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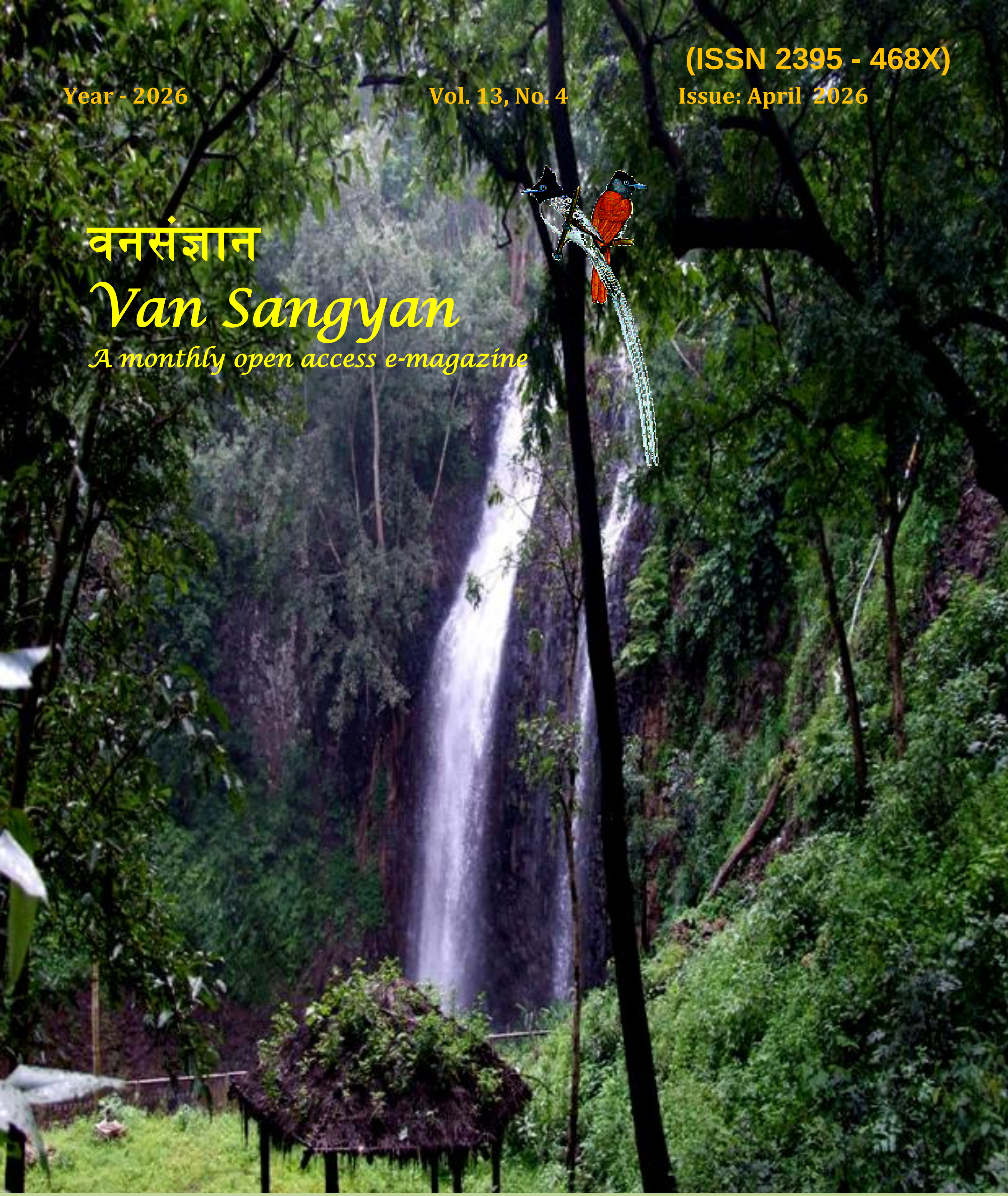

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Van Sangyan

Note to Authors:

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The articles can be in English, Hindi, Marathi, Chhattisgarhi and Oriya, and should contain the writers name, designation and full postal address, including e-mail id and contact number.

TFRI, Jabalpur houses experts from all fields of forestry who would be happy to answer reader's queries on various scientific issues. Your queries may be sent to The Editor, and the expert’s reply to the same will be published in the next issue of Van Sangyan.

Cover Photo: Panoramic view of Achanakmar-Amarkantak Biosphere Reserve

From the Editor's desk

Myrothecium leaf spot, caused by Myrothecium roridum, is emerging as a serious foliar disease of bael (Aegle marmelos Correa.), particularly in nurseries and young plantations under warm and humid conditions. The disease is characterized by small brown necrotic lesions that enlarge into irregular dark-bordered spots with grayish centers, chlorotic halos, and shot-hole symptoms due to tissue disintegration. Severe infection leads to premature defoliation, reduced photosynthetic efficiency, poor seedling vigor, and economic losses in bael cultivation. The pathogen survives in infected debris and spreads rapidly through rain splash, irrigation water, and contaminated nursery conditions. Effective management requires an integrated approach involving sanitation, removal of infected leaves, proper spacing, avoidance of overhead irrigation, and balanced nutrient management. Fungicides such as propiconazole, mancozeb, carbendazim + mancozeb, and tebuconazole-based formulations have shown significant efficacy against the pathogen, while biological agents such as Trichoderma spp. offer eco-friendly alternatives for sustainable disease management. Continuous surveillance, resistant genotype identification, and climate-resilient plant protection strategies are essential to safeguard bael cultivation against this emerging fungal threat.

In line with the above this issue of Van Sangyan contains an article on Myrothecium Leaf spot an emerging disease of Bael (Aegle Marmelos Correa.): A study on symptom and management There are also useful articles viz.. The need for pyrosilviculture for landscape resilience, Insects in the forest ecosystem, Carbon trading in agroforestry: Bridging sustainability and profitability, Agroforestry: A strategy for climate change mitigation through carbon sequestration, Rhizosphere engineering: A new frontier in forest soil management, Seeds that save forests: Unlocking seed science strategies for climate resilience, Effect of kerf treatment and center boring on drying behavior of round logs, Healing from forests: Medicinal plants and minor forest produce in ayurveda in India and Blockchain: A digital tool for traceability, fair payments, and better forest governance in Indian Himalayan Region.

Looking forward to meet you allthrough forthcoming issues

Dr. Naseer Mohammad

Chief Editor

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Myrothecium Leaf spot an emerging disease of Bael (*Aegle Marmelos* Correa.): A study on symptom and management

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Abstract

Myrothecium leaf spot, caused by the fungus *Myrothecium roridum*, is emerging as a significant disease affecting bael (*Aegle marmelos* Correa), a tree known for its medicinal and economic value. This disease has recently gained attention due to its increasing prevalence in bael-growing regions, posing a threat to both fruit yield and tree health. The primary symptoms of Myrothecium leaf spot include the appearance of small, circular to irregular dark brown or black lesions on the leaves. As the disease progresses, these lesions expand, forming concentric rings with a necrotic center and yellow halos. Severe infection can lead to premature defoliation, reducing the plant's photosynthetic ability, and subsequently affecting fruit production. The fungal pathogen *M. roridum* thrives in warm, humid conditions, making monsoon and post-monsoon seasons favorable for its spread. The fungus produces sporodochia, which are tiny fruiting bodies on the surface of infected tissues, contributing to the rapid dissemination of spores through wind and rain splash.Management of Myrothecium leaf spot involves an integrated approach. Cultural practices such as the removal and destruction of infected leaves help reduce inoculum levels in the field. Ensuring proper plant spacing to facilitate air circulation can also minimize disease development by reducing humidity around the foliage. Chemical control methods include the application of fungicides, such as mancozeb and copper-based formulations, which have shown efficacy in reducing disease severity. Additionally, biological control agents like *Trichoderma* spp. have been investigated for their antagonistic effects *on M. roridum*, offering a sustainable alternative for disease management. The increasing incidence of Myrothecium leaf spot highlights the need for ongoing research to develop resistant cultivars of bael and explore eco-friendly management strategies. Effective disease control will not only help in sustaining bael cultivation but also ensure the continued availability of its medicinal and nutritional benefits.

Keywords: Myrothecium leaf spot, bael, *Myrothecium roridum*, disease management, fungicides, integrated disease management

Introduction

Bael is susceptible to various fungal and bacterial diseases that can impact on its growth and overall health. Several prevalent diseases that were recently documented to affect bael trees diseases like leaf blight due to bacteria, root rot, collar rot, wilt, Myrothecium leaf spot, Alternaria leaf spot. Bacterial shoot-hole, sooty mould and gummosis.Numerous of the fungal foliar diseases which damage plants at the nursery stage are root rot caused by *Fusarium solani*, leaf spot and die back induced by *Myrothecium roridum*.

Symptoms

Initial Symptom

Spared Symptom

Create shot hole on leaf

Damaged bael plant

Myrotheciumleaf spot of bael, symptoms appeared on leaves as brown, irregularly shaped, small patches with chlorosis surrounding the lesions; however, over time, these spots grew larger and covered a larger area. The disease initially emerged as round brown patches on the leaf's upper surface during the rainfall season, which occurs in July as well as August.

Management

For the effective management of Myrothecium leaf spot, the efficacy of differentchemical fungicide, botanical extracts and bioagents are tested againstthe *Myrothecium roridum* in the laboratory, Department of Plant pathology, Acharya Narendara Deva University of Agriculture and Technology by using poisoned food techniques and dual culture methods respectively. On the basis of results, we are obtained in the lab following recommendation are suggested

- Application of chemical fungicidePropiconazole 25% EC orPyraclostrobin 20% WG @ 0.01%
- Application of Thiophanate Methyl 70% WP or Metiram 55% + Pyraclostrobin 5% WG @ 0.05%
- Application of Tebuconazole 25% + Trifloxystrobin 50% or Hexaconazole 4% + Zineb 68% @ 0.075%
- Application of Carbendazim12% + Mancozeb63% WP or Tebuconazole 25.9% w/w EC @ 0.1%
- Application of botanical extracts of Neem leaves and Garlic cloves @ 10%
- Application of botanical extracts of Eucalyptus leaves @ 5%
- Application of bio fungicide *Trichoderma viridae*and *Trichoderma harzanium* in soil application with FYM.
- Clean Cultivation of Nursery.
- Field Sanitation.
- Regular pruning of infected leaves.

Conclusion

Myrothecium leaf spot represents a significant challenge to bael cultivation. By adopting comprehensive management strategies and continuing research efforts, the impact of this emerging disease can be mitigated, ensuring the sustainability and productivity of bael orchards.

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The need for pyrosilviculture for landscape resilience

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Introduction

Wildfires have always been a part of many ecosystems worldwide, but recent decades have seen a dramatic rise in the number, intensity, and destructiveness of these fires. From the vast forests of the western United States to the bushlands of Australia and the Mediterranean scrublands of southern Europe, wildfires are increasingly threatening not just nature but also human communities (Silvestro *et al*., 2021).

In this context, Pyrosilviculture has emerged as a critical and innovative approach to landscape management. By integrating fire's natural role with silvicultural (forest management) techniques, pyrosilviculture aims to build landscapes that are better able to withstand and recover from fire and other environmental stresses. This article explores why pyrosilviculture is needed more than ever and how it contributes to landscape resilience.

What is Pyrosilviculture?

The term might sound technical, but pyrosilviculture boils down to a simple idea: managing forests by working with fire rather than against it."Pyro" means fire, and "silviculture" is the science and practice of growing and managing forests. Together, pyrosilviculture refers to forest management strategies that incorporate controlled and carefully planned use of fire to mimic its natural ecological functions (York *et al*., 2021).

Natural role of fire in forests

In many ecosystems, fire is a natural process that has shaped forests for thousands, sometimes millions, of years. Regular, low-intensity fires historically swept through these landscapes, clearing dead wood and undergrowth, recycling nutrients back into the soil, and helping fire-adapted plants and animals thrive (Awadhiya, 2025**)**.

For example

- Ponderosa pine forests in the western U.S. evolved with frequent, low-severity fires every 5 to 25 years, which kept tree density low and reduced fuel accumulation (Haffey *et al*., 2018).
- Lodgepole pine cones in Canada and the U.S. only open to release seeds after exposure to intense heat from fire(Lotan*et al*., 1983).
- Australian eucalyptus trees have thick bark and other adaptations that allow them to survive and even regenerate after fire(Burrows, 2013).
- Unfortunately, decades of strict fire suppression policiesintended to protect lives and propertyhave disrupted these natural fire cycles. This has led to dense forests choked with trees and shrubs, creating conditions ripe for massive, uncontrollable wildfires.

Pyrosilviculture seeks to restore fire's role as an ecosystem regulator by using prescribed burns (controlled fires) and forest thinning to reduce fuel loads and maintain healthy forest conditions.

Why landscape resilience is crucial today

Landscape resilience is an ecosystem's ability to absorb disturbances like fire, pests, or drought without collapsing or losing its essential functions.

Today, resilience is more important than ever because:

Climate change increases fire risks

Rising global temperatures, prolonged droughts, and shifting precipitation patterns have created hotter, drier landscapes. This means:

- Fire seasons are longer.
- Fires burn more intensely and unpredictably.
- Previously fire-resistant areas are becoming vulnerable.

For example, the 2020 California wildfires burned over four million acres, devastating communities and ecosystems, with climate change playing a significant role in creating conditions for such megafires (Yu & Chaturvedi, 2025).

Human expansion into wildlands

As more people build homes and infrastructure near or within wildlands (the wildland-urban interface), the risk of fires impacting lives and property increases. At the same time, fire suppression around these areas often results in fuel accumulation, paradoxically raising the chances of extreme fires.

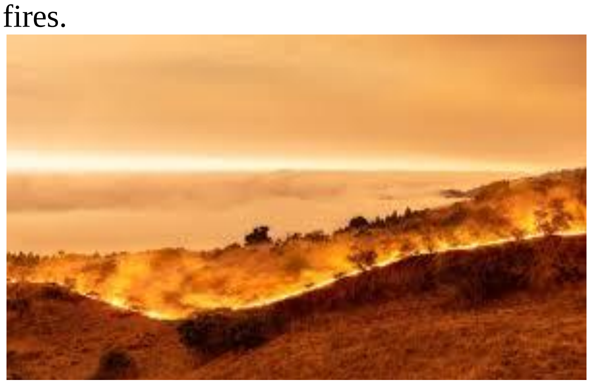


Fig: California's wildfire

Ecosystem Services Depend on Healthy Landscapes

Forests and wildlands provide vital services such as:

- Carbon storage that mitigates climate change.
- Clean water supplies from healthy watersheds.
- Habitat for wildlife and plant diversity.
- Recreational, cultural, and economic benefits.

Severe fires can degrade these services for decades or permanently if ecosystems lose resilience.

How pyrosilviculture enhances Landscape resilience

Pyrosilviculture combines fire management and silviculture to create forests that can better withstand and recover from fire and other stresses.

Reducing hazardous fuels

One of the most important goals is reducing the amount of flammable material on the forest floor. Accumulated dead trees, branches, shrubs, and dense understory plants act like kindling for large, uncontrollable wildfires.

Prescribed burning uses carefully planned, controlled fires under specific weather conditions to safely consume excess fuels without harming mature trees.

Mechanical thinning involves physically removing some trees and shrubs, especially smaller, dense trees that contribute to fire spread.

These treatments help prevent fires from becoming catastrophic, lowering the chance of crown fires that leap from treetop to treetop and cause the most damage.

Restoring Natural Fire Regimes

By mimicking the frequency and intensity of historical fires, pyrosilviculture supports species that depend on fire for regeneration. For example:

- Some pines require heat to open their cones.

- Fire can clear competing vegetation, giving fire-adapted species a competitive edge.
- Low-intensity fires recycle nutrients and stimulate new growth.

Restoring these cycles improves forest health and biodiversity.

Creating Diverse and Mosaic Landscapes

Fire does not burn landscapes evenly; it creates patches of different ages and vegetation types. This patchiness, or **mosaic**, is important for wildlife habitat and ecological balance.

Pyrosilviculture promotes this heterogeneity by managing fires and treatments across landscapes, creating a mix of open areas, dense stands, and recently burned patches that support varied plant and animal communities (North *et al*., 2021).

Protecting Soil and Water Resources

Severe fires can damage soils by destroying organic matter and increasing erosion risks. This can reduce soil fertility and lead to sediment runoff that pollutes streams and reservoirs.Controlled fire and silvicultural treatments reduce the risk of severe fires, helping protect soil structure and water quality.

Increasing Community Safety and Preparedness

When implemented around homes and towns, pyrosilviculture can create defensible spaces—areas where fire intensity is lowered and firefighting efforts are more effective.Coupled with community education and planning, this approach can reduce fire-related losses and improve safety.

Real-World Examples of Pyrosilviculture in Action

The Western United States

In places like California, Oregon, and Colorado, forest managers increasingly use prescribed burns and thinning to reduce wildfire risk.

- The Collaborative Forest Landscape Restoration Program works with communities, scientists, and agencies to apply pyrosilviculture across millions of acres.
- Studies show treated areas experience less severe fires and faster recovery.

Australia's Indigenous Fire Practices

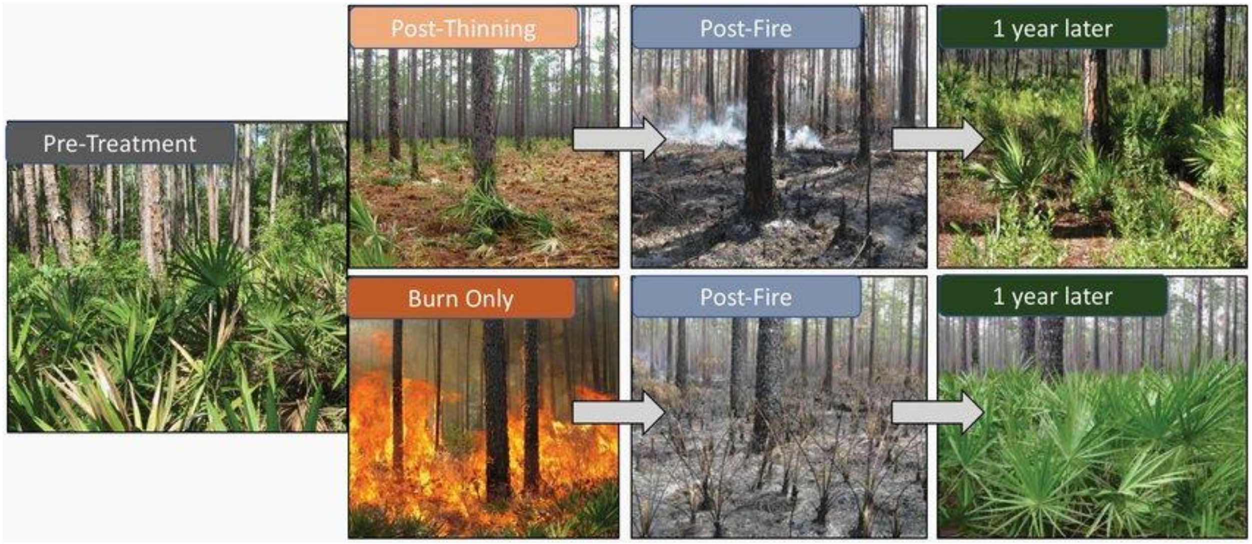
For thousands of years, Indigenous Australians used **"cool burns"**—low-intensity, patchy fires—to manage the landscape, encouraging new growth and reducing wildfire hazards.

Modern pyrosilviculture integrates this traditional ecological knowledge with scientific fire management to better protect ecosystems and communities.

Mediterranean Europe

Countries like Spain and Portugal have long fire seasons with dense shrublands.

Integrating prescribed fire and silviculture has improved landscape resilience by reducing fuel loads and promoting fire-adapted species.



(Source: North *et al*., 2021)

Fig: Pyrosilviculture for Landscape resilience

Challenges and Opportunities

Despite its benefits, pyrosilviculture faces obstacles:

Public Fear and Misunderstanding

Many fears prescribed fire due to smoke, escape risks, or past bad experiences. Effective public outreach and education are essential.

Climate Variability

Unpredictable weather makes timing controlled burns more complex.

Resource and Policy Constraints Adequate funding, trained personnel, and supportive policies are needed to implement pyrosilviculture at scale.

Nevertheless, advances in remote sensing, fire modeling, and community engagement tools offer new opportunities to overcome these challenges.

Conclusion: A New Vision for Living with Fire

Pyrosilviculture invites us to rethink how we relate to fire—not as an enemy to be eliminated but as a powerful natural process to be respected and managed wisely. As wildfires grow more intense and frequent under changing climate conditions, this approach offers hope for healthier forests, safer communities, and resilient landscapes.By embracing pyrosilviculture, we can create a future where fire helps renew and sustain our forests rather than destroy them. It is a crucial step toward harmony between people, forests, and fire in a changing world.

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Insects in the forest ecosystem

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Abstract
Ecosystems, including forest environments, are vitally dependent on insects. It is common for insects to live in symbiosis with a wide variety of microorganisms in their habitat. It is possible for their interactions with the micro biome to be neutral, beneficial, or detrimental, depending on each of their respective interests. In this chapter, we summarize and discuss insects' ecological roles and general characteristics so that we can gain a better understanding of their diversity and importance in forest ecosystems. Various insect orders representing different life stages are interconnected with diverse micro biomes (e.g., bacteria, fungi, and viruses). There are many functionally diverse micro biota associated with insects, such as pathogenic and mutualistic microbes. The larval stages of most lepidopteron and coleopteran insects have bacterial endosymbioses. This article also discusses the relationship between forest insects' microbiomes and their transmission routes and interactions. There are also challenges and constraints in the availability of baseline diversity and global data on the insect micro biome.

Ecosystems of forests and insects
There is often a misunderstanding about insects when it comes to naming the most significant organisms in forests. The diversity and health of forests depend on them for reproduction, soil fertility, and plant health.
Intended audience

- The pollination of plants and the spreading of seeds
- A process by which nutrients are converted
- In the process of decomposing wood
- Health of the forest
- Food chains and regulation: eating or being eaten
- Construction of habitats

As one compares the importance of different groups of organisms from a biomass perspective and consider the importance of each group from the point of view of species diversity, it becomes apparent that trees dominate in terms of biomass or species diversity. Even so, insects (and fungi), when viewed from the point of view of the diversity of species, are clearly all dominant with respect to biodiversity.

The pollination of plants and the spreading of seeds
A significant portion of the trees and bushes in the world are pollinated by insects around 80 percent of the time. There are many forest trees that reproduce by wind pollination. However, some plants invest a lot of energy into producing large, tempting blooms that are filled with nectar. There are maples, dogwoods, hawthorns, horse chestnuts, cherries, buckthorns, willows, Rowan berries, and limes among them. A wide variety of insects, such as bees, wasps, flies, beetles, and butterflies, feed on the nectar and pollen. In addition to pollinating their flowers, they carry pollen to other plants.
A wide variety of ants spread the seeds and fruit of herbaceous plants. Approximately 150 plant species are known to exhibit this behavior. In some plants, special seeds are

produced that are collected and eaten by ants. A seed never eaten by ant germination occurs along its paths or on its "rubbish tips". It is advantageous to grow such plants for two reasons. In addition, being near the ant heap protects them from other seed predators, as well as allowing them to cover long distances on windless ground.

A process by which nutrients are converted

Besides regulating nutrient levels and energy sources, leaf-eating insects feed on needles and leaves. By eating excrement, larvae consume plant material already well digested by animals. The microorganisms in excrement colonize and mineralize it quickly. Thus, plant growth is accelerated due to rapid nutrient availability.

In the process of decomposing wood

A forest's natural dynamic includes dying trees. Many factors may cause this, including age, lightning, storms, forest fires, drought, insect infestations, or pathogens. It is essential to make the nutrients and energy in the bark available to the soil. The microorganisms that decompose wood are more difficult than those that decompose leaves or herbaceous plants. Besides being difficult for fungi to colonize, bark also protects wood from decomposition caused by fungi.

There are many specialized pioneer insects that colonize freshly dead wood. Drilling holes in the bark or into the wood makes the substrate accessible to other wood and bark-eating insects and fungi. By converting raw wood into chippings and excrement, microorganisms can break down the material more easily than hard wood. The decomposition of a tree trunk by microbes would take twice as long without insects that consume wood. There are different phases of decomposition for dead trees.

During the first phase of colonization, pioneer insects colonize newly dead trees. A saprophyte is a species of tree that feeds upon the bark or sapwood of certain types of trees. There are many different beetle families included in this category, such as bark beetles, longhorn beetles, jewel beetles, and timber worm beetles. In addition to wood wasps, this category includes paper wasps. Since wood lacks nutrients, it often takes longhorn beetles and wood wasps many years to develop. It is believed that some fungal species carry spores with them to help them utilize wood more efficiently. Through their activities, pioneer insects loosen the bark from wood and tap into the substrate wood, which allows further decomposition to occur. One to two years usually pass before the colonization phase begins.

During the second phase, the wood decomposes. There is a fall of twigs and branches as well as a separation of the bark from the tree. Changes in insect assemblages.The presence of various beetle groups dominate this phase of decomposition, including anobiid beetles (furniture beetles), stag beetles and darkling beetles. As well as various flies and midges, tunnels and mulms are also home to various flies and midges. The wood has predators and parasites, just as during colonization, which feed on wood eaters. Decomposing organisms such as bacteria and fungi play an increasingly important role during this process.

The final phase of the process is humification, during which the wood slowly decomposes into soil. There are now ants, fly maggots, various beetles, mites, and springtails living in wood mulch. When rotting wood is exposed to the soil organisms, such as worms, snails, woodlice, various insects, they enter the wood. A faunal population reduces particle sizes and increases surface area, which then allows microbes to decompose cellulose, hemicelluloses, lignin, and pectin. This results in raw humus and "soil".

Health of the forest

Insects can colonize weak but still living trees and kill them by feeding on them. Certain bark beetles are examples of this. Trees that are old, weak, ill, or under stress are eliminated during this process. Nevertheless, this contributes to the health and resilience of the forest. Insects that smell like carrion, such as blowflies and flesh flies, colonize and dispose of dead forest animals' excrement and carcasses.

Food chains and regulation: eating or being eaten

Food is provided by insects themselves to a wide range of animals. Bird species such as woodpeckers, titmice, warblers, sparrows, and cuckoos are common insect feeders. There are also vermin that consume insects, such as mice, shrews, bats, salamanders, and frogs. At the same time, it is important to note that many insects also live as predators or parasites that consume other insects. It is possible to control pest insect outbreaks through these methods.

Construction of habitats

New habitats are created by the destruction of individual trees and the decay of wood by insects. By killing trees, insects can allow light into the forest, creating new breeding opportunities, eating grounds, and living grounds for herbaceous plants and pioneer trees. The elimination of dead wood and insect decomposition provide new habitats for other organisms.

Conclusion

There are a variety of insects living in forest ecosystems, including those that feed on insects for survival and those that maintain a diversity of insects that are both harmful and beneficial. They are harmful because they complete the life cycle of a particular host and damage the main season of plants. In addition to alternative hosts, such as forest trees, grasses, etc., other things are necessary to complete their life cycles. This benefit can be attributed to the production of lac, silk, honey, propolis, venom, wax, and other products made by honey bees.

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Carbon trading in agroforestry: Bridging sustainability and profitability

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Abstract

This article explores the concept of carbon trading in agroforestry and its potential to bridge sustainability and profitability. Agroforestry, a land-use system combining agriculture and tree planting, has emerged as an effective tool for climate change mitigation. Carbon trading is an economic approach to reducing greenhouse gas emissions, offers incentives for farmers to adopt agroforestry practices by monetizing the carbon sequestration potential of such systems. This article highlights the benefits of carbon trading in agroforestry, including enhanced carbon sequestration, increased farm income, and rural development. It also addresses challenges related to measurement, market access, capacity building, and social equity. By addressing these challenges, carbon trading in agroforestry can unlock the potential for sustainable land management and contribute to global climate change mitigation efforts.

Keywords: Carbon trading, Agroforestry, Climate change mitigation, and Carbon sequestration

Introduction

In recent years, the need to mitigate climate change and its adverse effects has prompted the exploration of innovative solutions. Agroforestry, a sustainable land-use system that combines agricultural crops with tree planting, has emerged as a powerful tool for combating climate change while enhancing food security and promoting rural development. To further incentivize agroforestry practices, carbon trading has gained prominence as a mechanism to reward farmers for sequestering carbon dioxide (CO_2) and reducing greenhouse gas emissions. This article delves into the concept of carbon trading in agroforestry, highlighting its potential benefits and challenges.

Carbon Trading

Carbon trading, also known as emissions trading or cap-and-trade is an economic approach designed to reduce greenhouse gas emissions. The premise behind carbon trading is that countries, companies, or individuals can buy and sell carbon credits, which represent a quantified reduction or removal of CO_2 or other greenhouse gases from the atmosphere. By placing a monetary value on carbon emissions, the aim is to create economic incentives for entities to reduce their emissions and invest in sustainable practices.

Agroforestry's role in Carbon Sequestration

Agroforestry systems have demonstrated considerable potential for carbon sequestration due to the presence of trees. Trees act as carbon sinks, absorbing atmospheric CO_2 during photosynthesis and storing it in their biomass and soils. By integrating trees into agricultural landscapes, agroforestry practices facilitate increased carbon sequestration compared to conventional farming methods. Climate conditions, site features, tree species, stand age, and cultivation practises all affect sequestration capacity. As a result, estimates of carbon sequestration capacity in AFSs vary widely. According to Nair *et al.* (2009), the aboveground carbon sequestration range of AFS is 0.29-15.21 Mg C $ha^{-1}year^{-1}$, while the belowground range is 30-300 Mg C ha^{-1} up to 1m depth in the soil.The shade provided by trees also reduces soil moisture evaporation, further enhancing the overall productivity and resilience of agroforestry systems.

Carbon Trading as an Incentive for Agroforestry

Carbon trading can provide economic incentives for farmers to adopt agroforestry practices. By quantifying and monetizing the carbon sequestration potential of agroforestry systems, farmers can participate in carbon markets and earn carbon credits. Agroforestry systems have been selected for carbon trading based on their efficacy in minimizing emissions or capturing and preserving carbon **(Nath*et al.*, 2015).** These credits can then be sold to companies, organizations, or governments seeking to offset their own emissions and meet sustainability goals.

The income generated through carbon trading can supplement farmer's agricultural revenue, making agroforestry a financially viable option. It also encourages the expansion of agroforestry systems, contributing to landscape restoration, biodiversity conservation, and rural development. In addition to the economic benefits, carbon trading empowers farmers to become active participants in climate change mitigation, fostering a sense of stewardship and environmental responsibility.

Challenges and Considerations

While carbon trading holds great potential for agroforestry, several challenges and considerations must be addressed to ensure its successful implementation:

Measurement and Verification

Accurate measurement of carbon sequestration in agroforestry systems is crucial to determine the number of carbon credits a farmer can earn. Robust methodologies and monitoring techniques are needed to ensure transparency and credibility.

Market access and Infrastructure

Farmers need access to carbon markets and supportive infrastructure to engage in carbon trading. Building the necessary institutions, such as carbon registries and trading platforms, is essential for effective market participation.

Technical knowledge and Capacity building

Farmers may require technical assistance to adopt agroforestry practices and understand the complexities of carbon trading. Investing in capacity-building programs can empower farmers and enhance the long-term success of carbon trading initiatives.

Social equity and Inclusion

Ensuring that the benefits of carbon trading reach smallholder farmers, who often lack resources and representation, is crucial. Mechanisms should be in place to safeguard against exclusion and ensure equitable distribution of carbon revenue.

Conclusion

Carbon trading in agroforestry presents a win-win solution, combining climate change mitigation, sustainable land management, and rural development. By harnessing the carbon sequestration potential of agroforestry systems, farmers can generate additional income while actively contributing to global efforts to combat climate change. However, addressing challenges such as measurement accuracy, market access, capacity building, and social equity is crucial to realizing the full potential of carbon trading in agroforestry. Through collaborative efforts among governments, organizations, and farmers, we can pave the way for a more sustainable and prosperous future.

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Agroforestry: A strategy for climate change mitigation through carbonsequestration

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Introduction

The term "agroforestry" refers to a combination of forestry and agriculture that has been used for a long time (Raj *et al*. 2014 and Raj *et al*. 2016). Similarly, Indian forests include a diverse range of plants and animals and have a significant role in mitigating the effects of climate change (Toppo *et al.* 2014, Toppo *et al*. 2016). As a social forest, agroforestry, reforestation, and the restoration of waste areas and degraded industrial lands, it is very important (Jhariya*et al*. 2013). Through increased tree and shrub growth, agroforestry techniques also hold great promise for storing carbon and removing carbon dioxide from the atmosphere. According to (Nair 1993) agroforestry is a land-use system that intentionally preserves, adds, or mixes trees or other woody perennials with grasslands, livestock, and/or agricultural crops in order to take advantage of the ecological and financial interactions between the various elements. It covers the ecological and economic interactions of woody perennials with crops and/or livestock. Animals, woody perennials (tree crops/forest plants), and agricultural crops (herbaceous plants) make up agroforestry. We can all see that the climate is changing. It's an international issue that impacts every nation. Climate change is more concerning and urgent than ever for everyone on the planet. In particular, poorer nations would be the ones most affected by climate change and its harmful effects. The effects of climate change will only be somewhat lessened by mitigation efforts. It is generally acknowledged that human activity is now having a greater impact on changes in the global climate. (Chakraborty 2011). Agroforestry practices are becoming a feasible alternative to mitigate the adverse effects of climate change in the current context (Singh *et al.* 2013). Because of the secondary environmental benefits—such as food security and secure land tenure, increased farm income, restoring and maintaining above- and below-ground biodiversity, maintaining watershed hydrology, and soil conservation—agroforestry systems may be a better option for mitigating climate change than the ocean or other terrestrial options. In addition to its environmental benefits, agroforestry currently provides for about half of the need for fire wood, two thirds of small timber, 70–80% of plywood's wood, 60% of the raw material for paper pulp, and 9–11% of livestock's green fodder needs (NRCAF 2013). Environmental and socioeconomic factors greatly influence the shape and function of the agroforestry system that is implemented, which in turn determines how much carbon is sequestered. Agroforestry systems' ability to store carbon is also influenced by tree type and system management.

Carbon sequestring potential of different agroforestry systems:

Agroforestry system	**Carbon accumulation**
Taungya agroforestry system	174MgC/ha

Mixed multostory system	162MgC/ha
Coffee multistory system	92MgC/ha

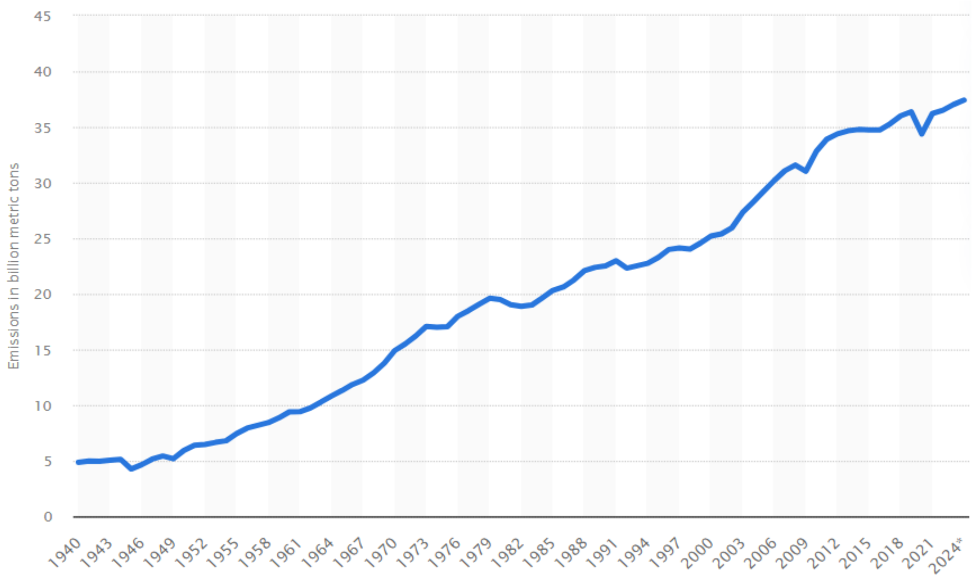
Agroforestry in India

Agroforestry techniques have a long history in India. The custom of planting common trees on farmlands in India is very old and hasn't changed much over the years. These trees serve a variety of purposes, including shade, fodder, fuel wood, fruit, vegetables, and medicinal purposes. Farm-grown trees, community forestry, various local forest management techniques, and ethnoforestry are all part of India's agroforestry systems. Large portions of India have adopted various agroforestry systems; however, because different organizations do not use the same approach, it is still difficult to estimate the area under agroforestry and conduct periodic monitoring.According to (Kumar *et al*. 2014), the whole area that is used for multi-strata systems can be categorized as various agroforestry systems, such as home gardens, farm forestry, border planting, and perennial tree-crops cultivation systems. Around 25.32 million hectares, or 8.2% of India's total land area, are currently covered by agroforestry, according to (Dhyani 2014).Prominent and promising agroforestry tree species in India include Poplar (*Populus deltoides*), Sisham (*Dalbergia sissoo*), *Jatropha curcas*, Teak (*Tectona grandis*), Willow (*Salix alba*), Eucalytpus, *Prosopis juliflora*, *Leucaena leucocephala*, and *Acacia spp*. According to Forest Research Institute's Country Report on Poplars and Willows (2012–2015), timber from willow and poplar is the backbone of the board, plywood, paper, match, and sports industries. Indigenous poplar provides wood for fuelwood, packing cases, fodder, etc., while willows are used for baskets, cricket bats, and other handicrafts in the cottage industries. These two species have greatly improved the economy and environment while also lessening the pressure on natural forests. Populus deltoides covers 2,70,000 hectares of agroforestry plantings in India, whereas willow covers 1,37,300 hectares. A carbon pool of 23.46–47.36 Mg C/ha/yr is found in tree-bearing desert agro-ecosystems of Rajasthan, while 19.56 Mg C/ha/yr is found in the north indian state of Uttar Pradesh. (Pandey 2020).

Climate Change: An overview

Climate change is a burning issue of the world. The use of fossil fuels, industrialization, and other factors can raiseCO_2, which can subtly alter the climate. The primary cause of global warming and climate change is greenhouse gases, such as CO_2, N_2O,CH_4, and CFC, among others. The primary heat-trapping gas that has contributed significantly to the majority of the average warming over the previous few decades is carbon dioxide (CO_2) (Forester *et al*. 2007). In contrast to natural climatic variability, climate change is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a long-term shift in the climatic pattern that is attributed, either directly or indirectly, to human activities that alter the composition of the entire aerosphere. According to Intergovernmental Panel on Climate Change (IPCC) fifth assessment report, more than half of the observed increase in average surface temperature between 1951 and 2010 was due to an increase in greenhouse gases concentrations and other anthropogenic activities. Recently, it has been observed that the total CO2 concentration has increased from 280 ppm in 1750 to more than 400 ppm in 2013 (Change1990, Maier 2015).Anthropogenic activities cause GHG emission rates to rise, which elevates the global temperature and causes a number of problems. Therefore, it is important to periodically check the GHGs. Numerous academics worldwide have created methods to forecast the amount of greenhouse gases in the atmosphere. Unusual climate conditions have a significant impact on Earth biodiversity, which results in the depletion and destruction of natural resources and the environment. Floods and droughts brought on by changes in the meteorological regime, such as rainfall patterns, have an impact on agricultural output as well as the advent of infectious diseases.

Annual carbon dioxide emissionsworldwide from 1940 to 2024



Source: Global carbon project: Robbie Andrew, Friedlingstein*et al*. (2023)

Mitigation Stratigies

Mitigation of climate change often involves lowering anthropogenic (human) greenhouse gas emissions. Reforestation is one way to increase the capacity of carbon sinks, which is another way to mitigate. Policies for mitigation can significantly lower the risks brought on by human-caused global warming. The "tragedy of the commons" is climate change, but mitigation is a public benefit. We cannot effectively mitigate climate change if each agent (person, institution, or nation) acts in its own self-interest. The most significant environmental issue affecting all living things, including people, is climate change, which disrupts natural ecosystems, agriculture, and human health. This change in climate and weather patterns results agricultural production in unsustainable. In this situation, agroforestry plays a viable option to mitigate climate change and reduce global warming by absorbing greenhouse gases (CO_2) through the process of carbon sequestration. Carbon dioxide is the most commonly produced greenhouse gas. Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change.

Agroforestry for climate change mitigation through carbon sequestration

Agroforestry plays a crucial role in climate change mitigation and sustainable development. Protecting the existing forests and establishing the new same time conserving biodiversity and in some cases generating income from timber and on-farm/off-farm employment (Sharma *et al*. 2016). According to (Monteith *et al.*1991), the biomass generated in agroforestry systems moderates the weather and decreases the temperature. There is a global discussion about increasing carbon sinks and decreasing atmospheric concentrations of greenhouse gases (GHGs), particularly CO emissions. Despite being a significant carbon sink, the country's forest area cannot be expanded. However, there is much room to expand carbon storage through agroforestry, reforestation, and afforestation. The transfer of carbon-containing materials, especially CO2, into a different reservoir with a longer residence time is known as carbon sequestration (IPCC 2007). Carbon sequestration is the process of storing atmospheric CO_2 through physical, chemical, or biological processes in long-lived carbon pools including soil, the ocean, vegetation (particularly forests), and geologic formations such that it won't be released back into the atmosphere anytime soon. A key technology for maintaining the ideal CO_2 level in the atmosphere, which helps to mitigate climate change, is carbon sequestration. One strategy to reduce the buildup of greenhouse gases in the atmosphere caused by the combustion of fossil fuels and other human activities is carbon sequestration.Agroforestry systems can be better climate change mitigation option than ocean, and other terrestrial options, because of the secondary environmental benefits such as food security and secured land tenure, increasing farm income, restoring and maintaining above ground and below ground biodiversity, maintaining watershed hydrology and soil conservation (Yadava *et al*. 2010). According to Singh and Pandey (2011), agroforestry is appealing for sequestering carbon because: (i) it sequesters carbon in soils and vegetation based on the pre-conversion soil C (ii) the increased use of land for agricultural production lessens the need for shifting cultivation or slash-and-burn; (iii) the wood products produced under agroforestry serve as a substitute for similar products that are harvested from the natural forest in an unsustainable manner; (iv) to the extent that agroforestry increases farmers' income, it lessens the incentive for further extraction from the natural forest for income augmentation; and (v) agroforestry practices may have dual mitigation benefits as high-nutrient-value fodder species can help to intensify diets of methane-producing ruminants while also sequestering carbon.In addition to increasing CO_2 intake or decreasing emissions, agroforestry can potentially remove a sizable quantity of CO_2 from the atmosphere if trees are harvested, replanted in the same or a different region, and the sequestered carbon is locked through non-destructive use of the wood. Because it can store carbon in its soil and many plant species, and because it can be used in both agricultural and reforestation settings, agroforestry is a valuable method for sequestering carbon. When agroforestry reduces stress on natural forests, the biggest sinks of terrestrial carbon, it can also indirectly aid in Csequestration.The application of agroforestry technology for soil conservation, which may improve C storage in trees and soils, is another indirect method of C sequestration. Practices like conserving biomass and soil carbon in existing sinks, improving harvesting and lopping techniques, increasing the efficiency of wood processing, preventing fires and making better use of burning in both agricultural and forest systems, increasing the use of biofuels, and converting more wood biomass into long-lasting wood products are all recommended to be fully utilized in order to increase the C sequestration potential of agroforestry systems. Through adaptation and mitigation of the consequences of climate change, agroforestry hence enhances agricultural resilience. According to (Dhyani *et al.*2009), there is growing evidence that agroforestry systems in India are a potential land use strategy for boosting and conserving aboveground and soil carbon stores in order to slow down climate change. Singh (2003) estimated the total carbon sequestered in farm forestry with species such as *Eucalyptus sp.,Populus deltoides, Tectona grandis, Anthocephalus chinensis* trees to be around 16,400Cper year.Similar studies have reported higher organic carbon levels in dry sub-humid and arid ecosystems when grass species are intercropped with annual crops in a silvipastoral system with no increase in organic carbon with grasses in an arid ecosystem (Venkateswaralu, 2010).

Conclusion

The potential of agroforestry systems in above- and below-ground carbon sequestration makes them one of the most effective ways to alleviate the growing problem of climate change, which has been a global concern for the past few decades. The ability of various agroforestry systems to gather and grow resources more effectively than monocultures makes them a strategic instrument for mitigating the effects of global warming. Additionally, agroforestry systems have been successfully implemented in a range of bio-geographical regimes with varying combinations of farming methods, supply numbers of goods, and ecosystem services. These systems also offer a variety of social, economic, and environmental benefits. The agroforestry system is a ray of hope for the future since it aims to improve the socioeconomic circumstances of farmers while simultaneously enhancing natural biodiversity and reducing the effects of climate change. Agroforestry can be used to reduce forest pressure for a number of ecological and economic advantages, however expanding the world's forest area has its limits. Therefore, agroforestry systems comprises different models in different region worldwide, which plays an enviable role to combat negative impact of climate change by increasing tree-crop diversification that’s leads to more carbon storage (carbon sequestration) capacity than alone cultivation of sole agricultural crops.

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Rhizosphere Engineering: A New Frontier in Forest Soil Management

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Introduction

Forests are complex ecological systems in which productivity, resilience, and sustainability depend not only on above-ground vegetation but also on biological processes occurring below the soil surface. While traditional forest management has emphasized tree growth, canopy structure, and biodiversity, growing evidence highlights the critical role of soil microbial interactions in regulating ecosystem functioning.Forest soils harbor diverse microbial communities, including bacteria, fungi, archaea, and actinomycetes, which drive essential processes such as nutrient cycling, organic matter decomposition, and soil structure formation (Baldrian, 2017). The rhizosphere—the narrow zone of soil influenced by plant roots—is a hotspot of intense biological activity where roots, microorganisms, and soil interact dynamically (Pathan et al., 2019).

The rhizosphere concept was first described by Lorenz Hiltner in 1904; it is now recognized as a highly active interface that significantly influences plant nutrition, health, and stress tolerance (Berg and Smalla, 2009). Plant roots release a variety of compounds known as root exudates, including sugars, amino acids, and secondary metabolites, which act as energy sources and signaling molecules for microbes. In turn, beneficial microorganisms enhance nutrient uptake, promote plant growth, and improve resistance to biotic and abiotic stresses (Canarini et al., 2019).In forest ecosystems, symbiotic associations such as mycorrhizal fungi and plant growth–promoting rhizobacteria (PGPR) play key roles in nutrient cycling, carbon sequestration, and soil stability (Mitra et al., 2024; Kumar et al., 2025). With increasing concerns over soil degradation and climate change, the concept of rhizosphere engineering has emerged, focusing on the deliberate manipulation of root–microbe interactions to improve soil health and plant performance. This approach offers significant potential for enhancing forest productivity, restoration success, and ecosystem resilience.

Understanding the rhizosphere: The living root zone

What is the rhizosphere?

The rhizosphere is the narrow region of soil directly influenced by plant roots, typically extending only a few millimeters from the root surface. Despite its small size, it is one of the most biologically active zones in terrestrial ecosystems. Within this region, plant roots, soil particles, microorganisms, and organic compounds interact continuously, forming a dynamic interface that regulates plant nutrition, soil fertility, and overall ecosystem functioning. Compared to bulk soil, the rhizosphere supports significantly higher microbial populations due to the continuous release of organic compounds by plant roots. Microbial abundance in this zone can be 10–100 times greater than in surrounding soil, comprising bacteria, fungi, actinomycetes, protozoa, and nematodes. In forest ecosystems, the rhizosphere is particularly crucial, as trees often rely on microbial associations to access nutrients in nutrient-poor soils. Thus, it acts as a key regulator of plant growth, nutrient cycling, and soil stability (Pathan et al., 2019).

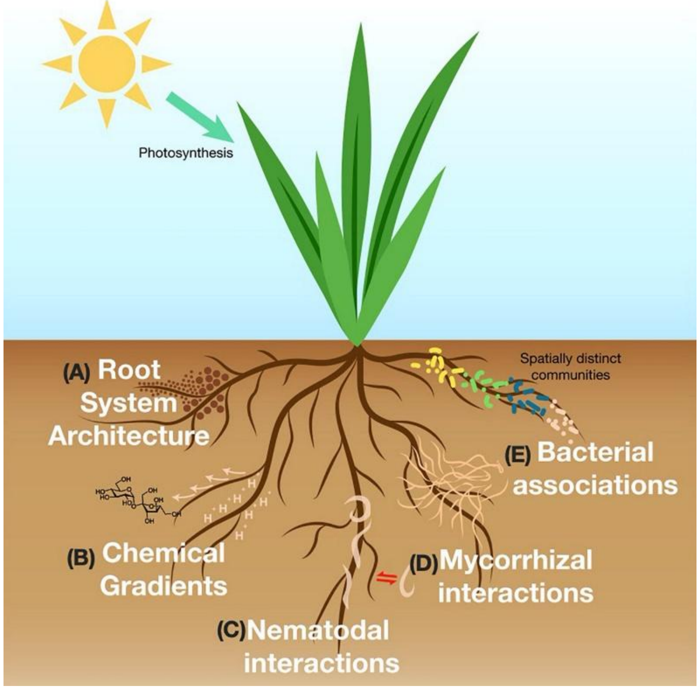

Figure 1: Conceptual diagram of the rhizosphere zone

Root exudates and their ecological role

Plant roots release a diverse range of chemical compounds known as root exudates, including sugars, amino acids, organic acids, fatty acids, enzymes, phenolics, and secondary metabolites. These exudates play a central role in shaping the rhizosphere environment.They serve as energy sources for microorganisms, stimulating microbial growth and activity near roots. Additionally, root exudates function as signaling molecules that attract beneficial microbes while inhibiting pathogens, enabling plants to selectively influence microbial community composition.Root exudates also enhance nutrient availability. Organic acids can solubilize essential nutrients such as phosphorus and iron by modifying soil pH and mobilizing mineral-bound nutrients. This function is especially important in forest soils, where nutrient availability is often limited. Importantly, plants can adjust their exudation patterns in response to environmental stresses such as nutrient deficiency, drought, or pathogen attack. This adaptive mechanism allows plants to recruit beneficial microorganisms that improve stress tolerance and survival (Bais et al., 2006).

Microbial diversity in the rhizosphere

The rhizosphere hosts highly diverse microbial communities that interact with plants through mutualistic, symbiotic, or antagonistic relationships. Among the most significant are mycorrhizal fungi, which form symbiotic associations with most forest tree species. Their hyphal networks extend beyond root zones; enhancing water and nutrient uptake, particularly phosphorus, in exchange for plant-derived carbon.PGPR also play vital roles by facilitating nitrogen fixation, phosphorus solubilization, phytohormone production, and pathogen suppression. Additionally, actinomycetes and fungal endophytes contribute to organic matter decomposition, nutrient mineralization, and biological control.The composition of these microbial communities varies with plant species, soil conditions, climate, and management practices. Understanding and managing this diversity is essential for improving soil fertility, forest productivity, and ecosystem sustainability (Mitra et al., 2024; Kumar et al., 2025).

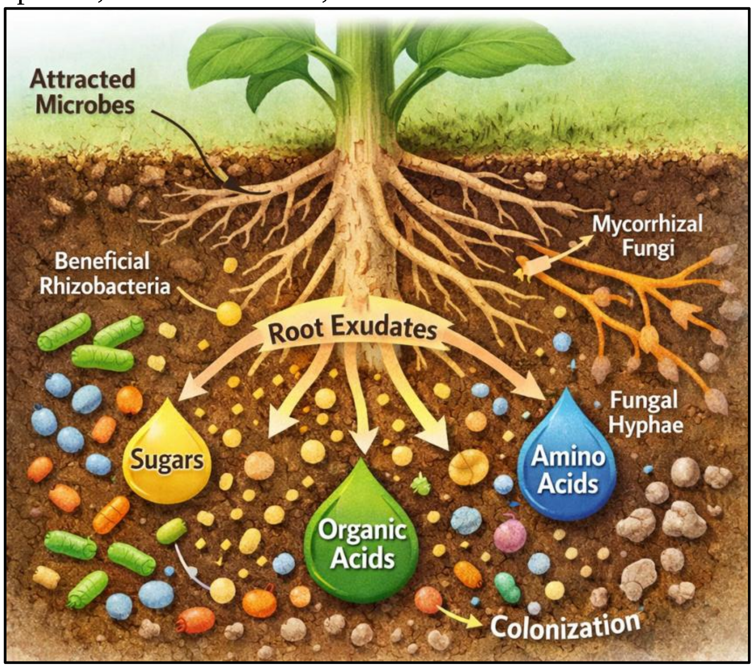

Figure 2: Root exudates as drivers of rhizosphere microbial assembly

Why rhizosphere processes matter in forest ecosystems

Forest ecosystems rely heavily on interactions occurring in the rhizosphere, where plant roots, microorganisms, and soil nutrients form a dynamic biological interface. These interactions regulate key ecological processes such as nutrient availability, soil structure, plant health, and overall productivity. Understanding rhizosphere functioning is therefore essential for sustainable forest management and improved ecosystem resilience.

Nutrient cycling and uptake

The rhizosphere plays a central role in nutrient cycling and plant nutrient acquisition. In forest soils, nutrients like nitrogen, phosphorus, and micronutrients are often present in unavailable forms. Rhizosphere microorganisms convert these into plant-accessible forms through mineralization, nitrogen fixation, and phosphorus solubilization.Mycorrhizal fungi are especially important, extending hyphal networks beyond root zones to enhance nutrient absorption from otherwise inaccessible soil microsites. In return, plants supply carbohydrates, forming a mutualistic association. PGPR further support nutrient availability through nitrogen fixation, enzyme production, and phosphate solubilization. These processes are critical in nutrient-poor forest soils, directly influencing productivity and regeneration (Marschner, 2007).

Soil structure and organic matter dynamics

Rhizosphere microbes significantly improve soil structure by producing extracellular compounds that bind soil particles into aggregates. This enhances soil porosity, aeration, and water retention; creating favorable conditions for root growth.Microbial communities also drive organic matter decomposition. Forest litter is broken down into simpler compounds, releasing nutrients and contributing to soil organic matter formation. Certain mycorrhizal fungi produce glomalin, a glycoprotein that promotes soil aggregation and carbon stabilization. Together, these processes maintain soil fertility and long-term productivity (Bais et al., 2006).

Protection against soil-borne pathogens

Beneficial rhizosphere microorganisms protect plants from pathogens through multiple mechanisms. They compete for nutrients and space, produce antimicrobial compounds, and stimulate plant defense responses.Some rhizobacteria release antibiotics, siderophores, and enzymes that inhibit harmful microbes, while also inducing systemic resistance in plants. These interactions reduce disease incidence in forest nurseries and plantations and enhance the resilience of natural forest ecosystems (Raaijmakers et al., 2009).

Contribution to carbon sequestration and ecosystem stability

The rhizosphere plays a vital role in soil carbon dynamics. Root exudates and microbial biomass contribute to soil organic carbon pools, supporting long-term carbon sequestration. Microbial processes regulate carbon transformation and stabilization, influencing ecosystem carbon balance.Healthy rhizosphere communities enhance soil fertility, support plant growth, and improve tolerance to stresses such as drought and nutrient deficiency. Thus, the rhizosphere is a key regulator of forest ecosystem stability, productivity, and climate resilience (Panchal et al., 2022).

Concept of rhizosphere engineering

The growing understanding of plant–microbe interactions has led to the emergence of a new concept in soil and plant sciences known as rhizosphere engineering. This approach focuses on managing and manipulating the biological and chemical processes occurring in the rhizosphere to improve plant growth, soil fertility, and ecosystem sustainability. In forest ecosystems, where soil conditions often limit nutrient availability and plant establishment, rhizosphere engineering offers promising opportunities to enhance forest productivity and resilience.

What is rhizosphere engineering?

Rhizosphere engineering refers to the intentional modification or management of the rhizosphere environment and its microbial communities to enhance plant performance and soil health. This approach involves influencing the interactions between plant roots, soil microorganisms, and soil nutrients in a way that promotes beneficial ecological processes.Rather than relying solely on external inputs such as chemical fertilizers, rhizosphere engineering aims to optimize the natural biological processes occurring in the root zone. By encouraging beneficial microorganisms and improving soil biological activity, plants can acquire nutrients more efficiently, tolerate environmental stress, and resist diseases more effectively.The concept recognizes that plant roots are not isolated structures but function as part of a complex biological system involving diverse microbial partners. By managing this root–microbe interface, it becomes possible to enhance ecosystem functioning in a sustainable manner (Ahkami et al., 2017).

Evolution of the concept

The idea of rhizosphere engineering has evolved from decades of research in soil microbiology, plant physiology, and microbial ecology. Early studies on the rhizosphere mainly focused on identifying microbial populations around plant roots and understanding their role in nutrient cycling. However, recent advances in molecular biology, metagenomics, and microbial ecology have revealed the remarkable diversity and functional importance of rhizosphere microbial communities.Scientists now recognize that plants can actively influence their rhizosphere microbiome through root exudates and chemical signaling. These interactions allow plants to recruit beneficial microorganisms that enhance nutrient acquisition, suppress pathogens, and improve stress tolerance.With increasing knowledge of these processes, researchers have begun exploring strategies to intentionally shape the rhizosphere microbiome through microbial inoculation, organic amendments, soil conditioners, and improved nursery practices. This transition from simply observing rhizosphere processes to actively managing them marks the development of rhizosphere engineering as a practical approach in agriculture, forestry, and ecosystem restoration.

Importance for sustainable forestry

In forestry, successful tree establishment and long-term productivity depend strongly on soil biological processes. Many forest plantations are established on degraded lands where soils are poor in nutrients, organic matter, and microbial diversity. Under such conditions, seedlings often experience slow growth, nutrient deficiency, and high mortality rates.Rhizosphere engineering offers a strategy to address these challenges by enhancing beneficial plant–microbe interactions. For instance, inoculation with mycorrhizal fungi can improve nutrient uptake and water absorption in tree seedlings. Similarly, beneficial rhizobacteria can promote root development, solubilize nutrients, and protect plants from soil-borne pathogens.By improving rhizosphere functioning, forest managers can enhance seedling establishment, increase plantation success, and accelerate the restoration of degraded forest landscapes. Moreover, healthy rhizosphere microbial communities contribute to improved soil structure, enhanced nutrient cycling, and greater resilience of forest ecosystems to environmental stresses such as drought, soil degradation, and climate variability.

Approaches to rhizosphere engineering in forestry

The practical implementation of rhizosphere engineering involves various strategies that aim to enhance beneficial microbial activity and improve the root–soil environment (Dubey & Kumar, 2022).

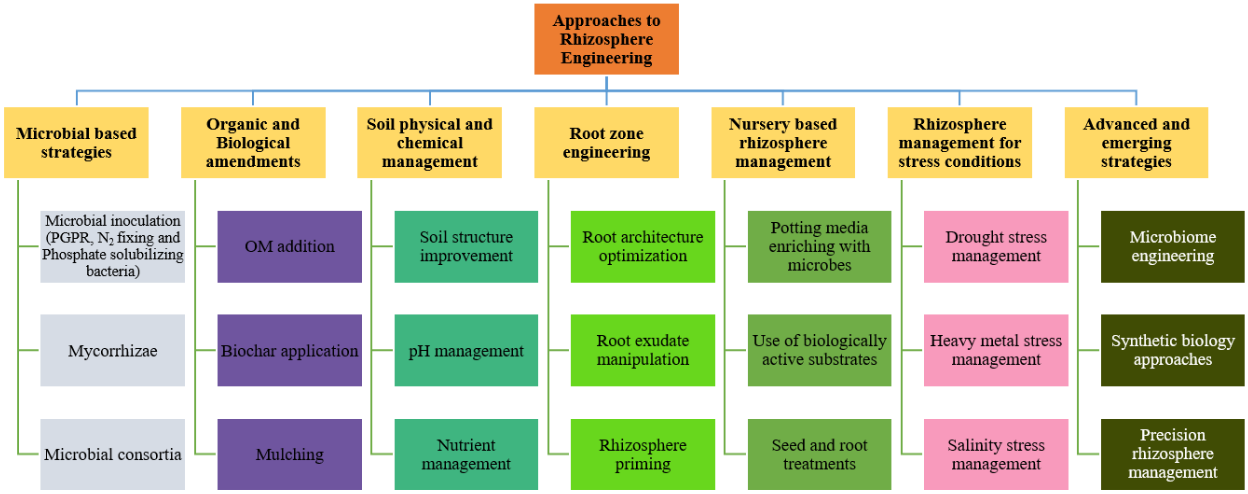

Figure 3: Multidimensional Strategies for Rhizosphere Engineering and Soil Health Enhancement

Microbial inoculation

One of the most widely studied approaches to rhizosphere engineering is the inoculation of beneficial microorganisms into the root zone of plants. Microbial inoculants commonly referred to as biofertilizers, include bacteria and fungi that promote plant growth through various biological mechanisms.PGPR are among the most important groups used for this purpose. These bacteria enhance plant growth by fixing atmospheric nitrogen, solubilizing phosphorus, producing plant growth hormones such as auxins and gibberellins, and suppressing soil-borne pathogens. By improving nutrient availability and stimulating root development, PGPR can significantly improve seedling vigor and survival.In forestry, microbial inoculation can be applied during nursery seedling production or at the time of planting. Introducing beneficial microbes early in the plant life cycle helps establish a stable and beneficial rhizosphere microbial community, which supports long-term plant growth.

Mycorrhizal symbiosis

Among the most important microbial partners of forest trees are mycorrhizal fungi, which form symbiotic associations with plant roots. These fungi colonize the root system and extend their hyphae into the surrounding soil, creating an extensive network that greatly enhances the plant's ability to absorb water and nutrients.Mycorrhizal fungi are particularly effective in improving the uptake of phosphorus, nitrogen, and micronutrients, which are often limited in forest soils. In addition to nutrient acquisition, mycorrhizal associations improve plant tolerance to environmental stresses such as drought, salinity, and heavy metal toxicity.In forest nurseries, inoculation of seedlings with appropriate mycorrhizal fungi can significantly enhance seedling quality and transplant success. Once established in the field, the mycorrhizal network continues to support tree growth and contributes to improved soil biological activity.

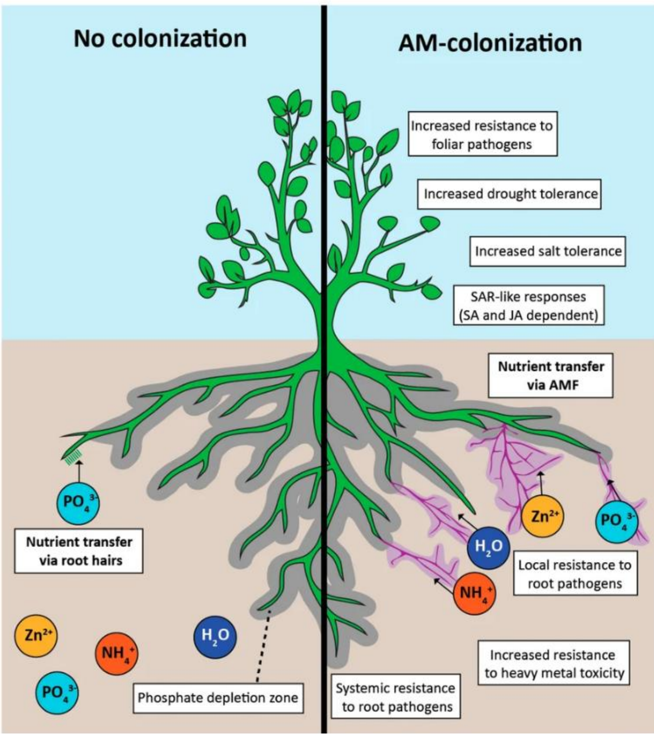

Figure 4: Functional role of AM fungi in enhancing plant health and soil interaction (Jacott et al., 2017)

Organic soil amendments

The application of organic amendments is another effective strategy for enhancing rhizosphere activity. Materials such as compost, farmyard manure, leaf litter, and other organic residues provide a rich source of organic matter that supports microbial growth and improves soil structure.Organic amendments stimulate microbial diversity in the rhizosphere and promote nutrient cycling processes such as mineralization and decomposition. Increased organic matter also enhances soil water-holding capacity and improves soil aeration, creating favorable conditions for root development.In degraded forest soils where organic matter content is often low, the addition of organic amendments can play a crucial role in restoring soil biological activity and improving plant establishment.

Biochar and soil conditioners

Biochar, a carbon-rich material produced through the pyrolysis of biomass, has gained increasing attention as a soil amendment for improving rhizosphere conditions. Biochar enhances soil structure, increases water retention, and provides a stable habitat for soil microorganisms.Because of its porous structure, biochar can serve as a microbial refuge, protecting beneficial microbes and facilitating their colonization in the rhizosphere. In addition, biochar can improve nutrient retention in soils and reduce nutrient leaching.In forest plantations established on degraded or nutrient-poor soils, the incorporation of biochar and other soil conditioners can significantly improve soil fertility and microbial activity, thereby supporting sustainable forest growth.

Root zone management in forest nurseries

Forest nurseries play a critical role in determining the success of plantation programs. The quality of planting material produced in nurseries strongly influences seedling survival and growth after transplantation.Rhizosphere engineering can be effectively applied during nursery production by managing the root zone environment. This may include the use of microbial inoculants, incorporation of organic substrates, and improvement of soil or potting media composition. Such practices promote the development of a healthy and active rhizosphere microbial community around seedling roots.Seedlings raised under biologically enriched conditions often show better root development, improved nutrient uptake, and higher tolerance to environmental stress. When transplanted into the field, these seedlings are more capable of establishing quickly and sustaining healthy growth.

Applications of Rhizosphere Engineering in Forestry

The concept of rhizosphere engineering has significant potential for improving forest management practices and restoring degraded landscapes. Several practical applications of rhizosphere engineering are increasingly being explored in forestry and ecological restoration programs.

Improving forest nursery practices

Forest nurseries serve as the foundation for successful plantation programs because the quality of planting material directly influences field survival and growth. Rhizosphere engineering can play an important role in nursery management by promoting the development of healthy root systems and beneficial microbial communities around seedling roots.Incorporating microbial inoculants such as PGPR and mycorrhizal fungi into nursery substrates can significantly improve seedling vigor. These microorganisms enhance nutrient uptake, stimulate root growth, and improve resistance to environmental stress. Seedlings raised under biologically enriched conditions often exhibit better physiological performance and higher survival rates after transplantation.Furthermore, the use of organic substrates, compost-based media, and improved potting mixtures can stimulate microbial activity in nursery soils, leading to the establishment of a healthy rhizosphere environment even before seedlings are planted in the field.

Restoration of Degraded Forest Lands

Large areas of forest landscapes around the world have been degraded due to deforestation, overgrazing, mining activities, and unsustainable land-use practices. In such degraded environments, soils often suffer from low organic matter content, reduced microbial diversity, and poor nutrient availability, which hinder the successful establishment of vegetation.Rhizosphere engineering provides a promising approach to restore these degraded soils by reintroducing beneficial microbial communities and improving soil biological activity. Microbial inoculation combined with organic amendments can accelerate the recovery of soil functions, enhance nutrient cycling, and support the establishment of tree seedlings.Mycorrhizal fungi, in particular, have shown considerable potential in the restoration of degraded lands. By improving nutrient acquisition and enhancing plant tolerance to environmental stress, mycorrhizal associations help seedlings establish more effectively in harsh soil conditions.

Phytoremediation of contaminated soils

Soil contamination by heavy metals and industrial pollutants has become a major environmental concern in many regions. Certain plant species can tolerate and accumulate toxic elements from the soil, a process known as phytoremediation. The efficiency of phytoremediation can be significantly enhanced through rhizosphere engineering.Microorganisms present in the rhizosphere can influence the mobility, availability, and detoxification of heavy metals in soils. Some rhizobacteria and mycorrhizal fungi can immobilize heavy metals in the soil matrix, while others help plants tolerate metal stress by activating detoxification mechanisms.By promoting beneficial microbial activity in the rhizosphere, it becomes possible to enhance the capacity of plants to survive and grow in contaminated soils. This approach can be particularly useful in rehabilitating mining areas, industrial sites, and polluted landscapes through ecological restoration.

Climate-resilient forestry

Climate change is increasingly affecting forest ecosystems through rising temperatures, prolonged droughts, and increased frequency of extreme weather events. In such conditions, maintaining soil health and plant resilience becomes crucial for sustainable forest management.Rhizosphere microorganisms play a vital role in improving plant tolerance to environmental stresses. Many beneficial microbes enhance root development, improve water uptake, and stimulate the production of stress-related compounds in plants. Mycorrhizal associations are especially important in helping plants cope with drought stress by increasing water absorption capacity.By strengthening plant–microbe interactions in the rhizosphere, rhizosphere engineering can contribute to the development of climate-resilient forest ecosystems capable of withstanding environmental stresses and maintaining ecosystem productivity.

Challenges and future perspectives

Despite its significant potential, rhizosphere engineering in forestry remains at an early stage, with several scientific and practical challenges limiting its large-scale application. A major constraint is the limited understanding of forest rhizosphere microbiomes, which are highly complex and vary across tree species, soil types, and climatic conditions. Unlike agricultural systems, forest ecosystems have received comparatively less attention, necessitating advanced approaches such as metagenomics, transcriptomics, and microbial profiling to identify key functional groups involved in nutrient cycling, stress tolerance, and plant health. Another critical challenge is the inconsistent performance of microbial inoculants under field conditions; microorganisms that perform well in controlled environments often fail in natural settings due to competition with native microbiota, environmental variability, and differences in host plant responses. This highlights the need for site-specific and ecologically compatible solutions. Additionally, the development of region-specific microbial technologies is essential, as microbes adapted to one ecosystem may not function effectively in another; thus, isolating and utilizing native beneficial microorganisms is crucial for success. Integrating rhizosphere engineering into conventional forest management practices also remains a challenge, requiring awareness, training, and collaboration between researchers and practitioners, along with the development of practical guidelines for nursery and field applications. Looking ahead, advances in microbial ecology, biotechnology, and bioinformatics are expected to accelerate progress, particularly through research on plant microbiomes, microbial consortia, and engineered communities. The integration of these innovations with precision soil management offers promising pathways for enhancing forest productivity, restoring degraded lands, and improving ecosystem resilience under changing environmental conditions.

Conclusion

Forests are sustained not only by above-ground vegetation but also by complex biological processes within the soil. The rhizosphere serves as a critical interface where plant roots interact with diverse microbial communities that regulate nutrient cycling; soil structure, plant health, and ecosystem stability.Advances in plant–microbe interaction research have highlighted the potential of rhizosphere engineering as a strategy to enhance forest productivity and resilience. By promoting beneficial microorganisms such as mycorrhizal fungi and plant growth–promoting rhizobacteria, improving soil organic matter, and optimizing root-zone conditions, it is possible to support better tree establishment and restore degraded lands.Integrating these approaches into forest management can strengthen sustainability and climate resilience. Ultimately, managing forests from the ground up—by understanding and nurturing soil microbial systems—offers a promising pathway toward healthier soils, productive forests, and long-term ecological stability.

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Seeds that save forests: Unlocking seed science strategies for climate resilience

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Abstract
Climate change refers to long term shifts in weather patterns through change in temperature, rainfall, wind, snowfall and increasing biotic and abiotic stresses that poses a serious threat to forest sustainability. In addition, elevated levels of carbon dioxide have an effect on forest ecosystems. Seeds are the overlooked foundation of forest regeneration and resilience. More than just reproductive units, seeds are sophisticated biological survival kits engineered to endure extreme environmental stresses. Their innate ability to withstand extreme heat and cold, prolonged drought, desiccation and high pressure makes ultimate means of survival of species and their populations in forest.

Seed Biology: Foundation of Forest Resilience

Seed biology governs germination, dormancy, vigor, and longevity traits that determine whether a plant successfully establishes in a changing environment. Seeds can sense environmental signals and adjust germination timing to maximize survival (Ewelina and Tomasz, 2021)

Key adaptive traits include:

- Dormancy mechanisms that delay germination under unfavorable conditions
- Desiccation tolerance, allowing seeds to survive dry seasons or in less water content
- Longevity, ensuring persistence in soil seed banks
- Stress-responsive metabolism, enabling survival under extreme climates

These traits make seeds the first line of defense against climate variability. As research shows, seeds are the earliest life stage exposed to environmental stress and thus play a decisive role in species survival and distribution.

Climate-Driven Shifts in Seed Mediated Forest Dynamics

Climate change is driving shifts in forest composition, species distribution, and regeneration patterns. Altered temperature and precipitation regimes directly impact seed production, dispersal, and germination success. Consequently, changes in seed rain composition are reshaping biodiversity and altering ecosystem functioning (Yue *et al.*, 2023). Species must adapt, migrate, or face decline under new climatic conditions (John *et al.*, 2023)

This highlights the need for strategic seed management to ensure forests remain resilient and functional.

Seed Sourcing Strategies for Climate Smart Forest

Selecting the appropriate seed source is a cornerstone of climate smart forest. Traditionally, local seeds were preferred due to their adaptation to local environments. However, due to rapid climate changes, selection of seeds that adapts to adverse climatic condition is a challenging approach.

Modern strategies include

Climate adjusted Provenancing

Selecting seeds not only from local sources but also from regions projected to share similar future climates. Many researchers confirm that seed origin affects growth, biomass, and resilience potential.

High genetic diversity within seed sources is critical for boosting adaptability to environmental change.

Assisted Migration

Transferring seeds or plant material to areas where future climates are expected to be suitable is technically known as Assisted Migration or Assisted Colonization. This proactive strategy addresses the increasing maladaptation of existing plant populations where local genetic adaptation can no longer keep pace with rapid climate change by facilitating the movement of species or genotypes to new more environments

Seed Provenancing

Seed provenancing is a strategic approach to seed sourcing that deliberately combines germplasm from both local and non-local populations to enhance the adaptive and evolutionary potential of restored ecosystems. By primarily utilizing locally adapted seeds, supplemented with a smaller proportion from geographically distant populations, this approach simulates natural gene flow while minimizing the risk of outbreeding depression. Such mixing of seeds from diverse populations ultimately enhances genetic diversity and ecosystem resilience

Dynamic Seed Zones

Dynamic Seed Zones represent a shift in forest and restoration from static, geographically fixed boundaries to flexible, climate-adapted guidelines. These zones are defined by ecological and climatic variables that are projected to change over time, rather than relying on historical data. This approach enables the selection of seed sources that are better suited for future climate conditions, aiming to move seeds from warmer/drier locations to currently cooler/wetter planting sites. These approaches ensure that planted forests are future ready rather than past-adapted.

Genetic Diversity in Ecosystem Stability

Genetic diversity within seed populations acts as a buffer against environmental uncertainties. Diverse seed lots increase the likelihood that some individuals will survive under changing conditions. Genetically diverse varieties show greater resilience to climate variability and stress conditions (Niels and Gigi, 2022). Diversity enhances ecosystem functions such as productivity, stability, and resistance to pests and diseases. In forest, maintaining genetic diversity is essential for long-term ecosystem stability and adaptive capacity.

Seed Banks and Conservation Strategies

Seed banks are vital for preserving plant genetic diversity and restoring damaged environments. They function as biological insurance, maintaining seeds to prevent extinction and provide resources for future restoration. Seed banks act as repositories of biodiversity, preserving seeds for future use. They support restoration of degraded ecosystems where natural regeneration is limited and they ensure availability of seeds during climate-induced disturbances (Piyush *et al*., 2025)

With increasing demand for restoration, sustainable seed sourcing and storage systems are becoming essential. Community seed banks and institutional seed systems also strengthen resilience by ensuring continuous access to quality seeds, even after environmental shocks.

Technological Interventions in Seed Science

Seed Priming

Seed priming, is a controlled pre-sowing hydration treatment that activates early metabolic processes such as enzyme repair, DNA restoration, and respiration without allowing radicle emergence, thereby preparing seeds for rapid and uniform germination (Bradford, 1986; Paparella *et al*., 2015). It is important for successful forest regeneration under changing climatic conditions. The need for seed priming in forest arises from the increasing frequency of abiotic stresses such as drought, salinity, and temperature extremes, which severely impair seed germination, seedling establishment, and overall plantation success. In many forest ecosystems, especially degraded lands, poor and erratic germination is a major bottleneck, making seed enhancement technologies essential for improving afforestation and reforestation outcomes.

Molecular and Omics Approaches

Omics approaches have significantly enhanced the understanding of molecular mechanisms underlying seed longevity, a key factor in forest regeneration and seed bank efficiency under climate variability. Integrated genomics, transcriptomics, proteomics, and metabolomics (multi-omics) analyses reveal that stress-responsive genes, QTLs, and metabolic pathways**,** facilitating the development of climate-resilient forest genotypes. Additionally, late embryogenesis abundant (LEA) proteins stabilize cellular structures during desiccation, ensuring prolonged seed viability (Rajjou and Debeaujon, 2008). These approaches support forest regeneration under climate change by enabling selection of stress adapted seed sources**,** improving seed longevity and storage**,** enhancing seedling establishment and vigor, and advancing precision seed technologies**.** Furthermore, seed priming induces coordinated molecular reprogramming at transcriptomic, proteomic, and metabolomic levels, linking conventional seed enhancement practices with modern omics-based strategies.

Seed Coating and Pelleting

Seed coating and pelleting are advanced seed enhancement technologies that improve seed handling, protection, and performance, particularly under degraded and climate stressed environments. It involves the coating of seeds with polymers, nutrients, pesticides, and beneficial microorganisms, to create a protective and functional microenvironment around the seed that enhances water uptake, reduce pathogen attack, and improve seed-soil contact, thereby promoting uniform germination and seedling establishment (Pedrini *et al.*, 2017). In forest systems, where seeds are often exposed to harsh field conditions such as drought, salinity, and poor soil fertility, coated and pelleted seeds improve stress tolerance and establishment success. Additionally, pelleting standardizes seed size and shape, enabling precision sowing in large-scale afforestation programs, which is critical for efficient resource utilization under climate variability (Halmer, 2008).

Controlled Storage Technologies

Controlled storage technologies, including modified atmospheric storage (MAS) and controlled atmospheric storage (CAS), are critical for maintaining seed viability and vigor during long-term storage. Seed deterioration is primarily driven by oxidative damage, membrane degradation, and metabolic imbalance; however, regulating oxygen and carbon dioxide levels, along with temperature and moisture, reduces respiration rates and minimizes reactive oxygen species (ROS) accumulation, thereby slowing seed ageing. Under climate change scenarios, where elevated temperature and humidity accelerates seed deterioration, MAS and CAS storage systems ensures long-term viability, genetic integrity, and reliable availability of high-quality planting material (Ellis & Roberts, 1980), supporting effective seed banking, reforestation, and climate-resilient forest regeneration

From a climate-smart forest perspective, these technologies collectively enhance seed system resilience by ensuring that seeds are not only viable but also performance ready under environmental stress. Seed priming, coating and pelleting improve field level establishment and protection, while multi-omics approach and controlled storage safeguards temporal availability and genetic integrity of seeds. Altogether, they contribute to improved afforestation success, restoration of degraded ecosystems, and adaptation of forest systems to climate change.

Table 1: List of some forest species seeds with it response constraints to climate change and seed science strategies to mitigate

Climate Factor	Species (Scientific name)	Common Name	Tree Response	Regeneration Issue	Seed Science Strategies
High Temperature	*Tecton grandis*	Teak	Reduced growth, leaf shedding under extreme heat	Poor seed germination at high temp	Seed priming (hydro/thermo-priming) selection of heat tolerant provenances
	Pinus roxburghii	Chir pine	Increased evapotranspiration	Reduced seed viability	Provenance selection, seed storage under controlled conditions
Cold Temperature	*Abies pindrow*	Himalayan fir	Frost injury to seedlings	Delayed or poor germination	Cold stratification, seed hardening techniques
	Cedrus deodara	Deodar	Damage to young seedlings	Seed dormancy issues	Pre-sowing treatments (chilling), nursery acclimatization
Drought	*Shorea robusta*	Sal	High mortality in prolonged drought	Recalcitrant seeds lose viability quickly	Rapid sowing after collection, moisture-controlled storage
	Prosopis juliflora	Mesquite	Highly tolerant	Hard seed coat delays germination	Scarification (mechanical/acid) to enhance germination
Salinity	*Avicennia marina*	Mangrove	Salt tolerance via exclusion/secretion	Vivipary limits storage	Direct planting, selection of salt-tolerant genotypes
	Casuarina equisetifolia	Casuarina	Moderate salt tolerance	Reduced germination in saline soils	Seed priming with salt tolerant microbes, bio-priming

Combined (High temperature + Drought)	*Acacia nilotica*	Babul	Highly resilient	Hard seed coat dormancy	Scarification + drought hardening treatments
	Eucalyptus camaldulensis	Eucalyptus	Adaptable but stress sensitive at early stage	Variable germination	Provenance testing, seed enhancement technologies

Conclusion

In the face of climate change, seeds are emerging as powerful tools for building resilient forests and stable ecosystems. By combining traditional knowledge with modern seed science, we can develop strategies that ensure sustainable forest regeneration and biodiversity conservation. Climate-smart forest is not just about planting trees; it is about planting the right seeds, in the right place, for the future climate. Seeds, though small, hold the blueprint for ecosystem stability. Investing in seed science today is an investment in the forests of tomorrow.

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Effect of kerf treatment and center boring on drying behavior of round logs

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Abstract
Drying of wooden logs is one of the most technically challenging operations in the forest products industry because of large moisture gradients, slow radial moisture movement, and high susceptibility to drying defects such as checking, splitting, and internal cracking. Conventional air drying and kiln drying methods are often inefficient for round timbers and large-diameter logs, resulting in long drying times and significant quality losses. Mechanical pretreatments such as kerf treatment and center boring have been developed to improve drying behavior by modifying the internal structure of logs. Kerfing involves cutting longitudinal cut on the log surface to relieve drying stresses and increase evaporation area, while center boring creates an internal channel for moisture escape from the log core. This paper reviews and critically analyzes the influence of kerf treatment and center boring on moisture movement, drying rate, stress development, and defect formation in wood logs. Published research shows that both methods significantly enhance drying efficiency and improve product quality, with center boring being particularly effective in reducing moisture gradients and internal stress, and kerfing being especially useful in controlling surface checking. The combined application of these methods offers a practical and economical solution for improving industrial log drying.

Introduction

Drying is a crucial process in the utilization of wood, directly affecting its dimensional stability, mechanical properties, durability, and service performance. Freshly felled logs typically contain moisture contents far above the fiber saturation point, often exceeding 100% on a dry-weight basis. Before wood can be used for construction, furniture, poles, or engineered wood products, this moisture must be reduced to a level compatible with the intended service conditions. However, drying of round wooden logs and large-dimension timbers remains a major technical challenge because of the long moisture diffusion path, non-uniform shrinkage, and high risk of defect formation.

Unlike sawn lumber, which has multiple exposed surfaces for moisture evaporation, logs have only an external cylindrical surface. Moisture trapped in the center of the log must travel a long radial distance to reach the surface, leading to severe moisture gradients between the shell and the core. These gradients cause large internal stresses during drying. As the outer layers dry below the fiber saturation point, they begin to shrink, while the inner core remains wet and dimensionally stable. This mismatch creates tensile stress in the shell and compressive stress in the core. When the tensile stress exceeds the strength of wood, surface checking and end splitting occur. At later stages, internal cracking and honeycombing may also develop as the core begins to dry and shrink.

To minimize these problems, conventional log drying often relies on slow air drying or mild kiln schedules. While these methods reduce stress development, they greatly increase drying time and do not always prevent defects. Therefore, there is strong industrial interest in methods that can accelerate drying while maintaining or improving wood quality. Mechanical pretreatments such as kerfing and center boring have been proposed as effective techniques to modify the moisture transport pathways and stress distribution in logs.

Moisture Movement and Stress Development in Logs

Moisture transport in wood occurs through a combination of capillary flow, vapor diffusion, and bound water diffusion within cell walls. In logs, moisture movement is highly anisotropic, being much faster in the longitudinal direction than in the radial or tangential directions. Because logs are oriented longitudinally in the kiln, radial movement becomes the limiting factor for drying.

During the early stages of drying, free water is removed from the lumens of cells near the surface. As drying continues and the moisture content drops below the fiber saturation point, bound water begins to leave the cell walls, causing shrinkage. Since the shell dries first, it tries to shrink but is restrained by the wet, swollen core. This restraint generates tensile stress in the outer layers and compressive stress in the inner region. If the tensile stress exceeds the tensile strength perpendicular to grain, surface checks form. These checks may propagate radially inward, severely reducing the structural integrity of the log.

Later in the drying process, when the core begins to dry and shrink, the stress pattern reverses. The core is now in tension while the shell is in compression, which can lead to internal cracking or honeycombing. Therefore, reducing moisture gradients and allowing the shell to shrink freely are essential for controlling drying defects in logs.

Kerf Treatment in Log Drying

Kerf treatment involves cutting one or more longitudinal grooves along the surface of a log. These grooves may extend partially or fully through the log thickness, depending on the application and log size. Kerfing is primarily intended to relieve tangential stresses and control surface checking.

The main mechanism of kerfing is stress relief. As the log dries and the outer shell begins to shrink, the kerf provides a free space into which the wood can move. Instead of building up tensile stress around the entire circumference, part of the shrinkage strain is accommodated by widening of the kerf. This reduces the likelihood of uncontrolled cracking across the log surface.

In addition to stress relief, kerfing increases the effective drying surface area. The surfaces inside the kerf act as additional evaporation sites, allowing moisture to escape more easily. This reduces the average moisture gradient in the log and slightly accelerates the drying process.

Experimental studies have shown that kerfed logs exhibit significantly fewer surface checks and end splits than untreated logs. Cracks tend to localize at the kerf location, where they cause minimal structural damage. However, kerfing alone does not greatly improve moisture removal from the core of large logs, and therefore its effect on drying time is moderate compared to center boring.

Center Boring in Log Drying

Center boring involves drilling a cylindrical hole along the longitudinal axis of the log. The diameter of the bore typically ranges from 10 to 20% of the log diameter, depending on the application. This method is designed to improve moisture movement from the log core, which is the slowest-drying region.

The central hole created by center boring acts as an internal drying surface. Moisture from the surrounding wood can move directly into this cavity and evaporate, significantly reducing the distance that moisture must travel to reach an open surface. As a result, the core dries much faster than in solid logs.

One of the most important benefits of center boring is the reduction of shell-to-core moisture gradients. By providing an internal evaporation surface, moisture is removed from both the inside and outside of the log, leading to more uniform drying. This reduces internal stress development and greatly lowers the risk of internal cracking and honeycombing.

Studies on kiln-dried logs have demonstrated that center-bored logs reach target moisture content much faster than untreated logs, often with reductions in drying time of 30 to 50%. In addition, the final moisture distribution is more uniform, and the frequency and severity of drying defects are significantly lower.

Combined Effect of Kerfing and Center Boring

Kerfing and center boring have complementary effects on log drying. Kerfing mainly addresses surface stress and checking, while center boring improves internal moisture transport and reduces moisture gradients. When both methods are used together, their benefits are additive.

The kerf allows the shell to shrink freely, reducing surface cracking, while the center bore ensures rapid and uniform moisture removal from the core. This combination results in faster drying, lower stress development, and superior log quality compared to either method used alone.

Industrial Implications

Kerfing and center boring are relatively simple operations that can be carried out using standard woodworking equipment before drying. These methods are particularly useful for drying utility poles, large structural logs, laminated wood feedstock, and round timber used in construction.

Although center boring removes some material, the reduction in drying defects, shorter drying times, and improved product quality usually outweigh this loss. From an economic and technical standpoint, these pretreatments offer an effective solution for improving industrial log drying.

Conclusions

Kerf treatment and center boring significantly enhance the drying performance of wooden logs. Kerfing reduces tangential stress and surface checking, while center boring improves internal moisture movement and moisture uniformity. Their combined application provides a powerful and practical strategy for accelerating log drying while maintaining high product quality.

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Healing from forests: Medicinal plants and minor forest produce in ayurveda in India

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Introduction

India is globally recognized as one of the richest countries in terms of biological diversity and traditional knowledge systems. For thousands of years, Indian forests have served not merely as ecological habitats but as living pharmacies providing humankind with food, medicine, shelter, and spiritual inspiration. Among the most profound contributions of Indian forests is their role in the development and sustenance of Ayurveda the ancient system of medicine that emphasizes harmony between humans and nature.

Ayurveda, meaning "the science of life" is deeply rooted in forest ecosystems. A large proportion of Ayurvedic formulations are derived from medicinal plants and minor forest produce (MFPs) also known as non-timber forest products (NTFPs) such as gums, resins, seeds, leaves, bark, fruits, and roots. Even today, forest-based resources continue to support primary healthcare, livelihoods of forest-dependent communities, and the growing global herbal industry.

This article explores the significance of medicinal plants and minor forest produce in Ayurveda in India, highlighting their cultural heritage, therapeutic value, economic importance and the need for sustainable utilization.

Ayurveda and Forest-Based Knowledge Systems

Ayurveda literally translated as the "science of life," is one of the oldest holistic medical systems in the world, practiced in India for more than 5,000 years with its origin intrinsically linked to forest ecosystems (Prajapati et al., 2024). Early Ayurvedic knowledge evolved through intimate and sustained interactions between humans and nature and is deeply embedded in the Vedic corpus.

Over time, Ayurveda evolved into a comprehensive healthcare system emphasizing harmony among the body, mind and spirit. Health and disease are conceptualized through the dynamic balance of the three fundamental ***doshas*** Vata, Pitta, and Kapha and therapeutic interventions are primarily based on plant-derived formulations aimed at restoring physiological equilibrium. To address specialized healthcare needs, Ayurveda was systematically classified into eight clinical branches collectively known as ***Ashtanga Ayurveda*** that are mentioned in the table 1.

Table1. Ashtanga Ayurveda: Branches and Their Clinical Scope (Directorate of AYUSH)

S. No.	Branch of Ayurveda	Sanskrit Name	Primary Area of Specialization
1	Internal Medicine	Kayachikitsa	Diagnosis and management of systemic diseases; focuses on metabolism, digestion, and chronic disorders
2	Pediatrics & Gynecology	Kaumarbhritya	Healthcare of infants, children, mothers; includes obstetrics, pediatrics, and reproductive health
3	Psychiatry	Bhutavidya	Management of mental disorders, psychological illnesses, and behavioral disturbances
4	Otorhinolaryngology & Ophthalmology	Shalakya Tantra	Treatment of diseases related to ear, nose, throat, eyes, oral cavity, and head

5	Surgery	Shalya Tantra	Surgical procedures, trauma management, wound care, fractures, and operative techniques
6	Toxicology	Agada Tantra	Management of poisoning, venomous bites, food toxicity, and environmental toxins
7	Geriatrics & Rejuvenation	Rasayana Tantra	Promotion of longevity, immunity enhancement, anti-aging therapies, and rejuvenation
8	Reproductive Health & Sexual Disorders	Vajikarana Tantra	Management of infertility, sexual health, and enhancement of reproductive vitality

In the modern era, Ayurveda's emphasis on natural resources, preventive healthcare and ecological balance aligns closely with the principles of sustainability and green entrepreneurship. The growing global demand for eco-friendly products and nature-based solutions has created significant opportunities to integrate Ayurvedic principles into sectors such as wellness, herbal pharmaceuticals, cosmetics and organic agriculture.

Medicinal plants of Indian forests: Pillars of ayurvedic therapy

India is endowed with rich medicinal plant diversity, with over 7,500 species used for therapeutic purposes the majority of which are harvested directly from natural forests (Indian Medicinal plans database). These forest-based medicinal resources play a crucial role in the primary healthcare systems of rural and tribal communities and also contribute substantially to the country's annual export earnings. Many of these medicinal plant species are integral to Ayurveda, where they are traditionally used to treat a wide range of diseases, as listed in the table 2.

Table 2: List of Botanicals and Part Used for Treatment of Various Diseases in India (Mazid et al., 2024)

Disease	Common Name	Botanical Name	Medicinal Properties	Scientific Basis / Action	Method of Use
Constipation	Isabgol	*Plantago ovata*	Stomachic, laxative	Relieves stomach pain and constipation	Mix 2 g seeds in half cup of curd
Diarrhoea	Adrak	*Zingiber officinale*	Carminative, appetizer, emollient	Destroys germs, stimulates appetite, soothing effect	Soak small quantity in one cup of buttermilk
	Dhania	*Coriandrum sativum*	Stomachic, carminative	Improves digestion, cures flatulence	Powder of sonth and black pepper taken orally
Dysentery	Tesu (Dhak)	*Butea monosperma*	Anthelmintic	Kills intestinal worms	Powder of stem bark mixed with gum
Stomach pain	Amla	*Phyllanthus emblica*	Anodyne, stomachic	Relieves stomach pain	Soak 130 g dried fruit overnight
Vomiting	Mint	*Mentha arvensis*	Antiemetic, antibacterial	Cooling ,effect, prevents,vomiting	Extract juice from 50 g leaves

Digestive disorders	Amla	*Phyllanthus emblica*	Laxative, stomachic	Improves digestion, cures flatulence	40 g dried fruit powder taken orally
Intestinal worms	Guarpatha	*Aloe barbadensis*	Anthelmintic, digestive	Kills worms, improves digestion	2–3 leaves eaten with salt
Loss of appetite	Bael	*Aegle marmelos*	Appetizer, restorative	Increases appetite, strengthens body	Paste of pulp mixed with mango seed
Scabies	Bael	*Aegle marmelos*	Laxative	Improves skin condition	Leaf paste applied externally
Bacterial skin infection	Semal	*Bombax ceiba*	Appetizer	Destroys bacterial spores	Powdered bark with honey
Sore wounds & eczema	Neem	*Azadirachta indica*	Antiseptic	Prevents infection, healing action	Bark/leaf paste applied
Ringworm	Papita	*Carica papaya*	Antifungal	Destroys fungal spores	Latex from unripe fruit applied

These medicinal plants are harvested in different forms- roots, bark, leaves, flowers, fruits, or whole plants-depending on the formulation. Their therapeutic efficacy is attributed to bioactive compounds such as alkaloids, glycosides, Phenol flavonoids, tannins, and essential oils.

Minor Forest Produce (MFPs): Hidden treasures of Ayurveda

Minor Forest Produce (MFP) often categorized as Non-Timber Forest Products (NTFPs) serves as the backbone of India's traditional medicine systems. These "hidden treasures" are an important source of livelihoods for tribal people are non-wood forest products or Minor Forest Produce (MFP). This includes non-timber forest produce of plant origin such as bamboo, canes, fodder, leaves, gums, waxes, dyes, resins and many forms of food including nuts, wild fruits, honey and lac. Minor Forest Produces provide both subsistence and cash income for an estimated 100 million people who live in or near forests. MFP forms a major portion of their food, fruits, medicines and other consumption items and also provides cash income through sale. Tribal's derive 20-40% of their annual income from Minor Forest Produce on which they spend major portion of their time. This activity has strong linkage to women's financial empowerment as most of the Minor Forest Produces are collected and used/sold by women. Minor Forest Produce sector has the potential to create about 10 million workdays annually in the country (Tiwary et al., 2020).

Role in primary healthcare and tribal livelihoods

For millions of people living in and around forests, medicinal plants and MFPs are the first line of healthcare. Tribal and rural communities rely heavily on forest resources to treat common ailments such as fever, wounds, digestive disorders, skin diseases and respiratory infections.

Simultaneously, MFPs provide critical livelihood support. Collection, processing and trade of forest produce contribute significantly to household income, especially for women and marginalized communities. Products like tendu leaves, gums, resins, medicinal roots and fruits are integral to the rural forest economy. Ayurveda thus represents not only a healthcare system but also a socio-economic bridge connecting forests, traditional knowledge and sustainable development.

Table 3: Effects and Side Effects of Commonly Propagated Ayurvedic Herbs (Kumar et al., 2024)

Herbs/Plants	Ayurvedic Perspective	Results of Improper Usage
Curcuma / Turmeric	Anti-inflammatory and anticarcinogenic actions. Pungent and bitter taste; hot potency. Used for vitiated states of *kapha* and *pitta*.	High doses over months can increase liver/thyroid weight and cause epithelial changes in bladder/kidneys. Contraindicated with platelet disorders, gallstones, aspirin, or warfarin.
Ginger	Pungent taste, hot potency. Helps reduce *kapha* and *vata* while increasing *pitta*.	Prolonged use can cause stomach irritation, heartburn, nausea, diarrhea, or ulcers. Can worsen gallbladder problems and increase bleeding risks.
Aloe vera	Bitter/sweet taste, cold potency. Good for vitiated *pitta* and *vata*. Used for inflammatory, skin, and liver diseases.	Dries out stools; overuse can lead to constipation. Long-term latex use may cause potassium deficiency or serious kidney disease. Avoid during pregnancy.
Tulsi	Pungent/bitter taste, hot potency. Increases *pitta* and decreases *kapha* and *vata*. Used against worms, parasites, and toxicity	Excessive use may aggravate *pitta* and blood disorders. Prolonged use is contraindicated in sterility due to marked antifertility action.
Moringa	Sweet/bitter taste, hot potency. Pacifies *kapha*. Roots and bark are used medicinally.	Can produce a burning sensation due to increased *pitta*. Not advised in pregnancy due to potential abortifacient effects.
Guduchi/Amrut	Bitter taste, heavy quality, hot potency. Pacifies all three *doshas*.	May cause mild constipation in some individuals.
Aswagandha	Bitter/astringent taste, hot potency. Pacifies *vata* and *kapha*, increases *pitta*. Used for mental health conditions.	Contraindicated in pregnancy and arterial congestion. Large doses may cause diarrhea and vomiting.
Triphala	Combination of three fruits. Drives out toxins by unblocking body channels (*srothus*).	Improper use can cause mucus destruction and drying of the intestinal flora. May cause headaches, nausea, or dehydration during toxin removal.

Scientific Validation and Modern Relevance

In recent decades there has been a significant resurgence of global interest in Ayurvedic medicinal plants. Advances in scientific research have substantiated many traditional Ayurvedic claims, leading to the identification of bioactive phyto constituents and elucidation of their pharmacological mechanisms of action.

This evidence-based validation has strengthened the credibility of Ayurveda within contemporary biomedical and pharmaceutical frameworks.

Advanced tools such as High-Performance Thin-Layer Chromatography (HPTLC), High-Performance Liquid Chromatography (HPLC), Gas Chromatography–Mass Spectrometry (GC–MS), and Liquid Chromatography–Mass Spectrometry (LC–MS) are now routinely employed for the quality control, standardization and authentication of forest-derived Ayurvedic raw materials and formulations. These techniques ensure batch-to-batch consistency detect adulteration and establish safety and efficacy parameters in accordance with international regulatory standards.

Challenges: Overexploitation and Conservation Concerns

Despite their immense ecological, medicinal and economic value, medicinal plants and minor forest produce (MFPs) are facing serious sustainability challenges. Unsustainable overharvesting, widespread habitat loss, climate change impacts and unscientific collection practices have resulted in the rapid depletion of several important species from their natural habitats. Additionally, weak market linkages, price exploitation by intermediaries and inadequate benefit-sharing mechanisms limit fair returns to primary collectors, particularly forest-dependent tribal and rural communities. Addressing these interconnected challenges through scientific management, policy support, capacity building and community participation is essential to ensure the sustainable utilization and conservation of medicinal plants and MFPs.

Conclusion

India's forests represent more than ecological reserves; they constitute vital repositories of bioresources and traditional knowledge that have sustained the Ayurvedic system of medicine for millennia. With the growing global demand for natural, plant-based and holistic healthcare solutions, the scientific and commercial relevance of forest-derived Ayurvedic resources is steadily increasing. However, realizing their full potential requires an integrated approach that respects indigenous knowledge systems while subjecting traditional claims to rigorous scientific validation. Sustainable harvesting, conservation-oriented management and value-chain development are essential to ensure long-term resource availability and quality. By harmonizing traditional wisdom with modern research, policy support and community participation, forests can continue to function as dynamic systems that simultaneously promote human health, biodiversity conservation and socio-economic well-being, thereby embodying the concept of "healing from forests" in a scientifically sustainable framework.

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Blockchain: A digital tool for traceability, fair payments, and better forest governance in Indian Himalayan Region

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Introduction

In the Indian Himalayan Region, forests are not only green landscapes on a map. They are part of everyday life. Many rural households depend on forest produce for income, food, medicine, fuel, and seasonal livelihood support. Leaves, herbs, seeds, gums, honey, and other non-timber forest products move through local markets and eventually reach distant buyers. In theory, this should create income for communities and incentives for conservation. In practice, the system is often far less fair.

One major problem is that the movement of forest produce is difficult to track. A collector may know what has been gathered, but not the final price. A trader may know the market, but not the origin of the product in detail. A processor may want clean records, but the supply chain may have too many missing links. As a result, the system becomes opaque. When records are weak, payments become slow, and trust breaks down.

This is where blockchain becomes interesting. The word sounds technical, but the idea is simple. Blockchain is a digital system that stores records in linked blocks. Once recorded, the information cannot be changed easily. That makes it useful for tracking products. If a batch of forest produce is entered into such a system at the point of collection, the same record can follow it through storage, transport, processing, and sale.

What blockchain means?

Blockchain is often linked to cryptocurrency, but that is only one use of it. In forest governance, its value lies in recording trustworthy information. Think of it as a digital notebook that many people can see, but no one can secretly erase or rewrite.

Each time something important happens in the forest produce chain, the event can be recorded:

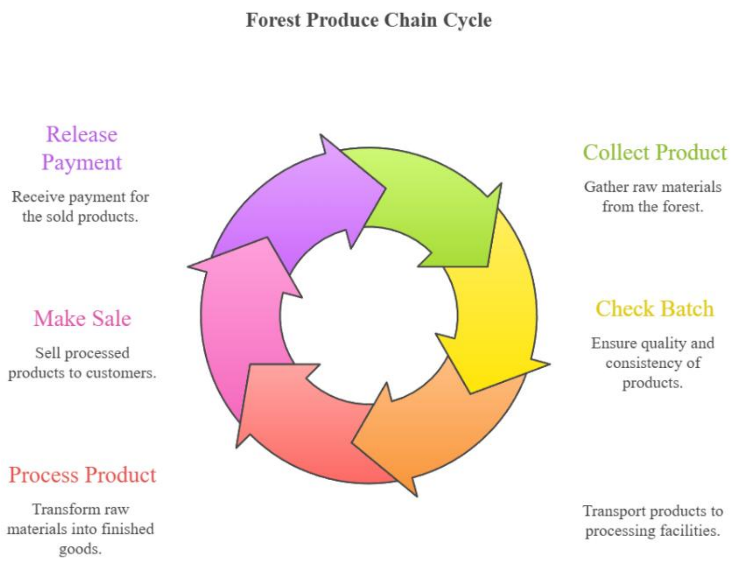

Fig. 1: Forest produces chain

Because the entries are time-stamped and linked, the entire chain becomes traceable.

This is especially useful for products whose quality and origin matter, such as medicinal plants, herbal raw material, wild honey, and resin.

For Himalayan communities, this matters because the market often rewards trust. Buyers want to know where a product came from. They want assurance that it was collected legally and sustainably. If that information is available in a secure digital record, the product may gain value. At the same time, collectors may gain a clearer record of what they sold and what they should receive.

Why current systems struggle?

The present system has several weak points. First, records are often scattered. Some are on paper, some in office files, and some are with local traders. Second, the same product may change hands several times without a full record of each step. Third, collectors usually have little information about the final price. Fourth, payment delays are common, especially when the chain includes several intermediaries.

These problems are not minor. They affect both livelihoods and conservation. When communities do not receive fair returns, there is less reason to follow sustainable harvesting rules. When products cannot be traced, it becomes harder to prove origin, quality, or legality. That weakens market confidence and discourages long-term investment in forest-based enterprises.

Table 1: Traditional forest produces chain versus blockchain-enabled chain

Aspect	**Traditional system**	**Blockchain-enabled system**
Record keeping	Paper-based and scattered	Shared digital record
Traceability	Often lost after aggregation	Batch-level tracking possible
Payment	Delayed and uncertain	Can be linked to verified events
Market confidence	Low to moderate	Higher due to transparent records
Dispute handling	Depends on manual evidence	Easier with digital audit trail

How blockchain could work in the Himalaya?

A blockchain system for forest produce does not need to be complex. It can start with a few simple steps.

When a product is collected, the batch can be assigned a digital identity. Basic details such as species name, collection date, location, quantity, and collector group can be recorded. A local validator, such as a trained community member or field official, can confirm the entry. Later, when the batch is transported or processed, each movement can be updated in the system. Finally, when the product is sold, the payment can be linked to the verified transaction.

This system creates a digital trail that can be checked by authorized users. It does not remove the need for field verification. On the contrary, it depends on honest and accurate field entry. But once the entry is made correctly, it becomes much easier to track the product.

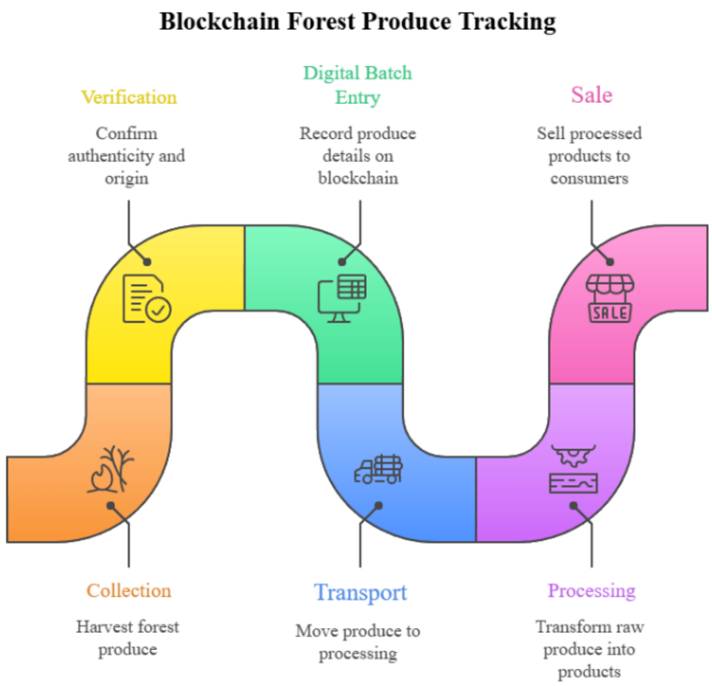

Fig. 2: Conceptual workflow for blockchain-based forest produces tracking

Where blockchain can help most?

The strongest use of blockchain is not everywhere at once. It is most useful where the product is valuable, traceability matters, and the number of actors is manageable. In the Himalayan context, this includes several products.

Medicinal and aromatic plants are a clear example. Their identity, quality, and origin affect price. If a buyer can verify that the material came from a known source and was handled properly, confidence increases.

Honey is another example. Consumers increasingly want to know whether honey is authentic, where it was collected, and how it was processed. A digital trace can improve trust.

Resins, gums, and selected tree-based products can also benefit, especially where transit and documentation are important.

The same logic can be extended to community forest products linked to local enterprises. When records are clear, communities are better positioned to negotiate, certify, and sell.

Smart contracts and fair payments

One of the most useful features of blockchain is the smart contract. A smart contract is a digital rule that releases payment when agreed conditions are met.

For example, once a batch has been verified, a part of the payment can be released immediately. When the batch reaches the processor, another installment can be paid. When the final sale is completed, the rest can be transferred. This would reduce long delays and make the system more predictable.

For collectors, this is important. Forest-based livelihoods are often seasonal and cash-sensitive. Waiting for payment for weeks or months can create hardship. A smart contract does not eliminate all risks, but it can reduce uncertainty and make payment terms more visible.

Table 2: Example of smart contract use in a forest produces chain

Trigger event	System response	Benefit
Batch collected and verified	Advance payment released	Collector gets quick support
Batch reaches processor	Second payment released	Transport and aggregation are recognized
Final sale confirmed	Balance payment released	Fairer distribution of revenue
Product fails verification	Payment paused	Reduces fraud and dispute

Conclusion

The Indian Himalayan Region needs forest-based livelihoods that are not only productive, but also fair and transparent. Blockchain can help by creating a secure digital trail for forest produce, supporting quicker payments, and improving traceability. It may also strengthen monitoring of sustainable harvest and ecosystem-service claims.

But the system will work only if it is built around local realities. Field verification, community participation, legal compliance, and simple user-friendly design are non-negotiable. If these conditions are respected, blockchain can become a useful support tool for Himalayan Forest governance.

In a region where forests support both biodiversity and people, trust is not a luxury. It is the basis of sustainable trade. A properly designed blockchain system may help build that trust, one verified batch at a time.

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