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Potential of Pine Needle Biomass as an Alternative Fuel to Mitigate Forest Fire in Uttarakhand Himalayas - A Review

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ABSTRACT

Pine needle is a typical biomass which is abundantly available in Uttarakhand hills. This shredded biomass contributes significantly in forest fire occurring regularly in Uttarakhand. Different energy harnessing routes as direct combustion, anaerobic digestion, pyrolysis, gasification, and briquetting for pine needle were reviewed. These routes were further compared on the basis of energy consumption and energy efficiency of the processes as per the available literature. The review suggested that briquetting of pine needle and its anaerobic digestion are two most energy efficient methods having energy efficiency of 88% and 41.6%, respectively. The estimated energy required for briquetting of 1 ton pine needle was 1370.5 MJ, whereas for gasification it was 1170 MJ.

Continuously depleting available fossil fuel sources and emission of green house gases (GHG) from the same have made it necessary to find alternate fuel sources. The power generated from various renewable sources in the country during the year 2019 was about 69,194.5 MW (Anon., 2019), which includes approximately 12.6% energy from crop residues (Fig. 1). Biomass has been contemplated widely as renewable, feasible and carbon neutral fuel source (Goyal *et al.*, 2008; Kaygusuz, 2009). Recently, several studies have been conducted to find out the viability of different biomass including their utilization methods as prospective fuel sources (IEA, 2006; Efika *et al.*, 2012).

Pine needles are abundantly available biomass from pine forests that are present in almost the entire globe. *Chir* pine (*Pinus roxburghii*) is the most widely spread species of Uttarakhand occupying about 26.07% of state forest, and is found mostly above 1000 m msl in the state (Anon., 2018). Pine needle regularly shed in the month of March and April in Uttarakhand pine forests, and an area of about 7.62 Mha is covered under *chir* pine (*Pinus roxburghii*) forest in North Western

Himalayan region comprising of India, Nepal and Bhutan (Tiwari *et al.*, 2020). Pine needle productivity has been estimated to be about 6 t.ha⁻¹ per year in Indian hill state of Uttarakhand (Singh *et al.*, 2016). It usually decomposes very slowly and rarely removed from the forest bed. Shredded pine needles form a thick layer on the surface which is one of the potential causes of fire hazard. It also prevents growth of grasses on which the cattle feed upon in hilly region (Dwivedi *et al.*, 2016). Large scale forest fires caused by thick layer of pine needle contribute to significant air pollution with devastating environmental impacts (Tzamtzis *et al.*, 2006). Therefore, finding alternate uses of pine needle is of utmost importance to reduce risk of forest fire.

Pine needles are available on the hilly terrain from difficult to very difficult topography, and hence its collection and transportation using completely mechanized system is not feasible. Since the pine forests shed their needles in summer season, its collection and storage are required to be done in the months of April to June for making its use during the whole year. It would also be desirable to collect the

pine needles in very large quantity for its utilization as a fuel source. The stored pine needles thereafter can possibly be converted to various forms of fuel like fuel briquettes, deriving bio-oil and producer gas that may support the fuel requirement in rural households as well as a source for decentralized electricity generation. Energy generation through forest biomass is confronted by several challenges. Some of the main barriers of using forest biomass as an energy source are high moisture content, low energy density, seasonal variation or availability, conversion technology limitations and storage space requirements (Zhu *et al.*, 2011; Mirkouei *et al.*, 2017). Loose pine needles have bulk density in the range of 40-100 kg.m⁻³, and therefore, its large-scale use round the year requires storage in densified form. The bulk density of densified pine needle ranges from 150-200 kg.m⁻³, which facilitates easy transportation and minimal area for its storage.

Rural household locally uses pine needles as bedding material for poultry and cattle during the winter season and as fuel source for cooking. These uses are not to its fullest potential considering its large quantity availability. Being a ligno-cellulosic biomass, it has huge potential as an energy source. Ligno-cellulosic biomass can be converted to energy products by different routes such as high-pressure briquetting, gasification for producer gas, fermentation for ethanol, anaerobic digestion for biogas production and thermo-chemical conversion for production of bio-oil and biochar (Mandal *et al.*, 2017). All these processes have their relative merits and demerits. The best route for a catchment can be decided based on detail scientific study on the conversion processes and kinetic study of the biomass material.

Availability of Pine Biomass

Pinus roxburghii, commonly known as *Chir* pine or long leaf Indian pine, is a native species to the Himalayas. Its home extends from Tibet and Afghanistan through Pakistan, northern states of India, Nepal, and Bhutan up to Myanmar. In India, three states namely Himachal Pradesh, Jammu & Kashmir, and Uttarakhand share its maximum availability (Fig.2). Out of these three states, Uttarakhand alone shares a major portion (0.412 Mha) of *Chir* pine forests (Singh and Kaur, 2018).

Pine is especially exploited for its wood and resin products. Timber of *P. Roxburghii* is used for making furniture, railway sleepers and as a construction material. The use of pine needles to produce essential oil is one of the other possibility for integral profit of pine forests (Iravani and Zolfaghari, 2014).

Properties of Pine Biomass

Table 1 depicts the properties of pine needle biomass. It has very low ash and high volatile contents that makes it a suitable material for thermo-chemical conversion. Being a ligno-cellulosic biomass, the major constituents of pine needles are lignin (29.15%) and cellulose (27.17%). The high amount of lignin content increases the compatibility and adhesion, and thus makes it suitable for high pressure briquetting and thermo-chemical conversion. The calorific value of pine needle is comparable to other agricultural waste biomass which makes it a viable source for energy production. The elemental analysis of pine needles indicates carbon and oxygen content as 44.99% and 48.55%, respectively, that are in line with other agricultural biomass.

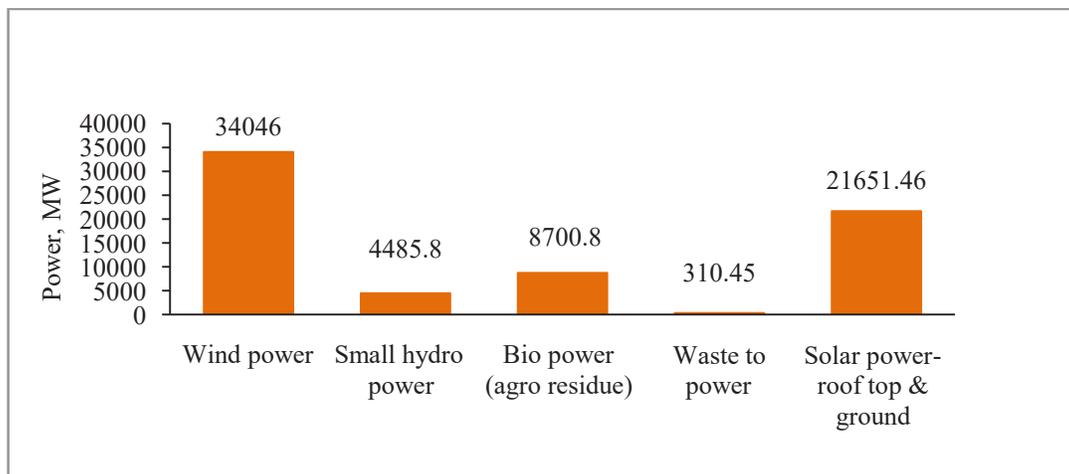


Fig. 1: Power from renewable energy sources in India (2019)

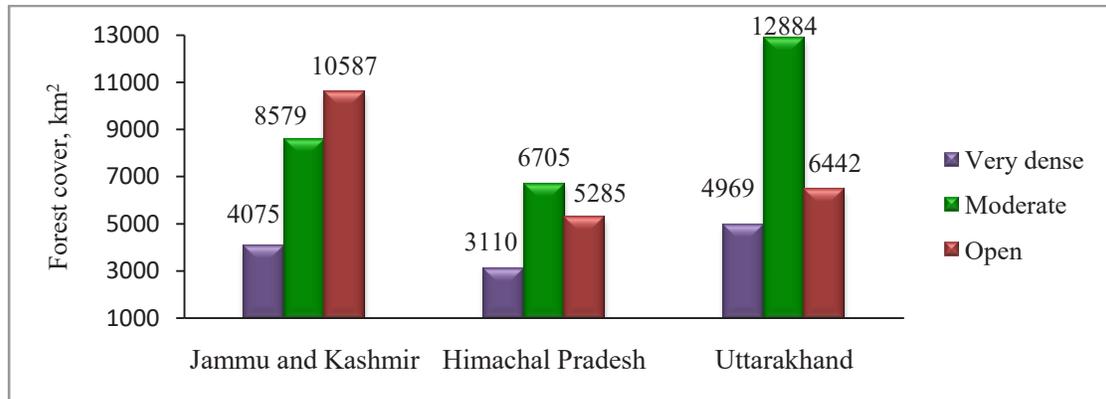


Fig. 2: Pine forest cover in Himalayan states of India

Various Energy Conversion Routes

There are several ways to convert lignocellulosic pine biomass into other forms of energy like steam, briquettes, pellets, biogas, producer gas, bio-oil, bio-char, hydrogen and ethanol. Figure 3 shows the possible energy harnessing routes to derive energy from pine needles. Among the available technologies hydrogen and bio-oil production are still in laboratory scale. The other available routes are discussed here in terms of

energy consumption and energy efficiency. The energy equivalents suggested by De (2005) and Sharma *et al.* (2020), Table 2, were used to study energy consumption in various conversion processes. The energy inputs incurred in various unit operations were collected from available literature. Tables 3-6 and Fig. 4 show the energy inputs in various conversion processes, energy consumption, energy output, and energy conversion efficiency in different energy harnessing routes.

Table 1. Properties of pine biomass

Sl. No.	Property	Pine needle (Mandal <i>et al.</i> , 2018)	Pine wood (Hassan <i>et al.</i> , 2009)
1.	Water content, % (w.b.)	7.78	6.34
2.	Volatile matter, % (d.b.)	71.58	78.54
3.	Ash content, % (d.b.)	2.08	0.46
4.	Fixed carbon, % (d.b.)	26.34	14.66
5.	Extractives, % (d.b.)	17.45	-
6.	Cellulose, % (d.b.)	27.17	-
7.	Hemicellulose, % (d.b.)	24.15	68.1
8.	Lignin, % (d.b.)	29.15	27.7
Elemental analysis (weight, %)			
9.	C	44.99	51.30
10.	H	5.46	5.83
11.	N	0.99	0.07
12.	S	Not traceable	0.01
13.	O	48.55	35.99
14.	H/C	1.46	1.36
15.	O/C	0.81	0.52
16.	Empirical formula	$\text{CH}_{1.46}\text{N}_{0.02}\text{O}_{0.81}$	$\text{CH}_{1.36}\text{O}_{0.52}$
17.	HHV (MJ.kg ⁻¹)	17.67	18.6

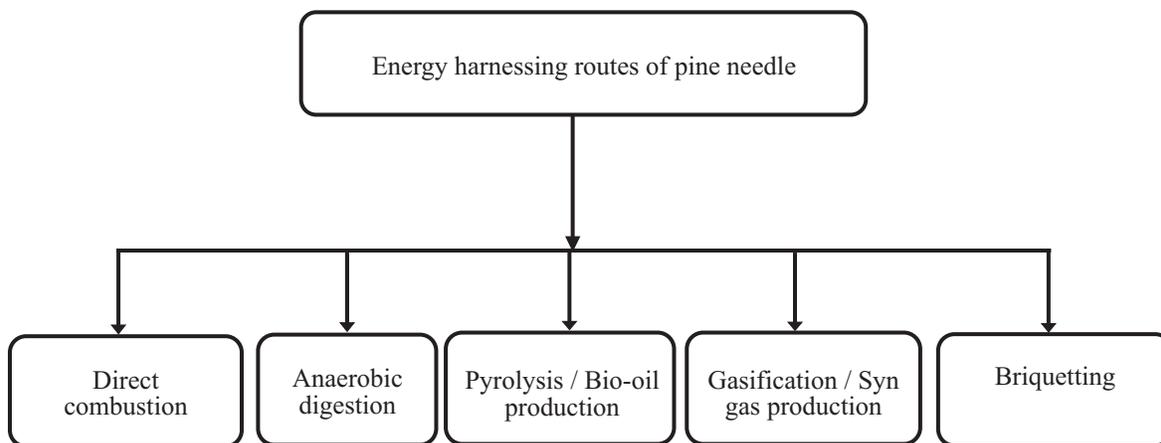


Fig. 3: Different energy harnessing routes for pine needle

Table 2. Energy equivalents used for conversion of energy inputs into energy

Sl. No.	Source	Unit	Energy equivalent, MJ
1.	Human	Man-h	1 adult man = 1.96 1 adult women = 0.8 adult man 1 child = 0.5 adult man
2.	Animal	Pair-h	10.10
3.	Diesel	L	56.31
4.	Electricity	kWh	16.93
5.	Machinery		
	Electric motors	kg	64.80
	Prime mover		68.40
	Farm machinery		62.10

Source: De (2005), Sharma et al. (2020)

Direct combustion

Pine needle has high calorific value and, therefore, is being utilized as a direct source of heat in the hilly region for domestic activities. Paddy straw run thermal power plants may also utilize this biomass as it has higher heat value compared to rice straw. The collection of pine needles is a labour intensive operation due to tough terrain. Kumain (2020) carried out a detailed study on collection methods of pine needle and assessed that it requires 10 man-h to collect 1 ton of pine needles from the forest, and is correspond to 19.6 MJ of energy. Transportation of same for a distance upto 20 km with a tractor trolley (2 tonne capacity) would consume 4.50 litres of diesel fuel and 4 man-h. For conveying, drying, elevating of bales and lighting of farm house, the requirement of man power, diesel, and electricity were assessed as 2 man-h, 6 litres and 12.8 kWh, respectively. Therefore, the total energy input to bring and store pine needles in the form of bales would be approximately 739.3 MJ.t⁻¹. Mandal et al. (2017) had

estimated total energy input of 900 MJ for generating steam through direct combustion of pine needle. It was further stated that by considering the calorific value of pine needle and thermal efficiency of a steam boiler as 25%, the direct combustion of pine needle would produce energy equivalent to 4400 MJ.t⁻¹.

Anaerobic process

Anaerobic digestion of lingo-cellulosic biomass is a promising technique to harness biomass energy. Anaerobic digestion of pine needle without any pretreatment resulted in lower biogas yield (Brown et al., 2012). Dighe (2011) reported that ground pine needle treated with 4 g urea per kg of pine needle mixed with cattle dung in a ratio of 1:6 produced 20 l of biogas in 35 days (HRT) when digested at 35°C controlled ambient temperature. During the process of bio-methanation of the substrate, the initial and final variation in pH was between 7.63 to 7.59, total alkalinity between 10.14 and 18.94 mg.l⁻¹, and C/N ratio

Table 3. Unit operations and forms of energy inputs in various energy conversion processes

Sl. No.	Conversion process	Unit operation	Energy Input
1.	Direct combustion	Collection	Human
		Transportation	Human, Fuel, Machinery
		Conveying, Drying, Elevating, Lighting	Human, Fuel, Electricity, Machinery
		Combustion	Human, Electricity
2.	Anaerobic process	Collection	Human
		Transportation	Human, Fuel, Machinery
		Elevating, Lighting	Human, Fuel, Electricity, Machinery
		Chopping	Human, Electricity, Machinery
		Mixing	Human
3.	Bio-oil production	Digester feeding and Fermentation	Human, Electricity
		Collection	Human
		Transportation	Human, Fuel, Machinery
		Conveying, Drying, Elevating, Lighting	Human, Fuel, Electricity, Machinery
		Chopping	Human, Electricity, Machinery
4.	Gasification	Pyrolysis	Human, Electricity, Fuel, Machinery
		Collection	Human
		Transportation	Human, Fuel, Machinery
		Conveying, Drying, Elevating, Lighting	Human, Fuel, Electricity, Machinery
		Chopping	Human, Electricity, Machinery
5.	Briquetting	Gasification	Human, Electricity, Machinery
		Collection	Human
		Transportation	Human, Fuel, Machinery
		Conveying, Drying, Elevating, Lighting	Human, Fuel, Electricity, Machinery
		Chopping	Human Energy, Electricity, Machinery
		Grinding	Human Energy, Electricity, Machinery
		Briquetting	Human, Electricity, Machinery

between 33.71 and 20.64. The reduction in cellulose content was also observed from 18.51% to 13.54% whereas hemicellulose decreased from 13.31% to 8.86 per cent. Dwivedi *et al.* (2016) carried out a study to enhance the biodegradability and biomethanation potential of treated pine needle (*Pinus roxburghii*) by using *Trichoderma* spp. and *Pseudomonas* spp. The study indicated that bio-pretreated substrate produced a cumulative biomethane yield of 21.3 l.kg⁻¹ of pine needle, and was 285% higher as compared to the untreated pine needle substrate (5.53 l.kg⁻¹). Keeping the other operations like collection and transportation of pine needle same, anaerobic digestion additionally requires feeding of chopped pine needle to the digester.

The process requires lot of manual hands, which may result in higher cost but lesser energy requirement. Digesters also need to be kept warm during winter to achieve mesophilic temperature range in which methanogenic bacteria are most active resulting in higher gas production. Pine needle is a woody biomass, and long needles can clog the digester causing less flow, or no flow, of slurry out of it which ultimately stops production of gas. For chopping and feeding the pine biomass, manual and electrical input energy was found to be 35.28 and 57.6 MJ.t⁻¹, respectively. Hot water is necessary for heating the digesters and therefore, the energy needed for this was approximately 900 MJ, which may be supplied by burning pine needles

Table 4. Energy output from different conversion routes of pine needles

Sl. No.	Conversion route	Process condition	Product	Output/t of pine needle	Energy in unit product	Total energy output, MJ
1.	Direct combustion	Direct burning inside furnaces with ample supply of air to generate steam	Steam	640 kg	3.33 MJ.kg ⁻¹	2131.2
2.	Anaerobic digestion	Digestion of pine needle inside an anaerobic digester in absence of air and production of methane enriched biogas	Biogas	213 Nm ³	20 MJ.Nm ⁻³	4260.0
3.	Pyrolysis	Conversion of pine needle into bio-oil, syngas and biochar using fast pyrolysis	Bio oil, syngas and biochar	250 kg	28.52 MJ.kg ⁻¹	7130.0
4.	Gasification	Conversion of pine needle using single stage or double stage gasifier and production of producer gas and char.	Producer gas enriched by CO,CH ₄ and H ₂	1840 Nm ⁻³	4.24 MJ.Nm ⁻³	7801.6
5.	Briquette production	Densification of smashed pine needles using piston mould at 85 kg.cm ⁻² pressure and 150 °C temperature or production of briquettes using pine needle biochar mixed with suitable binder	Briquette	950 kg	17.6 MJ.kg ⁻¹	16720.0

(Yadvika *et al.*, 2004). Therefore, total energy input in biogas production was estimated as 1654.3 MJ.t¹. Bio-gas production has a conversion efficiency of about 40% when only bio-gas energy is considered. This route gives clean energy with least pollution and manure as by-product. However, this process has practical limitation of digester feeding and decanting besides requirement of specially designed digester. High acid accumulation during digestion process is another reported problem. Anaerobic digestion for biogas production has been found to be environment-friendly. Although man-power was negligible in terms of energy value, it might be significant in terms of cost. Mahajan *et al.* (2017) studied the effect of different biochemical treatments on the anaerobic digestion of pine needles to utilize the biomass in sustainable way and reported that the most efficient method of pre-treatment of pine needle was the physico-chemical treatment following the procedure of milling, followed by steam treatment of biomass and acid–base–acid hydrolysis of pine needle. The treatment resulted in an increment of 65.92% in holocellulose content and a decrease of lignin content of about 21.34% in comparison of untreated biomass. The effect of pre-treatments on anaerobic

digestion using digested sludge as inoculum was also evaluated through biochemical methane generation. The mechanically ground pine needles produced 5.53 ± 0.11 mm of CH₄/g VS_{in} in 40 days during the digestion of pre-treated pine biomass. This methane production was 40.7% higher than anaerobic digestion of raw pine needle. It has also been established that 2.04 kWh of electricity can be produced by using 1 m³ of biogas (35% efficacy), which is equivalent to 21 MJ of energy (Murphy *et al.*, 2004).

Pyrolysis process

Bio-oil production through pyrolysis process of pine needle is also a promising approach to utilize pine needle as an energy source. This developed bio-oil can be utilized as an engine fuel or as a furnace fuel. Pyrolysis process is the thermal degradation of biomass in the absence of oxygen, which results in the production of charcoal, liquid, and gaseous products (Sipra *et al.*, 2018). The process is normally conducted in a closed container in the presence of inert gas. The volatiles produced during the process are partly condensed to produce a liquid fraction called ‘bio-oil’ or ‘pyrolysis-oil’. It is a complex mixture of

Table 5. Forms of energy input per tonne in conversion of pine needle through different routes

Sl. No.	Operation	Human, Man.h	Electricity, kW.h	Diesel, l	Input heat, MJ
1.	Direct combustion				
	Collection	10	0	0	0
	Transportation	8	0	4.5	0
	Conveying, Drying, elevating, lighting	2	12.8	6	0
	Combustion	1	16.9	0	0
	Total	21	29.7	10.5	0
2.	Anaerobic digestion				
	Collection	10	0	0	0
	Transportation	8	0	4.5	0
	Elevating, lighting	2	5	6	0
	Chopping	6	10	0	0
	Mixing	2	0	0	0
	Digester feeding and fermentation*	12	6	0	900
	Total	40	21	10.5	900
3.	Pyrolysis and Bio oil production				
	Collection	10	0	0	0
	Transportation	8	0	4.5	0
	Conveying, Drying, Elevating, Lighting	2	12.8	6	0
	Chopping	6	10	0	0
	Pyrolysis	12	363.9	0	0
	Total	38	386.7	10.5	0
4.	Gasification				
	Collection	10	0	0	0
	Transportation	8	0	4.5	0
	Conveying, Drying, Elevating, Lighting	2	12.8	12.8	0
	Chopping	6	10	0	0
	Gasification	1	16.9	0	0
	Total	27	39.7	17.3	0
5.	Briquetting				
	Collection	10	0	0	0
	Transportation	8	0	4.5	0
	Conveying, Drying, Elevating, Lighting	2	12.8	12.8	0
	Chopping	6	10	0	0
	Grinding	1	19	0	0
	Briquetting	2	52.5	0	0
	Total	29	94.3	17.3	0

*Electric heating of digester in hilly areas

numerous organic compounds with high calorific value, high density, viscosity, low acidity, and smoky odour. Mandal *et al.* (2018) reported pine needle as a good biomass to be converted into bio-oil (27.6%), biochar (31.2%), and producer gas (28%). The pyrolysis process additionally requires 363.9 kWh electricity to run the pyrolysis reactor for 1 ton of biomass. Thus, pyrolysis process requires 2,057.9 MJ.t⁻¹ of energy to convert pine needle into bio-oil with energy conversion efficiency of 52 per cent. There are several studies

which demonstrated successful utilization of pine needle as an energy source using pyrolysis process. Font *et al.* (2009) investigated the kinetics of pyrolysis process and combustion behaviour of pine needle and pine cone. It was also reported that the different fraction of pine biomass such as cellulose, hemicellulose and lignin decompose at different temperature regime. In the first stage, the moisture of pine needles evaporate. After the evaporation of volatiles in the first stage, a second fraction decomposes at 470–600 °K that

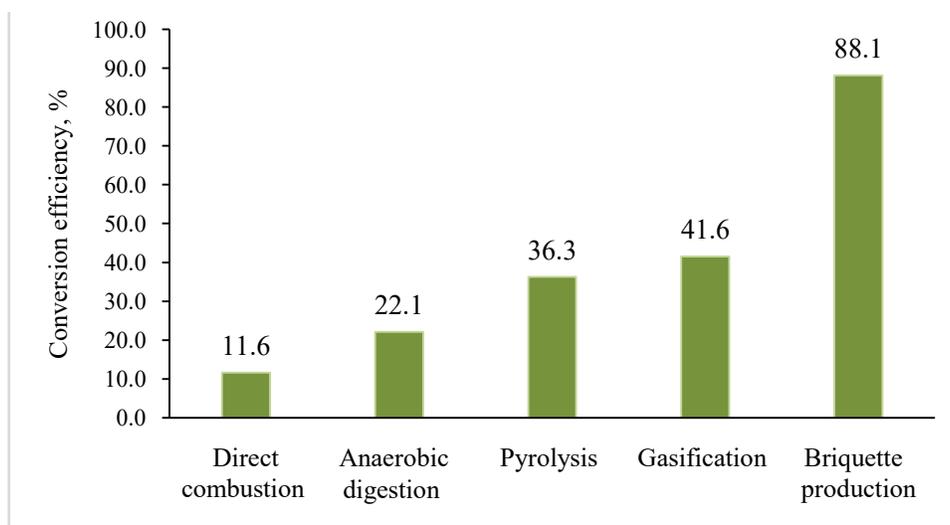


Fig. 4: Conversion efficiency of different energy conversion routes

Table 6. Total energy input (MJ.t^{-1}) for conversion of pine needles through different routes

Sl. No.	Conversion route	Human energy	Electricity	Diesel	Heat	Total
1.	Direct combustion	41.2	106.9	591.3	0	739.3
2.	Anaerobic digestion	78.4	75.6	591.3	900	1645.3
3.	Pyrolysis	74.5	1392.1	591.3	0	2057.9
4.	Gasification	52.9	142.9	974.2	0	1170.0
5.	Briquetting	56.8	339.5	974.2	0	1370.5

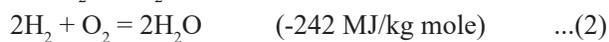
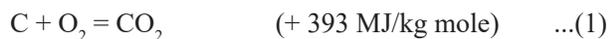
are corresponding to primarily hemicellulose. The decomposition of hemicellulose requires activation energy of about $130\text{--}140 \text{ kJ.mol}^{-1}$. In the third stage, cellulose decomposes in the range of $550\text{--}700 \text{ }^\circ\text{K}$ with activation energy requirement of about $200\text{--}240 \text{ kJ.mol}^{-1}$. There was a fourth fraction that decomposed in a wide temperature interval ($550\text{--}800 \text{ }^\circ\text{K}$), with apparent activation energy requirement of around $190\text{--}200 \text{ kJ.mol}^{-1}$ that corresponds mainly to lignin. The study defined the temperature regime for the pyrolysis of pine needle. Varma and Mondal (2018) carried out pyrolysis of pine needle in a semi-batch reactor and reported that up to 43.76% bio-oil yield can be obtained at pyrolysis temperature of $550 \text{ }^\circ\text{C}$ with a heating rate of $50 \text{ }^\circ\text{C.min}^{-1}$. Although, there is a potential of bio-oil produced from pine needle to be utilized as an engine fuel, yet due to high viscosity and high carbon content, there is a need to upgrade the pyrolysis mechanism by using a suitable catalyst. Kumari and Mohanti (2020) upgraded the pyrolysis process of pine needle using H-ZSM5 and reported that zeolite HZSM-5 catalyst enhanced the yield of aromatic hydrocarbon compounds and reduces the oxygenated compounds as compared to non-catalytic pyrolysis

bio-oil. It was also established that catalytic bio-oil produced more diesel and gasoline range compounds in comparison to non-catalytic bio-oil. Apart from the liquid fuels, pyrolysis of biomass also produces solid fuel (bio-char) and gaseous fuel (syn gas), which also have their own fuel characteristics. The bio-char can be used for the treatment of water as well as soil due to its unique porous morphology. The porosity of the char can be improved by using several activation methods (Masek *et al.*, 2019; Kamali *et al.*, 2019; Siipola *et al.*, 2020). In addition, gaseous fuels can be utilized as chemicals and fuels (Song *et al.*, 2018; Ding *et al.*, 2019).

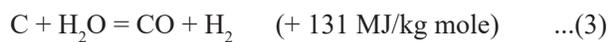
Gasification process

While pyrolysis process is mainly performed to convert biomass into solid, liquid and gaseous fuels in the absence of oxygen, the objective of gasification is to develop syn gases having high heating value in the limiting supply of oxygen (Arena, 2012). Biomass gasification is a promising bioenergy technique to turn raw low-value lignocellulose biomass into a high-value fuel gas, particularly for power generation (Caballero *et al.*, 2000; Bridgwater, 2003). Gasification or thermo-

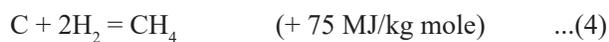
chemical conversion of pine needle in a gasifier leads to the generation of gas generally termed as synthetic gas or syn-gas containing CO, H₂ and CH₄ which are combustible with other incombustible gases including CO₂ and N₂ (Bharti and Awasthi, 2011). This process is defined as a thermo-chemical process limited to partial combustion and pyrolysis, which unlike the full combustion uses air/fuel ratios noticeably below the stoichiometric value (Warnecke, 2000; Martínez *et al.*, 2012). The chemical reactions for this process are shown below (Higman and Van der Burgt, 2003; Dutta *et al.*, 2014).



Water Gas reaction



Methanation reaction



Biomass gasification technology is a matured technology that can produce energy in a sustainable manner (Pereira *et al.*, 2009). Bio-gasification systems can ensure constant, long-term, stable power generation (Buragohain *et al.*, 2010). Pine needle can also be used for electricity generation predominantly in the rich regions of pine forest. Pine needle is a potential biomass for gasification, which has comparable characteristics to some of the popular gasification materials. The calorific value of the pine needle is 17.67 MJ.kg⁻¹, and is comparable to wood, the most common energy source for gasifier. However, it has lower bulk density as compare to wood and coal. This may render it unsuitable for gasifier unless densified similar to other low-density feedstock such as agricultural wastes and loose biomass (Sharma, 2006). Pine needle can be fed to gasifiers as whole bale or by chopping it to small pieces. For gasification alone, an additional need of 16.9 kW.h.t⁻¹ electrical energy was observed. Gasification of pine needle was found to be a good alternative with a conversion efficiency of 52%, but is associated with problems of high ash deposition. Mandal *et al.* (2018) optimized the gasification process of pine needles in an updraft gasifier and concluded that this feedstock can be used in an updraft gasifier to generate producer gas with calorific value of 4.24 MJ. Nm⁻³. It took 12 min to produce flammable gas. The gas from the gasifier can be burnt using specially designed burners in furnaces.

Pine needle briquetting

Pelleting and briquetting are being practiced in many countries for several years. Biomass briquetting process is a promising technique for converting waste biomass into energy (Sotannde *et al.*, 2009; Bhosale *et al.*, 2020). The conversion of biomass into useful energy is an acceptable method as it requires low capital investments (Kumar and Pranav, 2018). Conventional processes for biomass densification can be classified as baling, pelletizing, extrusion, and briquetting with the application of a baler, pelletizer, screw press, piston or roller press. Figure 5 provides the flow chart for conversion of pine needle biomass into briquette as product.

The second technique is densification of carbonized biomass with the help of suitable binder. Mandal *et al.* (2018) prepared pine needle briquettes using high pressure briquetting machine, and established that the pine needle particle size less than 2 mm, pressure of 9 MPa, and temperature of 150°C was optimum for the production of briquettes, with densification pressure having the highest influence on quality of briquettes. The briquettes produced had calorific value of 17.56 MJ.kg⁻¹, density of 1,228 kg.m⁻³ and compressive strength of 7.05 MPa. Pandey and Dhakal (2013) determined the physico-chemical properties, combustion characteristics and emission tests of the pine needle briquettes prepared from pine char ground to dust by grinder mill mixed with clay in proportion of 80:20. The briquettes were made using a piston press mould and sun-dried for three to five days. There was no or little smoke after the initial burning of briquettes, and thus suitable as a cooking fuel and space heating in the hilly regions. Furthermore, particulate matter emission from briquettes was 0.570 mg.m⁻³ that was below the guideline set by the Environment Protection Agency (EPA). The briquetting process additionally requires 52.5 kWh electricity and 2 man-h for briquette production. Therefore, the total energy consumption in briquette production is 1,370.5 MJ.t⁻¹. The energy consumption efficiency of briquettes is reported as 90 per cent. On the other hand, briquettes from pine needle biochar can be formed by using a suitable binder. Sharma *et al.* (2020) produced biochar beehive blocks using binding agents such as soil, cattle dung, cement, and lime in 30%, 40%, and 50% weight proportions. The study reported maximum calorific value was obtained for briquettes formed by biochar with soil as a binder in 70:30 ratio.



Fig. 5: Process diagram of conversion of pine needle into briquette

CONCLUSIONS

The energy efficiency for conversion of pine needle into energy source via different routes is discussed. Briquetting and gasification were promising processes as these routes have 88.1 and 41.6 % energy conversion efficiency, respectively. Briquetting is a good alternative when storability is concerned as it occupies very little space. Conversion of pine needle via pyrolysis route has 36.3% conversion efficiency. However, it may reduce the dependency on fossil fuels for IC engine application. Anaerobic digestion, as far as environmental issues are concerned, is also a sustainable route for energy production from pine needles having conversion efficiency of 22.1 per cent. The produced biogas will meet out the domestic need of the rural people in hilly region in Uttarakhand resulting into lower dependency on forest resources and LPG. A detailed site-specific field experiment may give a better insight of the specific energy-efficient process for the location. The indirect energy expenditure in terms of machinery and material involved in the process should also be included in future studies.

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