# Utilization of Himalayan Pine Needles for Sustainable Environmental Practices and Energy Recovery- A Circular Economy Approach

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**Abstract:**

Pine needles (PNs), a prominent lignocellulosic biopolymer, consists of hard to bio-degradable lignin content (38-40%). High lignin and the higher productivity ($1.9*10^6$ tons/year) of PNs over the span of $5*10^5$ $km^2$ poses a significant challenge as fallen PNs contribute to forest fires, groundwater recharge inhibition and air pollution. This paper explores diverse strategies to address this issue. PNs find applications in wastewater treatment (as an adsorbent), and indigenous fuel (briquettes). On the other hand, gasification offers promise for converting PNs into bioenergy (syngas) production, pyrolysis produces carbon-based materials biochar for wastewater treatment. Furthermore, pyrolysis also produces pyro-oil which can have application in energy generation plants. These applications underscore the potential of PNs in various industries, emphasizing sustainable solutions for waste management along with energy and resource recovery.

## 1.0 Introduction:

The genus Pinus, encompassing a diverse array of species, stands as the largest family within the coniferous group, constituting a vital component of global ecosystems. With over 120 species distributed worldwide, Pinus plays a crucial role in ecological systems, particularly thriving in subtropical and temperate zones [1]. These resilient trees exhibit impressive dimensions, with heights reaching up to 80 meters, though the majority of species typically ranges between 20-120 ft. [1]. The Himalayan region, covering an estimated area of 650 thousand $km^2$, boasts an abundant presence of pine trees, with specific species like P. sylvestris and P. roxburghii thriving in diverse altitudinal zones, from subtropical to alpine regions [2,3]. Pine (P. roxburghii) stands out as a major species in the lower reaches of the Himalayas, constituting a significant portion of the forest cover according to the India State of Forest Report (2019).

The ecological significance of Pinus arises from the vast forests it forms, either as pure stands or in conjunction with other coniferous species. In the Indian Himalayas, these pine forests account for approximately 16.2% of the total forest cover, spanning an expansive area of about $5*10^5$ $km^2$ [4]. The elevation range suitable for pine tree growth in the Indian Himalayan terrain spans from 300 to 2200 meters above sea level [5].

Pine tree residues, comprising pine needles (PNs), pine bark, and pine cones, constitute a substantial portion of forest residues in the Himalayan region, with a productivity rate of 6.3 tons per hectare per year [6,7]. These residues, characterized as lignocellulosic in nature, predominantly consist of lignin. Pine needles, in particular, exhibit a composition with cellulose content ranging from 22% to 27%, hemicellulose content between 24% to 28%, and a higher lignin content ranging from 38% to 40% [6–8]. Notably, in the Himalayan region of India, the PNs alone contributes significantly, amounting to a productivity of about 1.9 million tons per year [4].

Understanding the detailed composition of these PNs is crucial for various environmental and engineering considerations. The lignocellulosic nature of PNs, coupled with their significant lignin content, poses challenges for their efficient decomposition and utilization. The abundance and productivity of these residues underscore the need for sustainable management strategies to address the environmental impact and harness the potential benefits of PNs for biofuel production and sustainable methods for resource recovery to achieve the circular economy goal.

## 2.0 Methodology:

*2.1 Characteristics of PNs:*

Pine needles collected from the Mandi district of Himachal Pradesh were characterized for the lignocellulosic composition, specific surface area, elemental composition and proximate analysis. The flowchart for the characterization of PNs is presented in Figure 1.

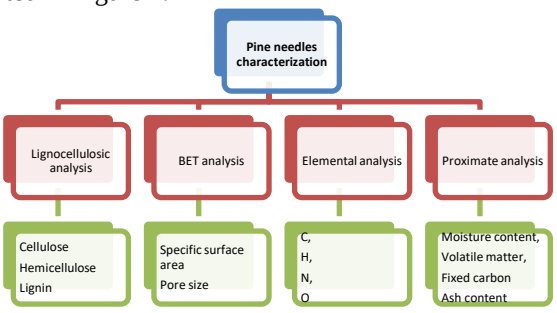


**Figure 1:** Flowchart for the various characterization of pine needles

*2.2 Methods for estimation of Himalayan pine needles:*

Assessing PNs availability for energy and resource recovery in Himachal Pradesh involves a three-step process. Firstly, determine the gross annual yield of PNs. Then, evaluate the losses incurred due to various factors such as collection methods, alternative uses, and limitations. Finally, obtain the net annual PNs yield by subtracting the losses from the gross yield. This approach provides a comprehensive understanding of the feasible PNs quantity for different applications in Himachal Pradesh.

**3.0 Results and discussion:**

*3.1 Characteristics of the Himalayan PNs:*

*Lignocellulosic composition:*
Date for the lignocellulosic composition of PNs listed in Table 1 is taken from our previous study [7]. Lignin content in PNs presented in the range of 33-44 % is reported by other researchers [9]. Lignin content reported from our previous study is 40 % as listed in Table. Researchers have reported that with the increase in lignin content carbon content in the biochar is also increased [10].

**Table 1:** Lignocellulosic composition of PNs [7]

| **Properties** | **Average values (%)** |
|---|---|
| Cellulose | 22 |
| Hemicellulose | 28 |
| Lignin | 40 |
| Ash and Extractives | 10 |

*Proximate analysis:*
The PNs were also analysed for the proximate and ultimate analyasis and it was found that the fixed carbon is about 16.1% and a carbon content of 45.4%.

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