emphasized the growth-promoting effects of organic bio-stimulants and sustainable soil inputs.

3.2 Pigment and Biochemical Content

Chlorophyll content was highest in plants treated with *Kunapajala* + *Panchagavya*, registering chlorophyll a: 1.45 mg/g FW, chlorophyll b: 0.64 mg/g FW, total chlorophyll: 2.09 mg/g FW, carotenoids: 0.38 mg/g FW, and anthocyanins: 0.37 mg/g FW (Table 2).

Table2. Photosynthetic pigment and biochemical contents in *Ocimum sanctum* leaves

Treatment	Chl-a (mg/g FW)	Chl -b	Total Chl	Carote noids	Anthocya nins
Control	**0.91**	**0.42**	**1.33**	**0.22**	**0.21**
FYM	**1.11**	**0.52**	**1.63**	**0.28**	**0.27**
NPK	**1.23**	**0.57**	**1.80**	**0.31**	**0.30**
Kunapajala	**1.34**	**0.61**	**1.95**	**0.36**	**0.35**
Panchagavya	**1.39**	**0.63**	**2.02**	**0.37**	**0.36**
Kunapajala* + *Panchagavya	**1.45**	**0.64**	**2.09**	**0.38**	**0.37**

Source: These values indicate improved photosynthetic capacity and antioxidative defense, supporting prior findings on bioformulations enhancing metabolic functions (Bhardwaj et al., 2021; Altieri & Nicholls, 2020).

3.3 Phytochemical Profile of *Ocimum sanctum*

GC-MS and spectrophotometric analyses showed higher secondary metabolite production under bioformulation treatments. The *Kunapajala* + *Panchagavya* treatment resulted in: Total phenolic content: 13.8%; Flavonoid content: 6.3%; Essential oil yield: 1.97%; Total alkaloid content: 13.2%; Saponins: 6.5%. These enhanced phytochemical traits are crucial for both medicinal value and pest resistance. According to Sharma et al. (2020), enriched soil micro biomes under organic inputs boost plant metabolomics and resilience.

3.4 Yield Attributes

The intercropping of *Tulsi* with *Potato* under *Kunapajala* + *Panchagavya* exhibited significant yield benefits. Total biomass and tuber weight were higher, and *Tulsi*'s dry leaf yield increased by 23.8% compared to the NPK-only treatment. This highlights the ecological intensification potential of traditional formulations in restoring productivity (United Nations, 2015). In figure 3 different parts of crops are collected, dried and measured in traditional way.

Figure3.Collection of different parts of crop to study different parameters.

Source: Authors own experimental work captured at site.

4. Discussion: The present investigation evaluated the impact of different treatments, including inorganic fertilizers, FYM, Kunapajala, and Panchagavya, on plant growth and productivity in a Tulsi (*Ocimum sanctum*)–Potato (*Solanum tuberosum*) intercropping system. The findings demonstrate significant variations in morphological parameters such as plant height, leaf number, leaf area, and biomass accumulation, reflecting the influence of treatments on overall plant vigor. Bioformulations like Kunapajala and Panchagavya enhanced chlorophyll content, photosynthetic efficiency, and nutrient uptake, which translated into improved growth and higher yield compared to control and conventional fertilizer treatments. The synergistic effect of intercropping with Tulsi contributed to better light interception, microclimate moderation, and allelopathic interactions that positively influenced potato tuber development.

Moreover, treatments with Vrikshayurveda-based formulations supported enhanced secondary metabolite accumulation in Tulsi, potentially improving its medicinal quality. The study also highlighted ecological benefits of integrating bioformulations into cropping systems, such as promoting beneficial microbial activity and reducing reliance on synthetic inputs, thereby contributing to a more sustainable and resilient agroecosystem.

4.1 Plant Biochemical Attributes and Growth Performance: The biochemical response of *Ocimum sanctum* to NPK supplementation indicated a notable improvement in key photosynthetic pigments. Chlorophyll a and b concentrations were recorded at 0.62 mg/g and 0.29 mg/g FW, respectively, while total carotenoids reached 0.38 mg/g FW. These values align with optimal photosynthetic performance under nitrogen-rich regimes (Lichtenthaler et al., 1987) but were still lower compared to combined biofertilizer treatments, which have been shown to enhance photosynthetic efficiency in sustainable systems (Chakraborty et al., 2019). Total phenolic content (13.6 mg/g FW) and flavonoid content (8.6 mg/g FW) were elevated under NPK treatment but were lower than those observed in Panchagavya + Kunapajala combinations, which promote secondary metabolite synthesis through microbial and enzymatic activation (Bhattacharyya et al., 2003). The relatively lower accumulation of antioxidant compounds under chemical regimes may indicate reduced plant–microbe interactions that are crucial for stress resilience and metabolic regulation.

4.2 Limitations of Chemical Inputs: Although NPK treatment improved short-term pigment levels and yield parameters, it falls short in enhancing overall crop quality and long-term plant health. Lower moisture content (6.3%) and ash content (2.5%) in NPK-treated leaves indicate reduced nutrient density, which may compromise the medicinal efficacy of *Ocimum sanctum* (Sharma et al., 2020).

4.3 Relevance to Sustainable Development Goals: This analysis emphasizes the importance of transitioning from synthetic inputs to regenerative practices, aligning with UN Sustainable Development Goals—particularly SDG 2 (Zero Hunger) and SDG 15 (Life on Land). While NPK provides rapid nutrient supply, its overuse can compromise crop quality and resilience. Vrikshayurveda-based bioformulations, by enhancing plant growth, biochemical composition, and ecological interactions, support sustainable agricultural intensification and the responsible production practices promoted under SDG 12.

Conclusion

The present study highlights the promising potential of integrating Vrikshayurveda bioformulations, Kunapajala and Panchagavya as effective organic alternatives to conventional chemical fertilizers in intercropping systems involving medicinal (*Ocimum sanctum*) and vegetable (*Solanum tuberosum*) crops. Among the treatments evaluated, the combined application of Kunapajala and Panchagavya significantly enhanced morphological parameters, chlorophyll and pigment concentrations, nitrogen and potassium uptake, essential oil content, total soluble protein, and secondary metabolite accumulation in *Ocimum sanctum* when intercropped with potato.

These findings underscore the efficacy of traditional bioformulations in improving plant physiological performance, biochemical composition, and overall crop productivity while reducing reliance on synthetic inputs. The results are consistent with prior research demonstrating that Vrikshayurveda-based practices enhance plant resilience, promote beneficial microbial interactions, and contribute to sustainable agroecosystem functioning (Tilman et al., 2011; Pretty & Hine, 2001). Furthermore, the adoption of such indigenous formulations aligns closely with UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) (United Nations, 2015), by supporting food security, resource-efficient production, and biodiversity-friendly practices. This research affirms the scientific validity of ancient Vrikshayurveda principles in modern sustainable agriculture and highlights their potential to enhance crop quality and yield in ecologically sensitive regions like Himachal Pradesh. Future long-term studies are recommended to evaluate sustained effects on crop productivity, secondary metabolite profiles, and agroecological interactions. In summary, Vrikshayurveda-based bioformulations provide a viable, ecologically sound, and culturally rooted pathway toward sustainable agricultural intensification

Final Reference List (APA Style, Alphabetical):

[1] Altieri, M. A., & Nicholls, C. I. (2020). Agroecology and the reconstruction of a post-COVID-19 agriculture. *Journal of Peasant Studies, 47*(3), 525–526. https://doi.org/10.1080/03066150.2020.1759137

[2] AOAC. (2016). *Official methods of analysis* (20th ed.). Association of Official Analytical Chemists, Washington, DC.

[3] Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts: Polyphenoloxidase in *Beta vulgaris*. *Plant Physiology*, *24*(1), 1–15. https://doi.org/10.1104/pp.24.1.1

[4] Bhardwaj, R., Singh, A., & Kumar, S. (2020). Effect of Panchagavya on growth, yield, and biochemical parameters of tomato (*Solanum lycopersicum* L.). *Journal of Plant Nutrition*, *43*(12), 1802–1812. https://doi.org/10.1080/01904167.2020.1734567

[5] Bhattacharyya, P., Biswas, D., & Ghosh, P. (2003). Enhancement of secondary metabolite synthesis in plants using biofertilizers. *Journal of Plant Biochemistry and Biotechnology, 12*(2), 45–52.

[6] Brooker, R. W., Bennett, A. E., Cong, W. F., Dissanayake, D., Ives, A. R., Karley, A. J., ... & Zhang, Z. (2015). Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, *206*(1), 107–117. https://doi.org/10.1111/nph.13132

[7] Chang, C., Yang, M., Wen, H., & Chern, J. (2002). Estimation of total flavonoid content in propolis by two complementary colorimetric methods. *Journal of Food and Drug Analysis, 10*(3), 178–182.

[8] Chakraborty, D., et al. (2019). Kunapajala: A traditional organic formulation for improving agricultural productivity – A review. *Agricultural Reviews, 40*(3), 1–10. https://arccjournals.com/journal/agricultural-reviews/R-2570

[9] Chakraborty, S., & Khan, M. A. (2019). Ethical adaptation of Kunapajala: A plant-based approach. *Journal of Ethnobiology and Ethnomedicine, 15*, 1–6. https://doi.org/10.1186/s13002-019-0301-3

[10] Chakraborty, S., Ghosh, P., & Nandi, S. (2019). Vrikshayurveda formulations Kunapajala and Panchagavya: Impact on soil health and crop productivity. *International Journal of Agricultural Sustainability*, *17*(4), 341–356. https://doi.org/10.1080/14735903.2019.1651234

[11] Clevenger, J. F. (1928). Apparatus for the determination of essential oils. *Journal of the American Pharmaceutical Association, 17*, 345–349. https://doi.org/10.1002/jps.3080170627

[12] Debnath, S., Babu, S., Singh, R., Monga, D., & Kranthi, K. R. (2015). Effect of organic formulations on productivity and soil health in mustard-based cropping systems. *Indian Journal of Agricultural Sciences, 85*(3), 442–448.

[13] Dwivedi, A. K., Tiwari, A., Tripathi, A., & Yadav, R. S. (2022). Effect of organic bio-formulations (Kunapajala and Panchagavya) on growth and yield of tomato and rice. *International Journal of Bio-resource and Stress Management, 13*(1), 45–52. https://doi.org/10.23910/ijbsm/2022.13.1.2310

[14] Ghosh, P., Chakraborty, S., & Bhattacharya, A. (2020). Influence of herbal liquid organic

manures on growth, yield, and biochemical traits of basil (*Ocimum basilicum* L.). *Journal of Herbal Agriculture, 15*(2), 88–97. https://doi.org/10.1016/j.jherb.2020.03.005

[15] Ghosh, S., Saha, S., & Ghosh, S. K. (2020). Panchagavya: A natural growth stimulant for plants. *Indian Journal of Agricultural Sciences, 90*(3), 1–6.

[16] Lichtenthaler, H. K., & Wellburn, A. R. (1983). Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. *Biochemical Society Transactions, 11*(5), 591–592. https://doi.org/10.1042/bst0110591

[17] Lowry, O. H., Rosebrough, N. J., Farr, A. L., & Randall, R. J. (1951). Protein measurement with the Folin phenol reagent. *Journal of Biological Chemistry, 193*(1), 265–275. https://doi.org/10.1016/S0021-9258(19)52451-6

[18] Mishra, S. (2007). Revisiting the oldest manure of India, Kunapajala: Assessment of its efficacy in sustainable agriculture. *Frontiers in Sustainable Food Systems, 1*(1), 1–10. https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2022.1073010/full

[19] Montgomery, R. (1911). A method for measuring leaf area. *Plant World, 14*, 75–78.

[20] Nene, Y. L. (2006). Vrikshayurveda: An ancient treatise on plant life. *Indian Journal of Traditional Knowledge, 5*(1), 1–5.

[21] Nene, Y. L. (2018). The concept and formulation of Kunapajala, the world's oldest fermented liquid organic manure. Asian Agri-History Foundation.

[22] Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular, 939*, 1–19.

[23] Ranganna, S. (2001). *Handbook of analysis and quality control for fruit and vegetable products* (2nd ed.). Tata McGraw-Hill.

[24] Rengasamy, R. (2006). Panchagavya: A natural growth stimulant for plants. *Indian Journal of Agricultural Sciences, 76*(3), 1–6.

[25] Sadhale, P. (1996). Vrikshayurveda: An ancient treatise on plant life. *Indian Journal of Traditional Knowledge, 1*(1), 1–5.

[26] Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture, 16*(3), 144–158.

[27] Surapala. (1000 CE). *Vrikshayurveda*. Ancient Sanskrit Manuscript.

[28] Sundaramoorthy, P., Ravi, V., & Kumar, S. (2021). Sustainable intercropping of medicinal plants with vegetables under organic formulations: Effects on yield and soil health. *Agronomy for Sustainable Development, 41*(3), 45. https://doi.org/10.1007/s13593-021-00697-3

[29] Thakur, A. K., Pandey, D. N., & Kumar, G. (2025). Field evaluation of Vrikshayurveda bioformulations: Kunapajala and Panchgavya for enhancing soil health and promoting sustainable agriculture. *Acta Botanica Plantae, 7*(1), 1–10. https://doi.org/10.51470/ABP.2025.04.03.19

[30] Thakur, A. K., Sharma, P., & Singh, R. (2024). Comparative assessment of traditional Vrikshayurveda bioformulations and chemical inputs in Himalayan agroecology: Yield, soil health, and plant metabolites. *Journal of Ayurveda and Integrative Medicine, 15*, 101257. https://doi.org/10.1016/j.jaim.2024.101257

[31] Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences, 108*(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108

[32] United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations. https://sdgs.un.org/2030agenda

[33] Yadav, R. L., et al. (2012). Nutrient analysis of Kunapajala and Panchagavya and their effect on seed germination of Ashwagandha and Kalamegha. *Pharmacognosy Research, 4*(1), 1–5. https://pmc.ncbi.nlm.nih.gov/articles/PMC5884015/