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Traditional Wisdom and Modern Science: Educational Pathways for Sustainable Medicinal Plant Conservation

Anju Kumari Thakur, Deep Narayan Pandey and Gulshan Kumar*

School of Basic & Applied Sciences, Career Point University, Bhoranj (Tikker-Kharwarian), Hamirpur, Himachal Pradesh 176041, India

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Corresponding Author: **Gulshan Kumar** | E-Mail: **(anjusai9omthakur999@gmail.com)**

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ABSTRACT

Medicinal plants are the cornerstone of traditional healing systems and modern pharmaceuticals, yet their survival is threatened by overharvesting, habitat degradation, climate change, and other anthropogenic pressures. Traditional knowledge systems such as Vṛkṣāyurveda, sacred groves, folk conservation practices, and organic bioformulations provide ecologically sustainable pathways for medicinal plant protection. Modern innovations—including biotechnological tools, gene banks, artificial intelligence (AI)-based biodiversity monitoring, and digital education platforms offer complementary solutions. The present study explores the integration of ancient practices with contemporary science to establish a holistic framework for medicinal plant conservation. Case studies from Indian agro-ecosystems, particularly the intercropping of Ocimum sanctum (Tulsi) with Solanum tuberosum (potato) using Kunapajala and Panchagavya, demonstrate both ecological benefits and economic feasibility. The role of education, libraries, and inclusive dissemination of indigenous and scientific knowledge is highlighted as a critical pathway for safeguarding plant biodiversity. The synthesis of traditional and modern strategies not only strengthens conservation practices but also aligns with the United Nations Sustainable Development Goals (SDGs), particularly those addressing biodiversity, sustainable agriculture, and health.

Keywords: *Biodiversity conservation strategies, Indigenous knowledge systems, Medicinal plant conservation, Sustainable agriculture practices, and Vrikshayurveda bioformulations.*

1. Introduction

Medicinal plants have been central to human civilization for millennia, forming the backbone of healthcare systems such as Ayurveda, Unani, Siddha, and Traditional Chinese Medicine [1]. Today, approximately 80% of the global population relies on plant-based remedies for primary healthcare needs [2]. Yet, unsustainable harvesting, shrinking forests, and climate change pose severe threats to the survival of these valuable species. The World Health Organization has identified over 21,000 medicinal plants at risk, with many species facing extinction [3].

In India, the cradle of *Vṛkṣāyurveda*, the ancient science of plant life, traditional knowledge offers ecological insights into sustainable plant growth and protection [4]. Ancient agronomic texts such as *Surapala's Vṛkṣāyurveda*, *Bṛhat Saṃhitā*, and *Kṛṣi Parāśara* detail organic inputs, intercropping, sacred groves, and soil management practices that remain highly relevant. However, while these methods are eco-friendly and cost-effective, they are often underutilized in contemporary agriculture due to modernization, loss of indigenous knowledge, and the dominance of chemical-based farming [5].

Simultaneously, modern scientific innovations have opened new frontiers in conservation biology. Techniques such as cryopreservation, DNA barcoding, micro propagation, and remote sensing support large-scale monitoring and conservation [6]. Artificial intelligence is increasingly being used to track species populations, while digital libraries and community-based knowledge platforms preserve and disseminate traditional wisdom for global access [7].

This paper argues that the convergence of traditional ecological wisdom and modern technological innovation is not only possible but essential for the sustainable conservation of medicinal plants. By blending *Vṛkṣāyurveda* bioformulations like *Kunapajala* and *Panchagavya* with AI-driven monitoring systems and modern gene banks, it is possible to develop an integrative conservation strategy that addresses ecological, economic, and cultural dimensions simultaneously. Furthermore, education—both formal and community-driven—plays a pivotal role in bridging generational gaps in knowledge and creating awareness of sustainable practices [8].

2. Literature Review

The conservation of medicinal plants has been a focus of scholarly research for decades, bridging the fields of ethno botany, agriculture, pharmacology, forestry, and environmental education. This literature review synthesizes the evolution of medicinal plant conservation by examining three interrelated domains: traditional conservation practices, modern scientific interventions, and educational frameworks that support dissemination of sustainable practices. Together, these strands form the theoretical and practical foundation for blending indigenous knowledge with contemporary innovations in sustainability science.

2.1 Traditional Conservation Practices

Traditional conservation of medicinal plants has historically relied on cultural, religious, and ecological wisdom, much of which remains embedded in local communities. Ancient Indian texts such as *Vṛkṣāyurveda* (Surapala, 9th–10th century CE) describe plant care techniques that align with ecological principles still relevant today [9].

Practices such as sacred groves, common in India, Nepal, and parts of Africa, have served as biodiversity reservoirs by protecting ecosystems through community-based spiritual beliefs [10,11]. Sacred groves conserve species diversity and act as microhabitats for endangered medicinal plants, illustrating how spiritual traditions functioned as informal conservation strategies.

In Ayurveda, medicinal plant conservation was closely linked to healthcare practices. For example, texts like *Charaka Saṃhitā* and *Suśruta Saṃhitā* emphasize both the sustainable harvesting of plants and the ethical dimensions of plant use [12]. Communities traditionally observed restrictions on collection seasons, avoided uprooting entire plants, and prioritized replenishing wild stocks [13]. Such ecological ethics minimized resource depletion and allowed regeneration.

The *Kunapajala* and *Panchagavya* formulations mentioned in *Vṛkṣāyurveda* illustrate another dimension of conservation: the enrichment of soil fertility and plant resilience through organic bioformulations [9,4]. These practices highlight the interconnectedness between soil health, crop sustainability, and biodiversity conservation, forming a holistic agroecological system.

Ethnobotanical research also documents how indigenous knowledge systems safeguard medicinal species. Studies across India, Africa, and South America reveal that traditional healers and farmers preserve rare plants in home gardens or community-managed lands [14,15]. This practice ensures continuity of both biological diversity and cultural heritage. However, pressures such as deforestation, habitat fragmentation, and commercialization threaten these traditional approaches [16].

2.2 Modern Scientific Interventions

Modern science has introduced new dimensions to medicinal plant conservation through biotechnology, cultivation methods, ex situ conservation, and policy frameworks. Cultivation of high-demand medicinal species such as *Withania somnifera* (Ashwagandha), *Rauwolfia serpentina* (Sarpagandha), and *Ocimum sanctum* (Tulsi) has been promoted to reduce dependence on wild harvesting [17]. Agricultural interventions—such as intercropping medicinal plants with staple crops—enhance both biodiversity and farmer income [18].

Biotechnological innovations such as plant tissue culture, micropropagation, and cryopreservation have emerged as reliable methods for conserving endangered species and producing uniform plant material [19,20]. For example, micropropagation techniques have successfully conserved endangered medicinal species like *Taxus baccata* and *Nothapodytes nimmoniana*, which are otherwise threatened due to overexploitation for alkaloid extraction [21].

Gene banks and seed banks play a crucial role in ex situ conservation by preserving genetic diversity for future generations [22]. Advances in DNA barcoding and molecular markers have improved species identification, reducing risks of adulteration in herbal medicine and supporting authenticity in conservation programs [23].

Government and policy initiatives also strengthen conservation. The National Medicinal Plants Board (NMPB) of India has promoted large-scale cultivation and community nurseries to protect biodiversity hotspots [24]. Internationally, the Convention on Biological Diversity and its Nagoya Protocol have reinforced the importance of fair and equitable sharing of benefits from biological resources [25,26].

Despite these interventions, modern conservation approaches face challenges. Large-scale cultivation may lead to monocultures, reducing genetic variability and resilience. Additionally, commercialization often prioritizes economically valuable species, neglecting less popular but ecologically important plants [27].

2.3 Educational Frameworks for Knowledge Dissemination

Education represents a pivotal link between traditional wisdom and modern science. Universities, research institutions, and community-based organizations are increasingly integrating medicinal plant conservation into curricula and outreach initiatives. Environmental education frameworks emphasize participatory learning, experiential engagement, and culturally contextualized pedagogy [28].

In India, several higher education programs now include ethnobotany and traditional medicine studies as part of life sciences and pharmacy curricula [29]. At the school level, biodiversity gardens and herbal plantations are used as tools to familiarize students with medicinal plant diversity and their role in health [30].

Digital platforms, such as online databases, e-herbaria, and mobile apps, are modern tools that help bridge gaps between traditional knowledge and scientific literacy [31]. Initiatives like the Traditional Knowledge Digital Library (TKDL) in India have digitized classical Ayurvedic texts, safeguarding indigenous knowledge from biopiracy while making it accessible to researchers worldwide [32].

Community education is equally vital. Studies suggest that involving local stakeholders in participatory resource management increases conservation effectiveness [5,33]. Non-formal education approaches such as farmer field schools, herbal fairs, and community seed banks empower people to adopt conservation practices at grassroots levels [34].

At the global policy level, the United Nations Sustainable Development Goals (SDGs), particularly Goal 15 "Life on Land", emphasize the need to integrate education, conservation, and sustainable use of terrestrial ecosystems [26]. Incorporating these goals into educational frameworks encourages multi-level participation across formal and informal institutions.

2.4 Gaps and Emerging Directions

While significant progress has been made, gaps remain in harmonizing traditional and modern approaches. Ethnobotanical knowledge is still under-documented in many regions, creating risks of knowledge erosion as custodians age [16]. Similarly, modern interventions often overlook socio-cultural contexts, leading to community disengagement. Education has yet to fully integrate transdisciplinary approaches that connect cultural heritage, science, and sustainability [35,36].

Emerging research advocates for innovative frameworks such as bio-cultural conservation models, which combine ecological science with cultural practices, and citizen science platforms, where communities contribute to biodiversity monitoring [37]. Furthermore, intercropping trials using *Vṛkṣāyurveda* bioformulations represent promising case studies that demonstrate how ancient practices can align with sustainable agriculture and biodiversity conservation [38].

3. Methodology

The methodology integrates traditional medicinal plant conservation approaches, *Vṛkṣāyurveda* bioformulations, and indigenous techniques with modern interventions such as intercropping, soil testing, and monitoring tools. The study design combined agronomic field trials, Ethnobotanical surveys, and educational synthesis to assess the effectiveness of integrated approaches [39][40].

3.1 Study Area

The experiment was conducted in Himachal Pradesh, in the mid-hill zone of the western Himalayas. The site has a subtropical climate with approximately 1100 mm annual rainfall and mean temperatures of 18–22 °C. It was selected for its medicinal plant use, reliance on traditional inputs, and ecological vulnerability due to soil degradation [41].

3.2 Experimental Design

A Randomized Block Design (RBD) with three replications was used to minimize variability [42]. Table 1 lists the treatments applied in sole and intercropping plots of Tulsi and potato.

Table1. Treatments Applied

Treatment Code	Description
T1	Control (No input)
T2	Farmyard manure (FYM) @ recommended dose
T3	Inorganic fertilizer (NPK) @ recommended dose
T4	Kunapajala (KJ) – Herbal *Vṛkṣāyurveda* formulation
T5	Panchagavya (PG) – Traditional bioformulation

Footnote: T1 = Control (No input); T2 = FYM @ recommended dose; T3 = NPK @ recommended dose; T4 = Kunapajala – Herbal Vṛkṣāyurveda formulation; T5 = Panchagavya – Traditional bioformulation.

Each treatment was applied to sole cropping (Tulsi or potato) and intercropping (Tulsi + potato). Plot size was 4 × 5 m with 50 cm buffer zones. Buffer zones were maintained to prevent nutrient or microbial cross-contamination.

Figure1. Experimental Layout of Sole and Intercropping Plots

Source: Author's own research work at selected site.

3.3 Crop Selection and Intercropping

Ocimum sanctum (Tulsi) was chosen for pharmacological significance, adaptability, and cultural importance. *Solanum tuberosum* (potato) was selected as a staple crop with contrasting growth. Intercropping followed complementarity principles: Tulsi enhances soil microbial activity and pest regulation, while potato improves space utilization and economic returns [43].

3.4 Bioformulation Preparation

Kunapajala was prepared according to *Vṛkṣāyurveda* principles to enhance soil fertility, plant growth, and microbial activity. Ingredients included pulses (as a nitrogen source), oilseeds (for micronutrients), jaggery (to support microbial fermentation), and selected medicinal herbs with growth-promoting properties. The mixture was fermented in earthen pots for 30 days with intermittent stirring to promote microbial proliferation and enzymatic activity [39]. The resulting solution was diluted 1:10 and applied as a soil drench and foliar spray to improve nutrient availability, enhance plant vigor, and reduce dependence on chemical fertilizers.

Panchagavya, a traditional biofertilizer, was prepared using cow dung, urine, milk, curd, and ghee, combined with sugarcane juice and banana to accelerate fermentation. This formulation enriches soil with macro- and micronutrients, beneficial microbes, and plant growth hormones such as auxins and gibberellins. Panchagavya was also diluted 1:10 and applied to the soil and foliage to improve nutrient uptake, enhance resistance to pests and diseases, and promote overall crop health [44].

Both formulations increase soil organic carbon, microbial biomass, and enzymatic activity, supporting long-term soil health. Foliar and soil applications improve morphological parameters (height, branching, leaf area) and biomass accumulation in Tulsi and potato. Using indigenous bioformulations reduces chemical input dependency, aligns with *Vṛkṣāyurveda* principles, and demonstrates eco-friendly strategies for medicinal plant cultivation.

3.5 Data Collection

Data were collected to evaluate the effectiveness of traditional bioformulations and modern intercropping strategies on plant growth, yield, soil health, and farmer practices.

3.5.1 Growth and Yield Parameters

Tulsi (*Ocimum sanctum*): Plant height, number of branches, leaf area index (LAI), and fresh and dry biomass were measured at key growth stages to assess morphological vigor and biomass accumulation [43].

Potato (*Solanum tuberosum*): Stem number per hill, tuber number, tuber weight, and total yield per hectare were recorded to evaluate productive performance and economic viability of intercropping systems [43].

3.5.2 Soil Health Indicators

Soil samples (0–15 cm) were collected before sowing and after harvest. Parameters analyzed included:

- Soil Organic Carbon (SOC) – long-term soil fertility
- Available Nitrogen (N), Phosphorus (P), Potassium (K) – nutrient dynamics
- Microbial Biomass Carbon and Dehydrogenase Activity – indicators of microbial activity and soil biological health [45][46]

3.5.3 Economic Analysis

Cost–benefit ratio (CBR) was calculated using labor, input costs (bioformulations vs. chemical fertilizers), and crop yields. Additional sustainability indicators, such as input self-reliance and resource circularity, were assessed to determine the economic and ecological viability of integrating traditional bioformulations into modern farming systems [8].

3.5.4 Ethnobotanical Survey

Semi-structured interviews and focus group discussions with 50 farmers and traditional healers documented practices such as seed exchange, home gardens, sacred groves, and other community-based conservation strategies. This survey assessed local knowledge retention, adoption of sustainable practices, and cultural dimensions of medicinal plant conservation [47][40].

3.6 Data Analysis

Quantitative data (growth, yield, soil parameters) were analyzed using ANOVA at $p < 0.05$ to determine the significance of treatment effects. Tukey's HSD test was applied for post-hoc comparisons of treatment means.

Ethnobotanical data were coded thematically and integrated with agronomic findings to develop a holistic conservation framework [42].

Table 2. Parameters Measured for Tulsi and Potato

Crop	Growth & Morphology	Yield	Soil/Physiology	Notes
Tulsi	Plant height, Branch number, LAI	Fresh & dry biomass	Chlorophyll, SOC, Microbial biomass carbon, Dehydrogenase activity	Pest incidence, flowering time
Potato	Plant height, Stem number	Tuber number, Tuber weight, Total yield	N, P, K, Soil enzymes	Disease incidence, e.g., late blight

Footnote: LAI = Leaf Area Index; SOC = Soil Organic Carbon; Microbial biomass carbon and dehydrogenase activity measured to assess soil health. Disease incidence for potato includes late blight severity.

3.7 Educational Integration

Findings were synthesized into teaching modules for higher secondary and undergraduate students, combining historical texts (*Vṛkṣāyurveda*), field evidence, and sustainability principles [40][48]. Such modules aim to promote knowledge transfer and sustainable practices for future conservation initiatives.

3.8 Background: Medicinal Plant Conservation Challenges

Medicinal plant conservation faces threats from overharvesting, habitat loss, climate change, and socio-economic pressures. Unsustainable collection has depleted species such as *Nardostachys jatamansi* and *Picrorhiza kurroa* in the Himalayas. Habitat fragmentation, urbanization, and climate variability further exacerbate these declines [39].

4. Results and Discussion

4.1 Effect on Tulsi Growth and Yield

Tulsi (*Ocimum sanctum*) exhibited significant improvement in growth and biomass under *Vṛkṣāyurveda* bioformulations compared to the control and chemical fertilizer treatments. Plants treated with Kunapajala (T4) achieved the highest plant height (58 ± 1.7 cm), number of branches (10 ± 0.6), leaf area index (1.8 ± 0.1), and fresh and dry biomass (46 ± 1.6 g and 20 ± 0.7 g/plant, respectively). Panchagavya (T5) also improved growth parameters, though slightly lower than Kunapajala. These results indicate that herbal and organic bioformulations enhance morphological vigor, likely due to improved nutrient availability, soil microbial activity, and plant resilience [39, 49].

Chemical fertilizers (T3) increased growth compared to the control (T1) but were less effective than organic bioformulations, suggesting that sustainable inputs can match or surpass conventional fertilizers while maintaining ecological balance [43].

4.2 Effect on Potato Growth and Yield

Intercropped potato (*Solanum tuberosum*) showed enhanced stem number, tuber number, tuber weight, and total yield under bioformulation treatments. Kunapajala (T4) produced the highest tuber yield (24 ± 1.0 t/ha), followed closely by Panchagavya (T5). This improvement reflects synergistic interactions in intercropping, where Tulsi enriches rhizospheric microbial communities and supports nutrient cycling, benefiting potato growth [43, 50].

Chemical fertilizer treatment (T3) increased yield over the control but did not significantly outperform bioformulations, emphasizing the economic and ecological viability of integrating *Vṛkṣāyurveda* practices into modern cropping systems [12, 17].

4.3 Soil Health Enhancement

Soil organic carbon (SOC) and nutrient availability (N, P, K) were higher in plots treated with Kunapajala and Panchagavya compared to control and NPK treatments. Microbial biomass carbon and dehydrogenase activity also increased, indicating enhanced microbial activity and soil fertility [45, 46].

These findings confirm that organic bioformulations not only support plant growth but also restore soil health, addressing long-term sustainability challenges in agroecosystems [39][44].

4.4 Integration with Conservation Objectives

The combined effect of bioformulations and intercropping aligns with traditional *Vṛkṣāyurveda* principles, demonstrating that indigenous practices can be effectively integrated with modern agriculture. By improving yield, promoting soil fertility, and reducing dependency on chemical inputs, these methods provide a holistic strategy for sustainable medicinal plant conservation [40, 48].

Moreover, the ethno botanical survey highlighted active farmer participation in seed exchange, home gardens, and sacred groves, indicating that community knowledge supports ecological sustainability [1, 7]. Integration into educational modules further ensures that these practices are documented, taught, and applied for future generations, bridging traditional wisdom and modern science in conservation education [29, 26].

Table 3. Effect of Bioformulations and Fertilizers on Growth, Yield, and Soil Health in Tulsi–Potato Intercropping

Crop / Parameter	T1 (Control)	T2 (FYM)	T3 (NPK)	T4 (Kunapajala)	T5 (Panchagavya)
Tulsi					
Plant height (cm)	45 ± 2.1	52 ± 1.8	55 ± 2.0	58 ± 1.7	57 ± 1.9
Number of branches / plant	6 ± 0.5	8 ± 0.4	9 ± 0.5	10 ± 0.6	9 ± 0.5
Leaf area index (LAI)	1.2 ± 0.1	1.5 ± 0.1	1.6 ± 0.1	1.8 ± 0.1	1.7 ± 0.1
Fresh biomass (g/plant)	30 ± 1.5	38 ± 1.7	42 ± 1.8	46 ± 1.6	44 ± 1.7
Dry biomass (g/plant)	12 ± 0.7	16 ± 0.8	18 ± 0.8	20 ± 0.7	19 ± 0.8
Potato					
Stem number / hill	4 ± 0.3	5 ± 0.2	5 ± 0.3	6 ± 0.2	6 ± 0.3
Tuber number / plant	8 ± 0.5	10 ± 0.6	11 ± 0.5	12 ± 0.6	12 ± 0.5
Tuber weight (g)	450 ± 15	520 ± 18	540 ± 20	580 ± 16	570 ± 17
Total yield (t/ha)	18 ± 1.2	21 ± 1.1	22 ± 1.3	24 ± 1.0	23 ± 1.2
Soil Health Indicators					
SOC (%)	0.48 ±0.02	0.55 ±0.02	0.53 ±0.03	0.60 ±0.02	0.58 ±0.02
Available N (kg/ha)	150 ± 5	170 ± 6	165 ± 5	180 ± 4	175 ± 5
Available P (kg/ha)	25 ± 1	28 ± 1	27 ± 1	30 ± 1	29 ± 1
Available K (kg/ha)	120 ± 4	135 ± 5	130 ± 4	145 ± 4	140 ± 5
Microbial Biomass C (mg/kg)	210 ± 8	250 ± 9	240 ± 8	270 ± 7	260 ± 8
Dehydrogenase activity (µg TPF/g soil/h)	18 ± 1.2	22 ± 1.1	21 ± 1.0	25 ± 1.1	24 ± 1.2

Footnote: T1 = Control (No input); T2 = Farmyard Manure; T3 = NPK (recommended dose); T4 = Kunapajala (herbal Vṛkṣāyurveda formulation); T5 = Panchagavya (traditional bioformulation). Values are mean ± SE (n = 3). SOC = Soil Organic Carbon; TPF = Triphenyl Formazan.

5. Conclusion

The study demonstrates that integrating traditional *Vṛkṣāyurveda* bioformulations *Kunapajala* and *Panchagavya* with modern intercropping systems significantly enhances growth, yield, and soil health in Tulsi–Potato agroecosystems. Kunapajala consistently produced superior results, promoting morphological vigor, biomass accumulation, and microbial activity, while Panchagavya also showed substantial benefits [39, 44].

Intercropping Tulsi with potato improved economic returns and fostered ecological sustainability by enhancing nutrient cycling and soil fertility [43, 50]. The incorporation of community knowledge, ethno botanical practices, and educational modules strengthens conservation outcomes, ensuring that traditional wisdom is documented and transmitted to future generations [1, 29, 26].

These findings highlight the synergy between traditional knowledge and modern science as a practical pathway for sustainable medicinal plant conservation. Adoption of such integrative strategies can reduce reliance on chemical fertilizers, promote biodiversity, and align with global sustainability goals, particularly the United Nations' SDGs on life on land, health, and sustainable agriculture [29].

Future Scope: Further research could explore large-scale implementation, long-term soil dynamics, and digital monitoring platforms to optimize conservation and educational outreach for broader ecological and socio-economic impact [16, 50].

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