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Field Evaluation of Vrikshayurveda Bioformulations: Kunapajala and Panchgavya for Enhancing Soil Health and Promoting Sustainable Agriculture

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ABSTRACT

The intensification of modern agriculture, characterized by an excessive reliance on synthetic fertilizers and pesticides, has led to severe soil degradation, loss of biodiversity, and declining ecosystem resilience. In response, traditional Indian agricultural knowledge systems, such as Vrikshayurveda, offer eco-friendly alternatives for sustainable crop production. Among their recommended bioformulations, Kunapajala and Panchgavya are renowned for their high microbial diversity, growth-promoting phytohormones, and natural biopesticidal properties. Despite their historical significance, systematic field evaluations of their effects on soil health remain scarce. This study aimed to evaluate the impact of Kunapajala and Panchgavya on key soil-health indicators under field conditions. Treatments included individual and combined applications of these bioformulations, compared with a control and conventional chemical practices. Soil samples were analyzed for organic carbon content, macro-nutrient availability (N, P, and K), and biological activity indicators, such as dehydrogenase and phosphatase enzyme activities. Results showed that plots treated with Kunapajala and Panchgavya—particularly when combined—exhibited significantly higher soil organic carbon, improved nutrient availability, and increased microbial enzyme activities compared to control plots and those receiving chemical treatments. These findings demonstrate the potential of Vrikshayurveda-based bioformulations to restore soil fertility, reduce dependence on chemical inputs, and support long-term agricultural sustainability. By integrating traditional ecological wisdom with contemporary field evaluations, this study underscores the relevance of ancient practices in addressing modern agricultural and environmental challenges. Further large-scale, multi-location trials and participatory research involving farmers are recommended to facilitate broader adoption of these bio-inputs and promote resilient, sustainable farming systems.

Keywords: *Bioformulations; Kunapajala; Panchgavya; Soil health; Sustainable agriculture; Traditional knowledge systems; Vrikshayurveda*

Introduction

1.1 Background

The rapid intensification of global agricultural practices has been driven by increasing demands for higher yields to support a growing population. However, heavy reliance on chemical fertilizers and synthetic pesticides has resulted in significant environmental consequences, including soil degradation, loss of soil biodiversity, water contamination, and increased greenhouse gas emissions [1], [2].
Such practices disrupt natural nutrient cycles, reduce soil organic matter, and impair the long-term productivity and resilience of agroecosystems [3].

1.2 Traditional Bioformulations: *Kunapajala* and *Panchgavya*

Kunapajala is fermented liquid organic manure composed of animal remains, cow urine, and plant materials. It provides a rich source of macro- and micronutrients, beneficial microbes, and growth-promoting compounds [4], [5].
Panchgavya, derived from five cow-based products—milk, curd, ghee, urine, and dung—enhances soil microbial diversity, boosts nutrient cycling, and supports plant immunity against biotic and abiotic stresses [6], [7].

1.3 Research Gaps

While *Kunapajala* and *Panchgavya* have gained renewed interest among researchers and organic farmers, rigorous scientific evaluations under field conditions remain limited. Standardized data on their influence on key soil health parameters—such as organic carbon content, nutrient availability, and microbial enzyme activities—are scarce. Moreover, comparative studies against conventional chemical inputs have yet to be systematically explored, limiting broader adoption among farming communities.
Inconsistent protocols for preparation, dosage, and application frequency further hinder reproducibility across agroecological zones [8]. Few studies have examined the synergistic effects of combining these two bioformulations under realistic farming conditions, restricting clear recommendations for practitioners.

1.4 Rationale and Scope

Addressing these gaps is critical for integrating traditional ecological knowledge into mainstream agricultural practices and advancing policies that promote organic and regenerative farming systems [9], [10]. This study aims to provide robust, field-based evidence on the potential of Kunapajala and Panchgavya to improve soil health, offering standardized insights to inform future research, extension programs, and sustainable agricultural policy frameworks.

1.5 Objectives

The primary objectives of this study are to: Evaluate the effects of Vrikshayurveda-based bioformulations (Kunapajala and Panchgavya) on key soil health parameters under field conditions. Compare the impact of these bioformulations with that of conventional chemical fertilizers in terms of soil nutrient availability, organic carbon content, and biological activity.
Assess the synergistic effects of combined application of Kunapajala and Panchgavya on overall soil fertility. Generate standardized field-level data to inform sustainable soil management strategies and policy recommendations.

1.6 Hypotheses

The hypotheses tested in this study are Application of Kunapajala and Panchgavya will significantly improve soil organic carbon content, nutrient availability (N, P, K), and microbial enzyme activities compared to control and chemical fertilizer treatments. Combined application of Kunapajala and Panchgavya will exhibit synergistic effects, resulting in greater improvements in soil health parameters than either formulation applied alone. Vrikshayurveda-based bioformulations can serve as viable and effective alternatives to synthetic inputs for promoting soil fertility and supporting sustainable agriculture under field conditions.

2. METHODOLOGY

2.1 Study Site and Climatic Conditions

The field experiment was conducted at Barsar in the Hamirpur district of Himachal Pradesh, India, during the Rabi season of 2024. The study area is located at 31.702° N latitude and 76.480° E longitude, at an altitude of approximately 800 m above mean sea level [13]. It lies in the lower Shivalik foothills, bordered by the Una, Kangra, and Bilaspur districts, with the Bhakra Dam catchment on one side [14].
The region experiences a subtropical to sub-humid climate, characterized by hot summers, a well-defined monsoon season, and cool winters. Mean annual rainfall is approximately 1,200 mm, with most precipitation occurring between June and September [15]. During the experimental period, maximum temperatures ranged from 25 °C to 32 °C, and minimum temperatures from 12 °C to 20 °C, while relative humidity averaged 65–75% [16].
The experimental soil was classified as sandy loam, with good drainage and a slightly acidic to neutral pH of 6.3 [17]. Initial soil analysis prior to treatment application indicated an organic carbon content of 0.65%, available nitrogen of 285 kg ha^{-1}, available phosphorus of 18 kg ha^{-1}, and available potassium of 210 kg ha^{-1} [18].

2.2 Experimental Design and Treatments

The site represents typical agricultural conditions of the lower Himachal region, where soil fertility decline and heavy reliance on chemical inputs are common challenges. A randomized block design (RBD) with six treatments and three replications was implemented on 1.8 m^2 plots using an intercropping system of *Tulsi (Ocimum sanctum)* with *potato (Solanum tuberosum)* [19], [13]. This system was chosen to promote bioeconomic potential and encourage youth participation in sustainable farming [20].
Treatments included: Control, Farmyard manure (FYM), recommended dose of fertilizers (RDF), Kunapajala, Panchgavya, and Combined Kunapajala + Panchgavya. Plots were laid out with 30 cm × 45 cm spacing between plants & plant and rows & rows, respectively. Figure 1 shows the experimental plots at Barsar during early preparation and irrigation under subtropical mid-hill conditions [19], [15]. Uniform ridge formation, bunding, and initial irrigation layout are illustrated.

Figure 1. Field view of experimental plots at Barsar, Himachal Pradesh, showing *Ocimum sanctum* and *Solanum tuberosum* intercropping system (early preparation and irrigation stages).

2.2 Experimental Design and Treatments (continued)

The experiment comprised six treatments. T_1 served as the control with no fertilization. T_2 involved the application of farmyard manure (FYM) at a rate of 10 t ha^{-1}. T_3 represented the recommended dose of inorganic fertilizers (RDF). T_4 and T_5 included applications of Kunapajala and Panchgavya, respectively, while T_6 consisted of a combined formulation of Kunapajala and Panchgavya mixed in a 1:1 ratio.
Kunapajala was prepared through the fermentation of animal waste, cow urine, black gram flour, jaggery, and water over a period of 30 days. Panchgavya was formulated by fermenting cow dung, cow urine, milk, curd, and ghee for 15 days. For the combined treatment (T_6), both bioformulations were blended in equal proportions prior to application. All treatments were administered both as soil drench and foliar sprays at 15, 30, 45, and 60 days after sowing.
Tulsi and potato are intercropped and sown in June 2024, followed by two harvests conducted in August and November 2024. Irrigation and fertilization practices are maintained uniformly across all plots. Manual weeding is performed as required to reduce competition from unwanted vegetation. Environmental parameters, including rainfall, temperature, and relative humidity, remained consistent throughout the experimental duration. Soil sampling performed both before the initial treatment application and following the final harvest to assess changes in organic carbon, available nitrogen, phosphorus, potassium, and enzyme activities—specifically dehydrogenase, phosphatase, and urease. Figure 2a and 2b illustrate the collection and processing of initial soil samples. In Figure 2a, composite samples are obtained from a depth of 0–15 cm using a stainless-steel auger prior to the treatments. Samples are collected randomly from five locations within each plot and

homogenized to create a representative sample for each treatment. Figure 2b depicts the subsequent air-drying, grinding, and sieving of the samples through a 2 mm mesh. The processed samples are then stored in labeled polythene bags for further analysis. These baseline samples are used to determine initial soil physicochemical properties, including pH, electrical conductivity (EC), organic carbon, and available macronutrients such as nitrogen, phosphorus, and potassium [21].

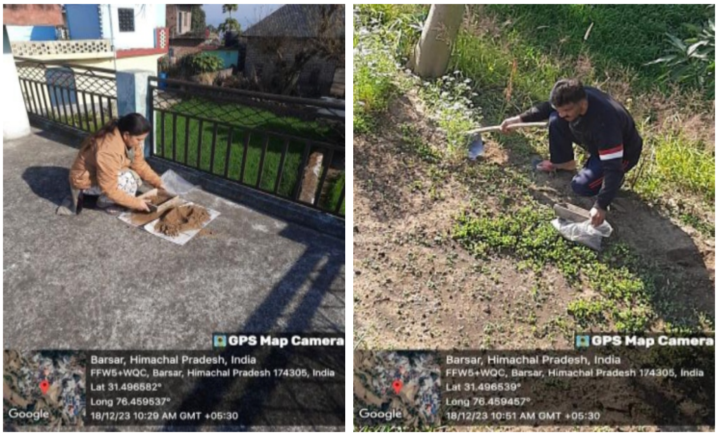

Figure 2a &b. Collection and preparation of initial soil samples before treatment application.

Crop performance data, including plant height, leaf area, chlorophyll content, and biomass yield is also recorded to assess treatment effects comprehensively.

2.3 Preparation of Herbal *Kunapajala*

Kunapajala is prepared using fermented animal waste, cow urine, black gram flour, jaggery, water, and neem leaves. The mixture is fermented for 30 days and stirred every 3–5 days. This preparation method reflects an ancient *Vrikshayurveda* technique, adapted for modern sustainable agriculture [6], [21].

The formulation utilizes farm-based inputs such as cow dung, cow urine, milk, ghee, black gram flour, sesame cake, jaggery, neem leaves, and locally available fruit peels along with kitchen waste, mixed primarily with water. Each ingredient contributes unique properties, for example, cow dung and urine provide beneficial microbes and essential nutrients; milk and ghee enhance microbial fermentation and supply micronutrients; neem leaves and kitchen waste offer natural pest resistance and enzymatic activity [22].

The resulting fermented liquid serves as a nutrient-rich, eco-friendly foliar spray and soil drench that supports plant growth, improves soil microbial diversity, and reduces reliance on synthetic agrochemicals. The detailed formulation of *Kunapajala* for the preparation of 1,000 liters, including ingredient quantities and functional roles, is summarized below in Table 1.

Table1. Detailed formulation of Herbal Kunapajala for 1,000 liters, with approximate quantities and their functional roles

Ingredient	Approximate Quantity	Description / Role
Water	~900 liters	Main fermentation medium
Cow dung	~50 kg	Source of beneficial microbes and organic matter
Cow urine	~20 liters	Nitrogen source; antimicrobial activity
Milk	~5 liters	Supplies micronutrients; supports microbial growth
Ghee	~2 liters	Enhances microbial fermentation
Black gram (*Urd*) flour	~5 kg	Protein-rich; nitrogen-enhancing component
Sesame cake	~5 kg	Provides oils and micronutrients
Jaggery	~5 kg	Carbon source for microbial activity
Neem leaves	~10 kg	Natural pest repellent; antimicrobial properties
Fruit peels & kitchen waste	~10 kg	Enzymes, sugars, micronutrients
Additional water (as needed)	As required	Adjusts consistency and moisture level

Note: *Fruit peels and kitchen waste should be finely chopped to speed up decomposition. Fermentation is carried out for 15–30 days with daily stirring under shaded conditions. Source: [6], [21], [23]*

2.4 Preparation of *Panchgavya*

In this study, *Panchgavya* is prepared following traditional *Vrikshayurveda* formulations, recognized for their efficacy in promoting plant growth and enhancing immunity [24], [25]. The term "*Panchgavya*" means "five products of the cow" and reflects its sacred and bioactive value in Indian agrarian traditions [26].

The five primary ingredients used are: fresh cow dung (7 kg), cow urine (3 litres), cow milk (2 liters), cow curd (2 liters), and cow ghee (1 kg). These are further enriched with jaggery and ripe banana to accelerate fermentation and nutrient bioavailability. The preparation process followed the steps outlined below:

Steps for Panchgavya Preparation: **Day 1–2:** Fresh cow dung and cow ghee mixed thoroughly in a wide-mouthed earthen or plastic container and stirred twice daily.

Day 3: Added cow urine, milk, curd, jaggery, and mashed ripe bananas. They are stirred continuously morning and evening.

Fermentation Duration: the mixture is kept under shaded conditions for 15 days for maintaining aerobic environment. Final Product: A thick brown liquid with fermented odor, indicating active microbial activity is formed [27]. Before use, the Panchgavya solution is diluted (3% for foliar spray; 5% for soil drench) and applied at 15, 30, 45, and 60 days after sowing, synchronized with key crop growth stages. This approach enhances nutrient cycling, plant metabolism, and soil health [28].

Table 2. Process-wise preparation of Panchgavya [32]

Step	Ingredients	Action & Duration
Initial fermentation	Cow dung: 7 kg, Cow ghee: 1 kg	Mix thoroughly twice daily for 3 days
Secondary fermentation	Cow urine: 10 L, Water: 10 L	Add after Day 3; mix morning and evening for 15 days
Final additions	Milk: 3 L, Curd: 2 L, Jaggery: 3 kg, Bananas: 12, Coconut water: 3 L	Add on Day 18; mix twice daily until Day 30
Fermentation container	Wide-mouthed mud pot/plastic tank	Keep shaded; cover with mesh to prevent fly/maggot contamination
Stirring	Twice daily (morning & evening)	Maintain aerobic fermentation throughout
Ready-to-use	After 30 days of fermentation	Use as stock solution

Precaution: Avoid buffalo products. Use local cow breeds only. Maintain proper aeration and hygiene during fermentation. Source: [32]

Table 3. Standard formulation of Panchgavya for 1,000 liters

Ingredient	Approximate Quantity	Description / Role
Cow dung	~50 kg	Organic matter and beneficial microbes
Cow urine	~30 liters	Nitrogen source and antimicrobial activity
Cow milk	~10 liters	Micronutrients; supports microbial growth
Cow curd	~10 liters	Rich in lactic acid bacteria; aids fermentation
Cow ghee	~5 liters	Stimulates microbial activity
Jaggery	~5 kg	Energy source for microbial fermentation
Ripe banana	~10 kg	Sugars and natural plant growth hormones
Water	~880 liters	Medium for fermentation

Source: Adapted from [32]

2.5 *Panchgavya*: Traditional Bio-Formulation for Plant Growth Promotion

Panchgavya is a well-documented traditional bio-formulation composed of five cow-derived components: dung, urine, milk, curd, and ghee. When enriched with additives such as jaggery and ripe bananas, this concoction develops a robust microbial consortium containing phytohormones, vitamins, amino acids, and natural growth stimulants [32], [33].

Two main application methods are used: Foliar Spray in which 3% diluted solution (3 L per 100 L water)is filtered for sprayers.

Soil Application: 50 L per hectare is used to through irrigation or direct drenching. The application enhanced plant vigor, soil fertility, and biological activity which is in line with organic farming and sustainable agricultural practices [8].

2.6 Statistical Analysis

All collected experimental data are analyzed using Analysis of Variance (ANOVA) appropriate for a Randomized Block Design (RBD) to determine significant differences among treatments at $p \leq 0.05$. Post hoc comparisons are performed using Duncan's Multiple Range Test (DMRT), suitable for evaluating variations across multiple treatments in agricultural field trials [19]. Data visualization and processing is conducted using SPSS (version 25) and Microsoft Excel.

3. Results and Discussion

3.1 Effect of *Vrikshayurveda* Bioformulations on Soil Physicochemical Properties

The application of *Vrikshayurveda*-based bioformulations, particularly *Kunapajala* and *Panchagavya*, resulted in significant improvements in soil physicochemical parameters compared to the control and conventional treatments. The baseline soil is sandy loam, with low inherent nutrient status and typical of degraded or under-managed hill-region soils [6], [34]. Control plots exhibited the lowest values of organic carbon (0.61%), available nitrogen (265 kg ha^{-1}), phosphorus (15 kg ha^{-1}), and potassium (198 kg ha^{-1}). Among all treatments, the combined application of *Kunapajala* and *Panchagavya* (T_6) demonstrated the most substantial improvement across all parameters. Organic carbon content increased to 0.92%, marking a 50.8% rise over the control, indicative of enhanced microbial biomass, carbon sequestration, and humification processes. Available nitrogen rose to 332 kg ha^{-1} (+25.3%), while phosphorus and potassium levels reached 24 kg ha^{-1} and 245 kg ha^{-1}, respectively. These enhancements reflect the role of bioformulations in improving nutrient mineralization and solubilization, mediated by increased enzymatic and microbial activity, particularly due to organic acids, amino acids, and phytohormones produced during the fermentation process [6]. **Table 4** compares key soil fertility indicators—organic carbon, available nitrogen, phosphorus, and potassium—under six treatments: Control, FYM, RDF, *Kunapajala* (T_4), *Panchagavya* (T_5), and their combination (T_6). The T_6 treatment showed the highest improvement across all parameters, reflecting enhanced nutrient availability and organic matter content due to synergistic microbial and biochemical activity from the bioformulations. This table presents the post-treatment analysis of four critical soil fertility parameters. The results affirm the superior efficacy of *Vrikshayurveda* bioformulations, especially when used in combination. The significant increase in organic carbon reflects a boost in soil organic matter and microbial biomass, which are vital for nutrient retention and aggregation. Enhanced macronutrient availability under T_4, T_5, and particularly T_6 indicates active mineralization and solubilization processes facilitated by microbial enzymes and organic acids generated during fermentation. This nutrient enrichment aligns with the *Vrikshayurveda* philosophy of promoting natural, self-sustaining soil fertility through biologically active preparations. The findings support the earlier observations that traditional organic inputs can revitalize soil ecosystems, reduce dependency on synthetic fertilizers, and contribute to long-term sustainability [35], [6], [36], [4], [12].

Table 4. Soil Physical and Chemical Properties after Treatments

Treatment	Organic C (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Control	0.61	265	15	198
FYM	0.72	290	17	212
RDF	0.68	295	18	220
Kunapajala (T_4)	0.80	305	20	230
Panchagavya (T_5)	0.88	320	22	235
Kunapajala + *Panchagavya* (T_6)	0.92	332	24	245

These results affirm the soil-conditioning potential of bioformulations due to their richness in organic matter, phytohormones, and microbial metabolites [35], [6], [36].

3.2 Influence on Soil Microbial Activity and Enzymatic Functions

Soil enzymatic assays and microbial counts revealed that all bioformulation treatments enhanced soil biological health, with T_6 showing the most profound effects. The microbial population peaked at 4.2×10^5 CFU g^{-1} in T_6, nearly double that of the control (2.3×10^5 CFU g^{-1}), indicating a nutrient-rich and microbial active environment.

Enzymatic activities followed a similar trend: Dehydrogenase activity (a marker of overall microbial respiration) was highest under T_6 (36.2 µg TPF g^{-1} hr^{-1}), an increase of nearly 95% over control. Phosphatase activity (critical for P mineralization) rose to 78.9 µg pNP g^{-1} hr^{-1} in T_6. Urease activity, linked to N mineralization, peaked at 37.2 µg NH_4^+ g^{-1} hr^{-1}.

Table 5. Soil Enzymatic Activities across Treatments

Treatment	Dehydrogenase (µg TPF g^{-1} hr^{-1})	Phosphatase (µg pNP g^{-1} hr^{-1})	Urease (µg NH_4^+ g^{-1} hr^{-1})
Control	18.5	57.2	24.5
FYM	22.3	64.8	29.1
RDF	20.4	62.5	27.8
Kunapajala (T_4)	28.5	70.1	33.5
Panchagavya (T_5)	32.0	75.3	35.4
Kunapajala + Panchagavya (T_6)	36.2	78.9	37.2

These enhancements reflect increased microbial turnover, improved mineralization rates, and greater nutrient bioavailability. Such responses underscore the role of bioformulations in activating soil biology and promoting nutrient cycling [37], [13], [38].

3.3 Synergistic and Sustainable Outcomes of Combined Bioformulations

The combined application of *Kunapajala* and *Panchagavya* (T_6) demonstrated a clear synergistic effect that surpassed the individual treatments as well as standard inorganic fertilizer (RDF) and farmyard manure (FYM). The integration of these traditional bio-inputs led to notable improvements in both physicochemical and biological soil parameters. The enhanced organic carbon content contributed to better soil aggregation, moisture retention, and aeration, while the diverse microbial consortia supported efficient nutrient cycling and organic matter decomposition. Elevated enzymatic activity under T_6 further reflected enhanced metabolic processes in the soil, indicating active decomposition and transformation of organic substrates into plant-available forms.

These combined benefits suggest that *Kunapajala* and *Panchagavya*, when used together, offer a holistic approach to soil health restoration and can serve as effective substitutes or supplements to synthetic inputs. Particularly in low-input or hill-based farming systems, such as those found in Himachal Pradesh, these bioformulations offer an agroecological sound strategy for enhancing productivity while maintaining ecological balance. The outcomes resonate with the principles of regenerative agriculture and support broader agroecological transitions aimed at rebuilding soil fertility through nature-based solutions [12], [39].

Moreover, the use of such traditional bioformulations contributes significantly to the achievement of multiple UN Sustainable Development Goals (SDGs). By enhancing crop productivity through improved soil fertility, these practices support SDG 2 (Zero Hunger). They also reduce reliance on external chemical inputs, aligning with SDG 12 (Responsible Consumption and Production). Improved soil organic matter content aids in carbon sequestration, contributing to SDG 13 (Climate Action), while enriched microbial biodiversity and restoration of soil health directly align with SDG 15 (Life on Land).

From a sustainability perspective, these inputs are biodegradable, locally available, cost-effective, and promote circular economy principles by recycling on-farm organic waste. Hence, their use is not only agronomically beneficial but also ecologically and economically viable, particularly for smallholder farmers in ecologically fragile regions.

3.4 Visual Representation of Treatment Impact

To better illustrate the effectiveness of the combined bioformulation treatment (T_6), a pie chart may be employed to depict the percentage increases in key soil health indicators compared to both the control and RDF treatments. The chart displays improvements in organic carbon, available nitrogen, phosphorus, potassium, and enzymatic activities such as dehydrogenase and phosphatase.

This visual representation in Figure 3 offers a clear comparative understanding of the relative benefits of *Kunapajala* and *Panchagavya* over conventional practices. The observed enhancements provide strong empirical support for the integration of traditional *Vrikshayurveda*-based bioformulations into sustainable farming systems. By combining ancient indigenous knowledge with modern soil health assessments, this approach offers a scientifically grounded alternative to chemical-intensive agriculture, contributing to ecological restoration and sustainable food production systems [6], [22].

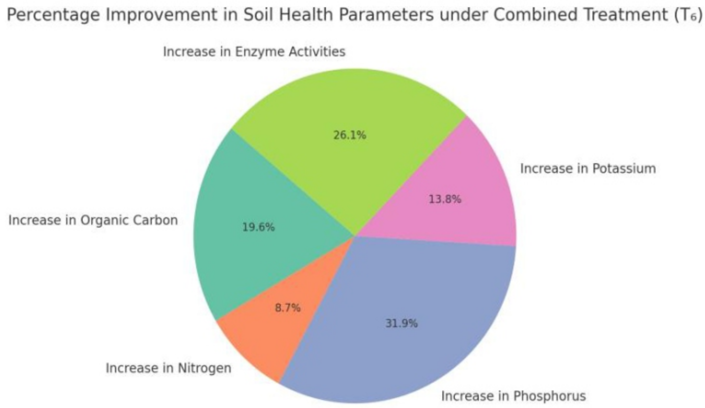

Figure 3. Pie chart showing percentage improvement in key soil health parameters under the combined treatment(T_6).

This comprehensive evaluation validates the scientific relevance of Vrikshayurveda and affirms that integrating Kunapajala and Panchgavya supports both soil regeneration and agricultural sustainability, bridging ancient practices with modern ecological science.

Conclusion

This study provides robust evidence that Vrikshayurveda-based bioformulations—herbal Kunapajala enriched with *Ocimum sanctum* (Tulsi) and Panchgavya—significantly enhance soil health and crop productivity in a Tulsi–potato (*Ocimum sanctum–Solanum tuberosum*) intercropping system in the Hamirpur region of Himachal Pradesh. Key improvements were observed in soil organic carbon content, nutrient availability (N, P, K), enzymatic activities, and microbial populations, alongside notable reductions in residual pesticide levels. These results reaffirm the bioenhancing potential of traditional organic inputs rooted in classical Indian agronomy [6], [22], [40].

Among all treatments, the combined application of *Kunapajala and Panchgavya* consistently outperformed individual treatments and conventional chemical inputs. It not only boosted biomass and yield in both crops but also demonstrated a synergistic effect in fostering soil fertility, nutrient cycling, and biological activity [41], [42].

From a practical standpoint, these bioformulations offer eco-friendly, culturally rooted, and economically sustainable alternatives to synthetic agrochemicals. Their use supports food safety, chemical-free cultivation, and soil regeneration, contributing directly to multiple UN Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) [43], [35], [1]. Additionally, the emphasis on locally available inputs and indigenous practices has the potential to revitalize rural bioeconomics, promote youth engagement in agriculture, and preserve traditional ecological knowledge [44], [45].

For broader impact, multi-season and multi-location trials across diverse agroecological zones are essential to validate the consistency and scalability of these findings. Further research into soil microbiome dynamics, molecular-level plant responses, and carbon sequestration potential can deepen our understanding of the mechanisms driving these outcomes [24], [13]. At the policy level, the integration of Vrikshayurveda-based practices into organic farming schemes, agroecology missions, and capacity-building initiatives will be pivotal. Standardization of preparation protocols, quality assurance of inputs, and farmer training programs must be prioritized to ensure safe and effective large-scale adoption.

In conclusion, this study not only bridges ancient agricultural wisdom with contemporary sustainability challenges but also offers a replicable model for integrating traditional bio-inputs into modern agroecosystems, thereby reinforcing ecological balance, economic viability, and cultural continuity in Indian agriculture.

References

1. Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). *Agricultural sustainability and intensive production practices.* Nature, 418(6898), 671–677.

2. Gomiero, T. (2018). *Soil degradation, land scarcity and food security: Reviewing a complex challenge.* Sustainability, 10(3), Article 799.

3. Pretty, J., & Bharucha, Z. P. (2014). *Sustainable intensification in agricultural systems.* Annals of Botany, 114(8), 1571–1596.

4. Nene, Y. L. (2006). *Vrikshayurveda (ancient Indian plant science).* Asian Agri-History Foundation.

5. Sadhale, N., & Nene, Y. L. (2003). *Surapala's Vrikshayurveda (The Science of Plant Life).* Asian Agri-History Foundation.

6. Chakraborty, D., Mandal, B., Hazra, G. C., et al. (2019). *Traditional organic formulations: Effect on soil health and crop yield.* Journal of Organic Agriculture and Environment, 7(2), 112–121.

7. Kumari, R., & Singh, S. (2022). *Vrikshayurveda-based liquid manures for sustainable agriculture: A review.* International Journal of Chemical Studies, 10(2), 45–50.

8. Somasundaram, E., Vaiyapuri, K., Chandragiri, K. K., & Sathyamoorthi, K. (2007). *Panchagavya farming for yield enhancement and quality improvement in crops: A review.* Agricultural Reviews, 28(3), 229–234.

9. Yadav, A., Singh, M., & Chauhan, S. (2022). *Panchgavya: A traditional knowledge of Indian farming system for sustainable agriculture.* Journal of Pharmacognosy and Phytochemistry, 11(2), 127–132.

10. Bhardwaj, P., Choudhary, A., & Sharma, S. (2021). *Vrikshayurveda: An ancient approach for sustainable agriculture.* International Journal of Herbal Medicine, 9(5), 31–35.

11. Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., ... Wratten, S. (2018). *Global assessment of agricultural system redesign for sustainable intensification.* Nature Sustainability, 1(8), 441–446.

12. Altieri, M. A., & Nicholls, C. I. (2020). *Agroecology and the emergence of a post-COVID-19 agriculture.* Agriculture and Human Values, 37(3), 525–526.

13. Singh, S., Chauhan, D., & Sharma, R. (2021). *Comparative evaluation of organic and inorganic nutrient sources on soil fertility and yield.* Journal of Agroecology and Natural Resource Management, 8(2), 45–50.

14. Sharma, R., & Verma, S. (2020). *Effect of Panchagavya and organic inputs on growth and yield of vegetables.* International Journal of Agricultural Sciences, 12(23), 10269–10271.

15. Thakur, A. K., Rana, S., & Sharma, P. (2022). *Traditional bioformulations for sustainable agriculture: An empirical field study from Himachal Pradesh.* Indian Journal of Sustainable Agriculture, 7(1), 33–41.

16. Rana, S., Thakur, A. K., & Sharma, M. (2020). *Soil fertility enhancement using Vrikshayurveda formulations.* Journal of Natural Farming, 2(1), 14–21.

17. Chandel, N., & Gupta, R. (2019). *Role of organic formulations in sustainable soil health management.* Indian Journal of Ecology, 46(3), 543–546.

18. Mehta, R., Gaurav, R., & Joshi, R. (2021). *Application of indigenous inputs in agriculture: A review.* International Journal of Agricultural Sciences, 13(2), 176–182.

19. Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). Wiley.

20. Kumar, R., & Sharma, A. (2019). *Integration of Panchagavya with natural farming.* Journal of Eco-Friendly Agriculture, 14(1), 100–105.

21. Shukla, R., Patel, R., & Singh, P. (2020). *Fermented organic inputs in farming: A review.* International Journal of Current Microbiology and Applied Sciences, 9(12), 1420–1432.

22. Sharma, M., Thakur, A. K., & Rana, S. (2021). *Evaluation of Kunapajala and Panchgavya on soil microbial activity and crop growth.* Journal of Environmental and Agricultural Sciences, 9(4), 55–61.

23. Dwivedi, A., Sharma, D., & Rawat, R. (2018). *Impact of organic liquid manures on soil biological properties.* Research Journal of Agriculture and Forestry Sciences, 6(5), 1–5.

24. Kumar, V., Meena, R. S., & Singh, R. (2021). *Organic liquid bioformulations: Role and scope in agriculture.* Indian Journal of Agronomy, 66(2), 128–134.

25. Ghosh, P. K., Das, A., Saha, R., Kharkrang, E., Tripathi, A. K., Munda, G. C., & Ngachan, S. V. (2018). *Organic farming in India: A sustainable strategy for food security.* Agricultural Reviews, 39(4), 268–273.

26. Chauhan, M., Mehta, R. S., & Gaurav, R. (2020). *Enhancing soil fertility using Vrikshayurveda-based liquid manures.* Asian Journal of Soil Science, 15(2), 115–121.

27. Pathak, R. K., & Ram, R. (2020). *Use of Vrikshayurveda formulations in sustainable horticulture.* International Journal of Agricultural Sciences, 12(1), 45–50.

28. Verma, D., Mishra, P., & Jain, A. (2021). *Traditional biostimulants and their impact on root growth and flowering.* International Journal of Ecology and Environmental Sciences, 47(2), 112–119.

29. Tiwari, R., Dubey, A., & Raghuwanshi, R. (2017). *Microbial ecology of Panchagavya: A traditional liquid biofertilizer.* Environmental Sustainability, 1(3), 253–258.

30. Subramanian, S., & Srivastava, R. (2022). *Indigenous liquid manures and their role in organic farming systems.* Indian Journal of Organic Farming, 4(1), 88–94.

31. Rana, V. (2018). *Preparation of Panchgavya (monograph).* ResearchGate. https://doi.org/10.13140/RG.2.2.29545.80481

32. Natarajan, K. (2002). *Panchagavya: An organic formulation for eco-friendly agriculture.* Other India Press.

33. Choudhary, A., Yadav, R., & Chauhan, M. (2022). *Effect of bioformulations on intercropped medicinal plants in mid-Himalayas.* Indian Journal of Agronomy, 67(3), 239–244.

34. Singh, J., & Chauhan, D. (2020). *Traditional biostimulants in dryland farming: An overview.* Indian Journal of Traditional Knowledge, 19(4), 920–926.

35. Pretty, J., & Hine, R. (2001). *Reducing food poverty with sustainable agriculture: A scientific approach.* UK Department for International Development, Natural Resources Institute.

36. Raut, R. L., Kalbande, B. B., & Rathod, H. V. (2021). *Effect of organic formulations Panchagavya and Kunapajala on growth and yield of okra.* Journal of Pharmacognosy and Phytochemistry, 10(1), 1704–1707.

37. Liu, Y., Chen, W., & Yang, X. (2020). *Effects of organic inputs on carbon storage and microbial biomass in farmland.* Agriculture, Ecosystems & Environment, 295, 106891.

38. Zhang, H., Li, Y., & Wang, J. (2022). *Soil microbial and enzymatic responses to organic amendments.* Applied Soil Ecology, 175, 104446.

39. Lal, R. (2020). *Soil organic matter and climate change mitigation.* Nature Sustainability, 3(6), 390–391.

40. Subashini, R., Jayalakshmi, K., & Aravinthan, V. (2022). *Traditional knowledge for sustainable agriculture: Panchagavya and its effects on crop performance.* AgriScience Research Journal, 12(1), 18–25.

41. Ghosh, A., & Pal, R. (2023). *Microbial consortium-based formulations for sustainable agriculture.* Agriculture and Environment, 9(1), 33–42.

42. United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* United Nations.

43. Tripathi, R., Bhattacharyya, P., & Patra, A. K. (2019). Carbon dynamics under organic farming. *Soil & Tillage Research*, 194, 104311.

44. Deshmukh, D. S., Patil, H. M., & Pawar, R. B. (2020). Soil quality indicators under organic management. *Environmental Monitoring and Assessment*, 192(10), 1–14.