

Utilisation of Chir Pine (*Pinus roxburghii*) Needles for Green Bioeconomy, Rural Enterprises and Climate-Resilient Development in Uttarakhand

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Abstract

Chir Pine (*Pinus roxburghii*) is the predominant conifer species of the western Himalaya that covers nearly 399,330 ha (16.4%) of Uttarakhand's recorded forest area. These forests generate approximately 1.3 million tonnes of pine needles (*pirul*) each year, with nearly 0.6 million tonnes of surplus available for gainful utilisation after meeting the traditional needs of rural people. Pine needles are highly flammable, a primary factor behind recurring forest fires that reduce biodiversity and forest ecosystem services, increase greenhouse gas emissions, and impose considerable annual fire-suppression costs on the state government. Pine needles contain abundant lignocellulosic biomass, offering significant opportunities as a renewable feedstock for bioenergy generation and advancing a circular bioeconomy. This article brings together recent scientific developments, technological progress, and institutional efforts aiming at industrial utilisation of Chir Pine needles in Uttarakhand and across the western Himalaya. Its important uses include renewable energy generation, biofuels, biochar, activated carbon, pulp and paper, biodegradable packaging materials, fibre composites, textiles, handicrafts, and a range of other value-added products. In this article, we emphasise the sustainable use of Chir Pine needles to reduce fuel loading on the forest floor and minimise forest fire risks, promote decentralised rural enterprises, improve climate resilience, and strengthen ecosystem services. The article also highlights prevailing challenges in biomass harvesting, transportation, technology transfer, commercialisation, and market expansion. The article concludes that combining scientific research, decentralised processing systems, community engagement, and enabling policy support can convert pine needle biomass from a major forest fire hazard into a valuable resource for green industries, climate change mitigation, and sustainable mountain development.

Keywords: Chir Pine (*Pinus roxburghii*); Pine Needles (*Pirul*); Forest Biomass; Circular Bioeconomy; Bioenergy; Rural Enterprises; Climate Resilience; Uttarakhand.

Introduction

Forests of the Indian Himalayan Region (IHR) provide a wide array of ecosystem services that benefit both mountain inhabitants and downstream populations by conserving biodiversity, regulating soil and water resources in watersheds, sequestering carbon, and sustaining rural livelihoods (Singh & Singh, 1992). However, these ecologically sensitive, fragile mountain landscapes are threatened by climate change, frequent forest fires, invasive alien species, and land degradation, which reduce ecosystem services and underscore the urgent need for sustainable bio-resource use and climate-resilient management approaches (FSI, 2023; IPCC, 2022).

Chir Pine (*Pinus roxburghii* Sarg.) is one of the most economically important and dominant forest-forming conifer tree species of the Western Himalaya (Fig. 1). In the mountains of Uttarakhand within the altitudinal range of 1,000–1,800 m, it extends over approximately 4,000 sq km, accounting for nearly 16% of the state's recorded forest area (FSI, 2023). It is a drought-tolerant species that can thrive under inhospitable environmental conditions, enabling it to spread across large tracts of the Middle Himalaya. The resin extracted

from this tree yields oleoresin, an important raw material for the resin-based industry. Oleoresin is processed into rosin and turpentine, which are widely used in manufacturing paper, paints, adhesives, pharmaceuticals, rubber products, and synthetic resins (Nimkar & Sharma, 2008). In Uttarakhand, resin production makes a substantial contribution to the state's economy (Uttarakhand Forest Department, 2016).



Fig. 1. Chir Pine (*Pinus roxburghii*) forest in Uttarakhand; Interior view of the forest.

Pine trees are widely used for furniture making as they have a clear cylindrical bole and are relatively easy to saw and work. In addition, various parts of the tree have traditional uses such as stems serving as poles for climbing vegetables; leaves are used for thatching, cattle bedding, and broom making; seeds are nutritious; cones are used for decorative items; and bark is used as fuel by blacksmiths (Negi et al., 2021). This early-successional species has a tremendous capacity to grow and regenerate on soils of poor fertility and low moisture, unlike the socially valued Oak (*Quercus* spp.). However, the bad aspect of this species is that the huge quantities of its needles dropped on the forest floor (locally called *Pirul*) are highly inflammable due to the presence of oleoresin that catches fire and make colossal loss every year to the forest wealth of Uttarakhand (Fig. 2). For example, the 1999 forest fires, among the largest recorded in Uttarakhand, affected approximately 5,086 km² (22.6%) of forest area, causing an estimated loss of ₹50 lakh as per the set norms of the Forest Department (Negi, 2019). Negi et al. (2025) estimated the loss of forest wealth due to forest fires in Uttarakhand at a mean value of ₹1,30,387/ha (range = ₹9,595–₹3,52,752/ha), which is about 65–90 times higher than previously reported. This is a major ecological concern in the Western Himalayan region.

Uttarakhand is estimated to produce approximately 0.96–1.66 million tonnes of pine needles every year. This biomass could produce 1,035–1,791 GWh of electricity (approximately 118–205 MW) through thermochemical conversion, making it an important decentralised renewable energy resource for mountain communities (Kala & Subbarao, 2017). From a biochemical perspective, pine needles constitute a valuable lignocellulosic feedstock containing about 45% carbon, 0.93% nitrogen, 6.5% hydrogen and 0.13% sulphur, with a carbon-to-nitrogen ratio of approximately 51, making them suitable for producing bioenergy, biochar, activated carbon, fibre products and biodegradable materials (Gupta et al., 2024).



Fig. 2. Pine needles (*Pirul*) collected from the forest, and *Pirul* being carried away by women

Despite their economic potential, accumulated pine needles become highly combustible during the dry summer season because of their high resin content and slow decomposition. Unlike broad-leaved litter, pine needles may persist on the forest floor for more than two years, creating a continuous fuel layer that substantially increases fire intensity and spread under conditions of high temperature, low humidity and prolonged drought (Tiwari & Tiwari, 2001).

Forest fires have become one of Uttarakhand's most serious environmental challenges. Since the formation of the State in 2000, more than 44,500 ha of forests have reportedly been affected by fire (Negi, 2018). During April 2024 alone, the Forest Survey of India recorded 3,338 forest fire alerts, highlighting the increasing frequency and severity of fire events (FSI, 2024). Studies during the COVID-19 lockdown further indicated that anthropogenic activities remain a major cause of forest fires in the region. Recurring fires degrade forest ecosystems by reducing natural regeneration, altering nutrient cycling, promoting invasive species such as *Lantana camara* and *Ageratina adenophora*, and accelerating soil erosion (Singh et al., 1984). They also impair watershed functions and contribute to declining spring discharge in Himalayan catchments (Negi & Pant, 2025). In addition, forest fires release substantial quantities of carbon dioxide, methane, carbon monoxide and black carbon, thereby reducing ecosystem carbon stocks and contributing to climate change. For example, the 2016 Uttarakhand forest fires increased atmospheric carbon monoxide concentrations by nearly 45% above the five-year average, while repeated burning has caused significant losses of above-ground biomass carbon in Chir Pine forests (Thakur et al., 2019; Bargali et al., 2024).

The economic consequences are equally significant. Assessments coordinated by the Indian Council of Forestry Research and Education (ICFRE) estimated direct losses from forest fires ranging from ₹9,595 to ₹352,752 per hectare, with an average loss of about ₹130,387 per hectare (ICFRE, 2021; Negi et al., 2025). These estimates exclude the much larger indirect losses associated with biodiversity conservation, watershed protection, tourism, carbon sequestration and other ecosystem services. Although considerable investments are made annually in fire lines, fire watchers and suppression measures, these approaches address the symptoms rather than the underlying accumulation of combustible biomass.

Sustainable utilisation of Chir Pine needle biomass therefore offers an opportunity to convert a recurring forest fire hazard into a valuable renewable resource. Recent advances in biomass conversion technologies have demonstrated the feasibility of producing briquettes, pellets, bio-oil, biochar, activated carbon, fibre composites, paper, biodegradable packaging, textiles and handicrafts from pine needles. These technologies not only reduce forest fuel loads but also support decentralised enterprises, women-led livelihoods and green manufacturing. Recognising this potential, the Government of Uttarakhand introduced the Policy for Power Generation from Pine Leaves and Other Biomass (2018) to promote organised biomass collection and decentralised renewable energy through the Forest Department, Uttarakhand

Renewable Energy Development Agency (UREDA), Van Panchayats, Gram Panchayats, Self-Help Groups, and private entrepreneurs. As biomass processing and circular bioeconomy approaches advance, opportunities now extend beyond electricity generation to diversified value-added products, carbon management, and climate-resilient rural development.

This review synthesises current scientific knowledge, technological developments and institutional experiences related to industrial utilisation of Chir Pine needles in Uttarakhand and the western Himalaya. The article explores emerging value-added industrial uses of Chir Pine needle biomass (*Pirul*), synthesises existing R&D knowledge, and recommends policy measures to promote a sustainable circular bioeconomy through efficient utilisation of Chir Pine needles and tree products.

Emerging Industrial Applications of Chir Pine Needles

Table 1 summarises the major industrial applications of Chir Pine needles reported by different R&D organisations, government departments, universities, and community-based enterprises; it indicates that *Pinus roxburghii* needles, as a renewable lignocellulosic biomass, have been utilised beyond their traditional uses. Pine needles, rich in cellulose, hemicellulose, and lignin, can be converted into a wide range of bio-based products through thermochemical, biochemical, and mechanical processes. Such utilisation pathways support a circular bioeconomy by converting Pine leaf litter into value-added products, reducing waste and dependence on fossil resources, and also mitigating forest-fire risks. Thus, it presents a significant opportunity to contribute to climate change mitigation.

Table 1: Industrial Utilisation of Chir Pine Needles (*Pinus roxburghii*): Major Products, Technologies and Key Institutions

Industrial Category	Process and Major Products	Representative Agencies / References
Renewable Energy	Direct combustion, briquetting, palletization and gasification for production of briquettes, pellets, producer gas, heat and electricity	Govt. of Uttarakhand (2018); Kala & Subbarao (2018); UREDA (2023); Jain & Choudhry (2021); https://avani-kumaon.org)
Biofuels and Biorefinery	Pyrolysis, hydrothermal liquefaction and biochemical conversion for bio-oil, bioethanol, syngas and green chemicals	Slathia et al. (2020); Singh et al. (2021); CSIR-IIP, Dehradun (2021);
Biochar and Activated Carbon	Slow pyrolysis and carbonization for biochar, activated carbon, adsorbents and soil amendments	Kumar et al. (2020); Azad et al. (2022); Rana et al. (2023) / GBPUAT, Pant Nagar
Paper and Pulp Industry	Chemical and mechanical pulping for handmade paper, stationery, packaging paper and molded fiber products	Kumar (2020); Negi et al. (2021); FRI, Dehradun / GBPNIHE, Almora
Textiles and Natural Fibers	Fiber extraction, retting and blending for yarn, fabrics, carpets, mats, home furnishings and eco-textiles	Kumar et al. (2021); FRI / Uttarakhand Bamboo and Fiber Development Board (2021); NITRA, Ghaziabad (2022)
Wood Composites and Building Materials	Compression molding and resin bonding for particle boards, medium-density fiber boards (MDF), insulation panels and composite boards	Singh & Vinay (2025); Pant Nagar University; ICFRE-FRI, Dehradun (2023)

Biodegradable Packaging and Bioplastics	Fiber molding and biodegradable composite technology for trays, disposable tableware, food containers and packaging materials	Chauhan et al. (2018); Gaikwad et al. (2021); Wali (2019); NIFT, Jaipur / IIT, Roorkee
Environmental Applications	Preparation of biosorbents, activated carbon and filtration media for wastewater treatment, heavy metal adsorption and air purification	Choudhary et al. (2020); Rana et al. (2023); Univ. of Petroleum & Energy Studies, Dehradun; JNU, New Delhi
Agriculture and Soil Improvement	Pyrolysis, composting and mulching for biochar, compost, soil conditioner, moisture conservation and carbon sequestration	Kumar et al. (2009); Choudhary et al. (2020); Nain et al. (2023); Jaiswal (2025); GBPNiHE, Almora / GBPUAT, Pant Nagar/ Estelar Enterprises, Almora
Essential Oils and Oleochemicals	Steam distillation and solvent extraction for pine oil, terpenes, resin derivatives, fragrances and pharmaceutical intermediates	FRI (2020); Gupta et al. (2026); UCOST, Dehradun
Handicrafts and Cottage Industries	Manual weaving, stitching and value addition for baskets, mats, trays, flower pots, decorative items, jewelry and household articles	GBPNiHE (2025), Almora/FRI-ICFRE, Dehradun (2021), UBFDB, Dehradun (2021)/ Pirul Handicrafts, Champawat; Maa Dunagiri Pirul SHG, Dwarahat, Almora; Mount Valley Development Association, Tehri Garhwal; Dhuri Foundation, Nainital
Carbon Management and Circular Bioeconomy	Sustainable biomass utilization, biochar production, substitution of fossil-based products and forest fuel-load reduction contributing to carbon sequestration and ecosystem services	IPCC (2022); Govt. of Uttarakhand (2018); Rana et al. (2023); Negi & Mehta (2026)

Renewable energy remains the most established application of Chir Pine needles. Their relatively high calorific value, seasonal availability and widespread distribution make them suitable for briquetting, pelletization, gasification and decentralised electricity generation. These technologies simultaneously reduce forest fuel loads, provide clean energy and generate employment through biomass collection and processing (Kala & Subbarao, 2018; Govt. of Uttarakhand, 2018). The State's biomass policy has further encouraged decentralised power generation and village-level biomass enterprises.

Recent advances have expanded the utilisation of Chir Pine biomass beyond conventional energy applications toward integrated biorefinery systems. The thermochemical conversion technologies, including pyrolysis and hydrothermal liquefaction, can produce bio-oil, syngas, biochar, and value-added chemicals, while biochemical conversion offers potential for biofuels and other bio-based products (Slathia et al., 2019; CSIR-IIP, 2021). UCOST, Dehradun, has also supported research and technology demonstration on pine-needle utilisation for bioethanol production (UCOST, 2007). Integrating these conversion pathways can improve biomass utilisation efficiency, diversify product streams, enhance resource recovery, and strengthen the overall economic viability of Chir Pine biomass.

Biochar preparation from Chir Pine biomass is emerging as a promising climate-smart technology. Biochar derived from pine needles can improve soil fertility, enhance water-holding capacity, and facilitate long-term carbon sequestration. Furthermore, activated carbon

produced from pine biomass has demonstrated considerable potential for wastewater treatment through the effective adsorption of diverse environmental pollutants (Kumar et al., 2020; Azad et al., 2022; Rana et al., 2023). These applications offer a dual benefit by contributing to environmental restoration while promoting the sustainable utilisation of forest biomass resources.

The utilisation of Pine biomass in the pulp and fibre sector offers yet another considerable scope for value addition. Owing to their relatively high cellulose content, Pine needles can be converted into handmade paper, stationery, multifiber products, and biodegradable packaging materials. Technologies developed by GBPNIHE, Almora, Forest Research Institute, Dehradun, and other research institutions have demonstrated the technical feasibility of using Pine needle biomass as an alternative source for producing environment-friendly handmade paper and other value-added products (Kumar, 2020; Negi et al., 2021).

Pine fibers also offer considerable potential for developing biodegradable composites, insulation panels, and engineered boards that can partially substitute synthetic materials in sustainable construction. However, further R&D is needed to optimise fiber extraction, processing, and product development for these applications. Advances in fibre-processing technologies have also enabled the production of textiles, carpets, mats, decorative articles, and other household products. Blending pine fibres with cotton, wool, or bamboo can improve product properties while creating opportunities for women-led enterprises and decentralized rural industries (Kumar et al., 2021; UBFDB, 2021). Community-based value addition has further demonstrated the socio-economic potential of pine biomass utilisation in Uttarakhand. Women Self-Help Groups and local organizations across Uttarakhand are successfully producing baskets, trays, mats, decorative articles, and other household products from pine needles, generating supplementary income while systematically *Pirul* from forests that is highly vulnerable to fire (GBPNIHE, 2025; FRI-ICFRE, 2021; UBFDB, 2021).

In addition to needle biomass, Chir Pine contains commercially valuable volatile compounds, including α -pinene, β -pinene, and limonene, which constitute important components of Pine oil and have wide applications in the fragrance, pharmaceutical, and specialty chemical industries. Although large-scale commercial extraction of Pine oil remains limited, integrating Pine oil recovery with existing biomass-processing technologies could improve resource-use efficiency, diversify value-added products, and enhance the economic viability and profitability of biomass-based enterprises (FRI, 2020; Gupta et al., 2026).

Overall, industrial utilisation of Chir Pine needles has progressed from conventional biomass energy to diversified applications in green materials, environmental technologies and rural enterprises. Nevertheless, most technologies remain at pilot or small-commercial scale. Scaling up decentralised processing, improving market linkages, and strengthening research–industry–community partnerships will be essential to establish a sustainable pine biomass economy in Uttarakhand.

Sustainable Utilisation of Chir Pine Needles for a Circular Bioeconomy in Uttarakhand

The increasing global emphasis on renewable bio-resources is driving a transition from conventional linear production systems towards circular bioeconomy models that maximise resource efficiency, minimise waste, and reduce dependence on fossil fuels. In this context, biomass is increasingly recognised as a key resource for generating renewable energy and bio-based materials within circular production systems (Sherwood, 2020). Accordingly, Chir Pine needles should no longer be viewed merely as hazardous forest litter, but as a valuable

lignocellulosic biomass with substantial potential for renewable energy generation, green manufacturing, carbon management, and the development of decentralised rural enterprises.

Given Uttarakhand's extensive Chir Pine forests, recurrent forest fires, and dispersed mountain settlements, this approach is particularly relevant to the state, as these conditions provide a strong basis for decentralised and locally integrated biomass utilisation. Organised collection and scientific valorisation of Pine needles can simultaneously reduce forest fuel loads, generate rural employment, diversify forest-based livelihoods, and contribute to climate change mitigation. Future initiatives in Uttarakhand should prioritise integrated biomass utilisation through diversified and value-added value chains, rather than dependence on a single end-use product, in alignment with the state's *Policy for Power Generation from Pine Leaves and Other Biomass, 2018*.

From Forest Residue to a Strategic Bioeconomy Resource

Pine needles are a lignocellulosic biomass resource with strong potential to replace fossil-derived raw materials in energy, packaging, textiles, chemicals, construction, and other value-added applications because of their cellulose, hemicellulose, and lignin content (Tewari, 1994; Gupta et al., 2024). Future utilisation of Pine biomass should therefore adopt a cascading approach, converting biomass progressively into higher-value products rather than limiting its use only to fuel. In Uttarakhand, decentralised village-level processing can reduce transportation costs, generate local employment, and strengthen rural value chains. The pine-needle processing facility established by GBPNIHE, Almora, which produces briquettes, handmade paper, and other products through community participation and public-private partnerships, demonstrates the feasibility of this approach (Negi et al., 2021; GBPNIHE, 2025). A UCOST-GBPNIHE-AGNI technology showcase in Champawat further demonstrated pine-needle-based briquettes and paper products, highlighting opportunities for decentralised value addition. Scaling such initiatives across Chir Pine-dominated areas could strengthen livelihoods, resource efficiency, and biomass-based enterprises in Uttarakhand.

Advanced Biomass Conversion Technologies

Although briquetting and biomass-based power generation remain important utilization pathways, recent technological advances have expanded the scope for producing a diverse range of higher-value products. Advanced thermochemical processes such as gasification, torrefaction, fast pyrolysis, and hydrothermal carbonisation can convert pine biomass into bio-oil, syngas, biochar, and other renewable materials, offering greater economic value than conventional fuel-based applications (Bhattacharya et al., 2022). Future research should therefore focus on improving conversion efficiencies, reducing production costs, and developing compact, decentralised processing systems adapted to mountain conditions. Integrating renewable energy production with modern biorefinery approaches can enhance resource-use efficiency, maximise biomass valorisation, and strengthen the long-term economic viability of biomass-based enterprises.

Biochar, Green Materials, and Climate-Smart Agriculture

Biochar has emerged as a promising value-added product from Chir Pine needles because of its potential applications in soil amendment, carbon sequestration, and sustainable management of pine-needle biomass (Nain et al., 2023). Controlled pyrolysis of Chir Pine

needles produces a stable, carbon-rich biochar with potential applications in soil improvement, water purification, and long-term carbon sequestration. The porous structure and surface properties of pine-derived carbon materials facilitate contaminant adsorption from water and other aqueous systems. Research at G.B. Pant University of Agriculture & Technology, Pantnagar, demonstrated that Chir Pine leaves can effectively remove heavy metals such as Cr(VI), Cu(II), Fe(II), and Zn(II) from industrial effluents, highlighting their potential for low-cost water and wastewater treatment (Tewari & Vivekanand, 2013). Such applications could support the development of decentralised and locally appropriate water-purification technologies for mountain communities. Beyond biochar, pine needles also offer opportunities to produce biodegradable packaging materials, fibre composites, insulation panels, and other environmentally friendly products that can partially replace petroleum-derived materials.

Integration with Carbon Markets and Payment for Ecosystem Services

An emerging opportunity for Chir Pine biomass utilisation lies in carbon markets and ecosystem-based financing. Sustainable collection and utilization of pine needles can support climate mitigation by reducing forest-fire risks, substituting fossil-based fuels and materials, and enhancing long-term carbon storage through biochar and durable bio-based products, consistent with circular bioeconomy principles and nature-based solutions (IPCC, 2022).

Initial studies on Van Panchayat forests of Uttarakhand have demonstrated the feasibility of quantifying carbon stocks and ecosystem services under community forest management following IPCC protocols (Negi & Mehta, 2026). Building on these efforts, standardised MRV protocols could quantify biomass availability, avoided fire emissions, biochar-based carbon sequestration, and benefits from fossil-product substitution. Robust carbon accounting would strengthen participation in voluntary carbon markets, Payment for Ecosystem Services (PES), and emerging climate-finance mechanisms, while generating additional income for mountain communities.

Community Participation, Women Empowerment and Rural Enterprises

The long-term sustainability of a Chir Pine-based circular bioeconomy will depend largely on active participation of local communities, particularly Van Panchayats, Self-Help Groups, Farmer Producer Organisations, and rural entrepreneurs. Uttarakhand possesses one of India's strongest community forestry systems, providing an institutional foundation for organised pine needle collection, decentralised processing and value-added enterprises.

Women already play a central role in forest resource management and forest-based livelihoods across the Himalayan region. Strengthening women-led enterprises in pine fiber processing, handicrafts, biodegradable packaging and other value-added products can diversify household incomes while reducing forest fuel loads. Successful initiatives supported by the Uttarakhand Bamboo and Fibre Development Board (UBFDB), GBPNIHE, the Forest Research Institute (FRI), and community organisations have demonstrated the technical and commercial feasibility of such enterprises (Kumar et al., 2021; UBFDB, 2021; GBPNIHE, 2025). Future efforts should focus on entrepreneurship development through skill enhancement, common facility centres, product design, branding, digital marketing and improved access to institutional finance. Linking producer groups with tourism, handicraft markets, e-commerce platforms and green procurement programmes would further improve market access and enterprise sustainability. Such community-based value chains can

simultaneously support livelihood enhancement, forest conservation and climate resilience (Agrawal, 2001).

Future Innovation Priorities

Although considerable technological progress has been achieved, several priority areas require further research and innovation before Chir Pine biomass utilisation can be scaled up commercially. Future research should prioritise: (1) GIS-, remote sensing- and AI-based assessment of pine biomass resources and digital supply-chain management. (2) Development of efficient technologies for biomass collection, storage, densification and decentralised processing under Himalayan conditions. (3). Techno-economic analysis and life-cycle assessment of alternative utilisation pathways. (4). Production of advanced bio-based materials, including nanocellulose, engineered composites, biodegradable packaging and speciality chemicals. (5). Standardised MRV protocols for carbon accounting, carbon markets and Payment for Ecosystem Services. (6). Stronger collaboration among UCOST, FRI, CSIR-IIP, GBPNiHE, universities, industries, Van Panchayats and private entrepreneurs to accelerate technology transfer and commercialisation. These priorities will strengthen innovation, improve industrial competitiveness and position Uttarakhand as a leader in sustainable mountain bioeconomy development.

Research Gaps and Future Needs

Although significant progress has been made in developing technologies for the utilization of Chir Pine (*Pinus roxburghii*) needles, most applications remain confined to laboratory studies, pilot-scale demonstrations or small community enterprises. The large-scale commercialization of Chir Pine biomass is constrained by fragmented supply chains, difficult mountain terrain, seasonal raw-material availability, limited processing infrastructure, and inadequate market linkages. Addressing these challenges is essential for developing a viable and sustainable circular bioeconomy based on Pine biomass in Uttarakhand.

Future priorities should therefore focus on efficient biomass supply systems, integrating scientific collection, storage, densification, and transportation with GIS, remote sensing, and digital inventories to ensure reliable feedstock for decentralised processing. Techno-economic, life-cycle, and standardised MRV assessments should guide technology selection, investment, and carbon accounting, including avoided fire-generated CO₂ emissions, biochar sequestration, and fossil-material substitution, thereby facilitating access to carbon markets, PES, and climate finance. Technological advancement should promote integrated biorefineries that convert Pine biomass into multiple high-value products, including renewable energy, biochar, activated carbon, fibres, essential oils, and green chemicals. Product standardisation, quality assurance, market development, and stronger collaboration among research institutions, industry, government, and communities are essential for technology transfer and commercialisation. Business incubation, common processing facilities, and skill development can further position Chir Pine biomass as a sustainable resource for green industries, rural livelihoods, and climate-resilient development in Uttarakhand.

Policy Perspectives and Roadmap for Utilisation of Chir Pine Needles in Uttarakhand

Uttarakhand's forests represent a vast yet underutilized renewable biomass resource, with nearly 399,330 ha under Chir Pine and an estimated 1.3 million tonnes of pine needles

generated annually, offering significant potential for green manufacturing, renewable energy generation, value-added enterprises, and sustainable rural livelihoods (Uttarakhand Forest Department, 2016; FSI, 2023). While the *Policy for Power Generation from Pine Leaves and Other Biomass* (2018) established an important foundation for biomass-based power generation, the next phase of policy development should move beyond energy-centric applications toward diversified, higher-value utilisation within a circular bioeconomy framework.

The following strategic priorities are recommended: (i). Diversification of Biomass Utilisation: Expand utilisation beyond electricity generation to include biochar, activated carbon, fibre composites, biodegradable packaging, engineered wood products, green chemicals and other high-value bio-based products. (ii). Strengthening Biomass Supply Chains: Establish village-level collection centres, biomass aggregation systems and decentralised preprocessing facilities for baling, briquetting, fibre extraction and biochar production to improve raw material availability while reducing transportation costs. (iii). Technology Commercialisation: Promote technology transfer through collaboration among UCOST, FRI, CSIR-IIP, GBPNIHE, IIT Roorkee, universities and private industries. Strengthen business incubation, pilot-scale demonstrations, and product certification to accelerate commercialisation. (iv). Community-Based Enterprise Development: Engage Van Panchayats, Self-Help Groups, producer organizations and rural entrepreneurs in biomass collection, processing and value addition. Place particular emphasis on women-led enterprises through skill development, concessional finance, branding, and digital marketing. (v). Carbon Finance and Ecosystem Services: Develop standardized MRV protocols for avoided fire emissions, biochar carbon sequestration and ecosystem service valuation to facilitate participation in voluntary carbon markets and Payment for Ecosystem Services. (vi). Monitoring and Adaptive Governance: Establish an integrated monitoring framework for biomass collection, enterprise development, forest-fire reduction, employment generation and environmental benefits to support evidence-based policy implementation. Adoption of these measures would transform Chir Pine biomass from a seasonal forest management problem into a strategic resource supporting renewable energy, green industries, climate mitigation and sustainable mountain livelihoods.

Conclusion

Chir Pine (*Pinus roxburghii*) needle biomass is one of the largest underutilised renewable resources in the western Himalaya and, rather than being viewed solely as a major forest-fire hazard, should be recognised as a valuable lignocellulosic feedstock for renewable energy, bio-based materials, carbon sequestration, and decentralised rural enterprises. Recent advances in biomass conversion technologies offer significant opportunities to transform Chir Pine biomass into high-value products, including briquettes, pellets, biochar, activated carbon, paper, biodegradable packaging, fibre composites, textiles, and handicrafts. Such diversified utilisation can reduce the accumulation of inflammable Pine needles on the forest floor and avoid forest fire risk while generating employment, strengthening rural livelihoods, and enhancing ecosystem resilience. Realising this potential requires coordinated investment in R&D, technology transfer, entrepreneurship, efficient supply chains, and market development, with active participation of the Forest Department, Van Panchayats, women's SHGs, and R&D institutions. Integrating biomass utilization with carbon accounting, voluntary carbon markets, and PES can further support sustainable forest management and climate action. Within a circular bioeconomy framework, Uttarakhand can transform Chir Pine biomass into a strategic

resource for green growth, climate resilience, and sustainable mountain livelihoods, while providing a replicable model for the wider Indian Himalayan Region and contributing to India's Nationally Determined Contributions (NDCs) on climate action.

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