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Deriving fuel from pine needles through pyrolysis, charring and briquetting and their GHG emission potential

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The present communication presents an overview of generating renewable fuels from pine needles through pyrolysis and briquetting technology. Pine needles are the products of leaf shedding in the forests from pine trees and are considered potential fire hazards. Studies conducted in the last few years show that this biomass can be effectively utilized for the production of bio-oil, biochar and briquettes in an environment-friendly manner. Through pyrolysis, pine needles could be converted to 35% bio-oil with a calorific value of 28.52 MJ kg^{-1}, which can be a base material for other fuels and chemicals. The process also yields 25% biochar, which has a half-life of 600–1000 years and is a suitable material for soil carbon sequestration. The proposed pine needle-based energy centre can produce about 3.8 t briquettes, 1.2 t bio-oil, 1.6 t biochar and 1240 Nm^3 pyrolysis gas from 10 t pine needles, with an energy efficiency of 87.2%. Greenhouse gas emissions were found to be considerably lower for charring and pyrolysis routes compared to forest burning.

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Keywords: Briquettes, charring, greenhouse gas emission, pine needles, pyrolysis.

FASTER reduction of conventional energy sources and an increase in their demand have led to the formation of renewable energy centres for the utilization of renewable resources of power, such as solar, biomass, wind and hydro. In the renewable sector, biomass is considered one of the most important renewable sources as it is abundantly available. It is the bioresidue generated by the plant kingdom like forests and agriculture, agro-based or food industries[1]. Biomass can be converted to energy through biochemical processes like bio-methanation, fermentation and trans-esterification, thermochemical processes such as gasification, pyrolysis and torrefaction; and mechanical routes like briquetting and pelleting[2].

Pyrolysis is a thermochemical process in which biomass is converted to solid (biochar), liquid (bio-oil) and gaseous fuels by thermally treating biomass in a closed system at 500°C in the absence of air. With advanced flash pyrolysis processes, bio-oil recovery of up to 80% is possible. The bio-oil can be upgraded to engine and furnace fuel, valuable chemicals and bio-pitch[3]. Processes like catalytic cracking, deoxyhydrogenation, fermentation and hydrogenation are employed for upgrading bio-oils[4]. Biochar, having a calorific value of about 30 MJ/kg, is a good industrial fuel as a replacement for coal and also a better domestic fuel. It has high porosity, carbon content and recalcitrance which make it a suitable material for soil reclamation and soil carbon sequestration[5].

Briquetting refers to the densification of lignocellulosic biomaterials to produce uniformly shaped blocks of higher density. Due to densification, the volumetric calorific value of briquettes is much higher than that of biomass. Also, the cost of transportation and storage space is significantly lower compared to raw biomass. The bulk density of loose biomass changes from 40–200 to 600–1200 kg m^{-3}. Briquettes are preferred in brick kilns, boiler-based industries and community cooking applications due to their uniform shape, size, high density and higher fuel properties[6].

Pine needles are the products of leaf shedding in the forests from pine trees and are considered potential fire hazards. In the summer season, about 6.3 t of waste biomass is generated per hectare of pine forest due to regular leaf shedding by pine trees. The thick layer of pine needles reduces water percolation, blocks sunlight from reaching the ground, stops the growth of grasses, and causes disastrous forest fires. Pine needles are not decomposed easily by microbes[7]. However, being a lignocellulosic biomass, pine needles contain about 29% lignin, 27% cellulose and 24% hemicellulose, which proves their suitability as a good biomass source for thermochemical and biochemical conversion. Through thermochemical processes, pine needles can be transformed into biochar, bio-oil and producer gas, which have a higher energy density than pine needles and can be stored for a longer duration[3].

Therefore, deriving fuels from pine needles would be a viable solution for the utilization of this waste biomass as a source of energy as well as to reduce forest fires, which damage huge amounts of natural resources. In this study, we have analysed the technical viability and greenhouse gas (GHG) emission potential of pine needle-based energy centre. This centre will be a one-stop solution for converting pine needles to various forms of energy, such as biochar and briquettes in solid form, bio-oil as liquid fuel and pyrolysis gas as gaseous fuel.

Table 1 presents the properties of pine needle biomass. The table shows that pine needles have high volatile matter and low ash content, which proves their suitability for pyrolysis and gasification. As the initial moisture content is high, it should be sun-dried before pyrolysis. The moisture content was reduced after sun-drying and found suitable for pyrolysis. Carbon, hydrogen and oxygen contents were at par with other agricultural and forest biomasses. From elemental analysis, the empirical chemical formula of pine needle biomass was determined as $CH_{1.46}N_{0.02}O_{0.81}$, which is typical for the biomass. Calorific value of pine needles was found to be higher than that of agricultural waste biomass[3]. The availability of pine needles in the Bhowali region in Uttarakhand, India, was found to be 3.9 t/ha.

Pyrolysis of pine needles was carried out in batch and screw pyrolyzers. The batch-type pyrolyzer was made of a stainless steel pipe with a 100 mm internal diameter and 400 mm length. It was electrically heated from the outside. Pine needles were ground to 1.0 mm size, followed by drying. In each experimental run, a 200 g sample was put inside the pyrolyzer. Temperature inside the reactor was recorded using a K-type thermocouple. Before every run, carbon dioxide was purged into the reactor to remove any air inside it. Thereafter, a flow rate of 3 l min^{-1} was maintained during the experiments. The pyrolysis vapour was condensed in a tube–tube heat exchanger using chilled water at 5°C as the cooling medium. The condensate was dissolved in dichloromethane. The organic phase of bio-oil dissolved in dichloromethane and formed two layers due to the difference in density. The organic layer was separated using a separating funnel and filtered. Dichloromethane from the bio-oil was separated by a rotary vacuum evaporator at 40°C. The residual black liquid that remained in the evaporator was considered as bio-oil. When the reactor temperature reached near ambient, char was decanted and weighed. The balance mass was considered as the product gas yield. Figure 1 shows the product distribution of batch pyrolysis of pine needles. At an average temperature of 500°C, 35% bio-oil, 25% char and 22% gas could be produced.

The continuous pyrolysis experiments were conducted in an augur reactor. The effective heating length of the reactor was 800 mm and the internal diameter was 44 mm. It was also externally heated by a pair of electric heating elements. The temperature was controlled by a PID controller and recorded using a K-type thermocouple. Feeding was controlled by a motor driven by a variable frequency

Table 1. Properties of pine needles biomass, biochar and bio-oil

Property	Pine needles	Biochar	Bio-oil
Appearance	Light brown	Black	Dark brownish
Density (15°C; kg m^{-3})	80–120	120–150	1105
Water content (% wb)	7.78	4.84	2.8
Volatile matter (% db)	71.58	37.09	–
Ash content (% db)	2.08	7.64	–
Fixed carbon (% db)	26.34	55.27	–
Extractives (% db)	17.45	–	–
Cellulose (% db)	27.17	–	–
Hemicellulose (% db)	24.15	–	–
Lignin (% db)	29.15	–	–
Elemental analysis (wt %)			
C	44.99	69.54	69.44
H	5.46	4.24	7.82
N	0.99	1.38	1.44
O	48.55	24.84	21.31
H/C	1.46	0.73	1.35
O/C	0.81	0.27	0.23
Empirical formula	$CH_{1.46}N_{0.02}O_{0.81}$	$CH_{0.73}N_{0.017}O_{0.27}$	$CH_{1.35}N_{0.017}O_{0.23}$
Empirical molar mass	26.7		
HHV (MJ kg^{-1})	17.67	28.62	28.57
pH	–	8.48	4.60
Pour point (°C)	–	–	(–)2
Cloud point (°C)	–	–	Not visible
Flash point (°C)	–	–	63
Fire point (°C)	–	–	68
Kinematic viscosity (cSt)	–	–	7.84
C residue (%)	–	–	16.13

Source: Mandal *et al.*[3].

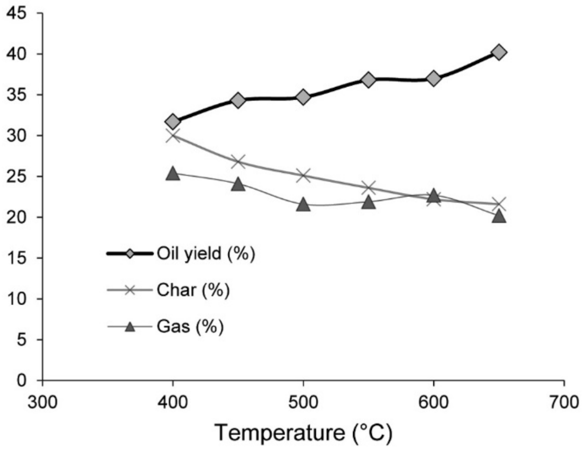

Figure 1. Product distribution from batch pyrolysis of pine needles.

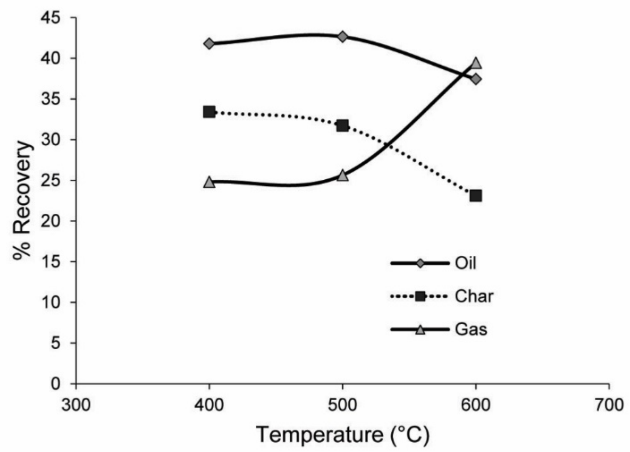

Figure 2. Product distribution from continuous pyrolysis of pine needles.

drive. The reactor ended in a vertically downward section through which char was decanted. The char outlet was closed with two separate ball valves to stop air from entering the reactor. The pyrolysis vapour, along with sweep gas (N_2), travelled upward to the condensing unit, where chilled water was used as the cooling medium. After the condensing unit, the gas was passed through four gas scrubbers filled with isopropanol maintained at 32°C. The gas was further passed through two gas scrubbers filled with glass balls and maintained at –20°C to trap lighter hydrocarbons. This experiment was also carried out at three different temperatures. Figure 2 depicts the product yield. A temperature of 500°C was found to be optimal for maximum bio-oil recovery in the screw pyrolyzer.

Table 1 shows the characteristic properties of bio-oil derived from pine needles. The colour of bio-oil was dark brownish to black. Its density was higher than that of water at 15°C. The pH of pine needle bio-oil was 4.6, which was similar to bio-oils from other lignocellulosic biomasses. The flash point, fire point and pour point values of bio-oil

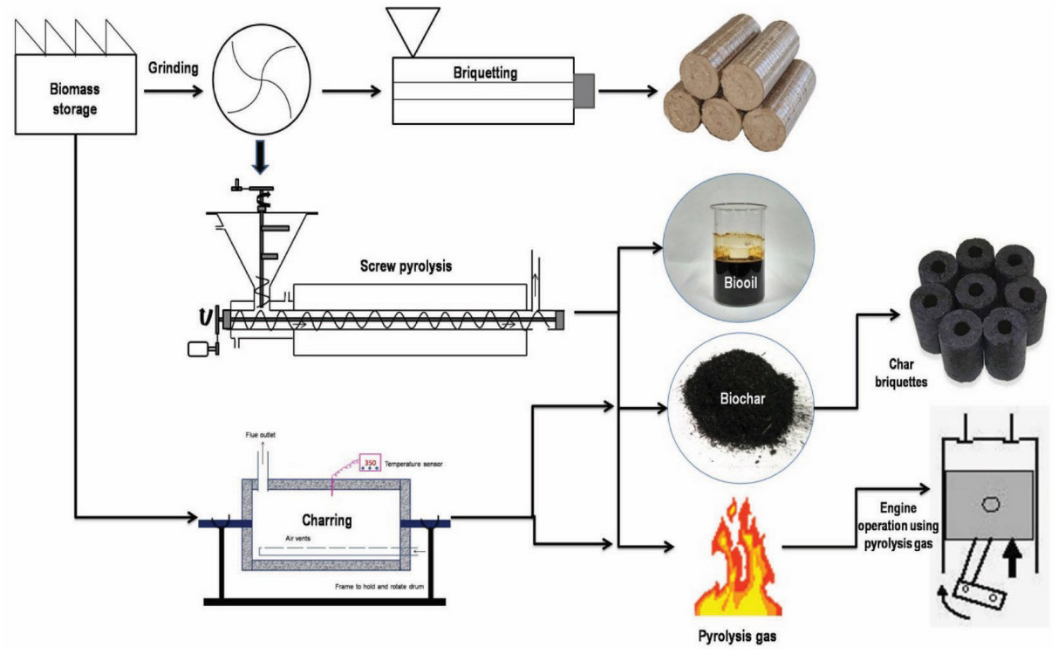

Figure 3. Schematic of the proposed Energy Centre.

were higher than those of high-speed diesel. Kinematic viscosity of pine needle bio-oil was found to be similar to diesel and suitable for the injection system of compression injection engines. Its calorific value was 28.52 MJ kg^{-1}, which was less than the calorific value of high-speed diesel but much higher than pine needles. The elemental analysis of pine needle bio-oil indicated that its oxygen content decreased after pyrolysis when compared with its parent biomass. Low oxygen content in the bio-oil is favourable for the production of transportation fuel. Some of the fuel properties of pine needle bio-oil were favourable for burning in furnaces and after blending with lighter fuels (ethanol, butanol), it could be used in internal combustion engines. GCMS analysis showed about 63 different chemicals in pine needle bio-oil. Therefore, it can be upgraded to higher quality fuels and chemicals through deoxyhydrogenation, emulsification and esterification[8].

Premium-quality biochar could be obtained from pine needles (Table 1). Moisture and volatile matter content of pine needle biochar were low. Carbon content and calorific values improved significantly compared to raw pine needles. The pH of pine needle biochar was in the alkaline range, which makes it a suitable amendment for acidic soils. The carbon content was also significantly higher in pine needle biochar, and so it can be recommended for soil carbon sequestration[5,9]. The oxygen/carbon ratio was 0.27, indicating a half-life of 600–1000 years according to Van-Krevelen plot[10]. Considering it is a stable form of carbon source, pine needle char can be a good material for use as a soil amendment.

Utilization of pine needles through a thermochemical route requires a pyrolysis set-up. This should be a continuous type of plant in which the following categories of pyrolysis reactors are included: (i) fluidized bed reactor and (ii) screw or auger reactor.

A fluidized bed reactor requires about 400 LPM/kg inert gas as the fluidizing medium[11]. In comparison, a screw or auger reactor requires less inert gas and can handle larger biomass particles with a reasonably good yield of bio-oil. The size of the plant should be based on the shortest payback period in terms of economy and energy. We considered a 500 kg/h screw pyrolysis plant for analysis. Figure 3 is a schematic of the proposed energy centre. Pine needles after collection should be baled and stored for a short period. The bales are then crushed to a suitable size for briquetting and pyrolysis units. Briquetting can be done directly without any binder, as pine needles contain higher amounts of lignin. In this process, the loss is negligible and the end-product is directly marketable. In the pyrolysis route, 30% bio-oil, 25% biochar and 25% gas are produced. Bio-oil can be used as furnace fuel or upgraded to transportation fuel. It also has the potential to be a substrate for valuable chemical extractions such as phenols, cyclopentens, ethyl-guaiacol, creosol, furans and ethanones. Thus, it has good commercial value. Pyrolysis gas is rich in H_2, CO and CH_4, and can be used to generate in-house power through internal combustion engines. It is also used for heating the pyrolysis reactor to reduce the requirement for electrical energy. On charring routes, we get biochar and product gas. Biochar can be used to produce briquettes and also as a soil amendment, which will also fetch good commercial value.

Total energy requirement for the collection, transportation and baling of pine needles was 1417 MJ, of which diesel was the major component. On continuous operation

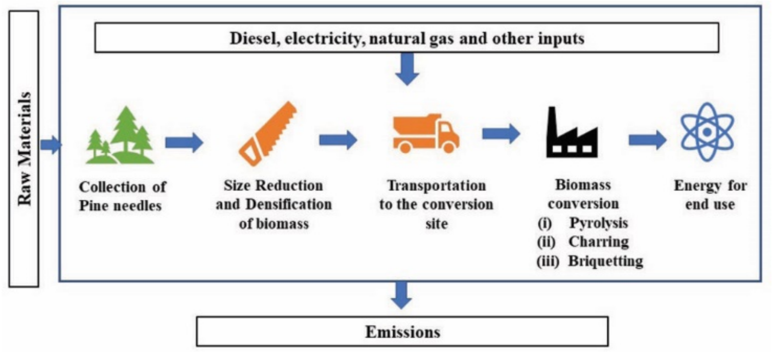

Figure 4. System boundary for greenhouse gas emission analysis.

Table 2. Input/output scenario of energy centre of 10 t/day biomass handling capacity

Energy input	Value (MJ)
Biomass	176,700
Collection	98
Transportation	39
Baling (man-h + fuel)	1,280
Briquetting	1,325
Pyrolysis	1,910
Charring	456
Total input	181,808
Energy output from 10 t biomass	
Briquettes (3.8 t)	72,200
Bio-oil (1200 kg)	34,284
Biochar (1600 kg)	45,792
Pyrolysis gas (1240 Nm^3)	6,200
Total output	158,476
Energy efficiency	87.2%

Table 3. Greenhouse gas (GHG) emission statistics of different inputs used

Input	GHG intensity ($t\ CO_2$-eq/unit)	Reference
Diesel (t)	4.5 E-01	13
Electricity (kWh)	6.89 E-04	13
Gasoline (t)	4.28 E-01	14
Loader truck (t)	1.39 E+00	15
Machines (t)	1.39 E+00	13

of 8 h in a day, the total biomass requirement will be 10 t/day considering a briquetting plant capacity of 500 kg/h, pyrolysis plant capacity of 500 kg/h and a charring drum capacity of 2000 kg/day (20 drums for providing producer gas to the augur reactor). Table 2 presents the input/output scenario on a per-tonne basis. For briquetting, the major energy needed is electrical energy, which is required for grinding and briquetting. In pyrolysis, the major energy requirement is for heating the reactor from the outside, which can be done by the product gas itself. In the charring drum, the only electrical energy needed is to operate a 375 W blower motor. It can be seen from Table 2 that we can achieve an energy efficiency of 87.2%.

GHG emissions were calculated for the assessment of the environmental impact of the developed energy conversion plans (Figure 4). GHG emissions were estimated by following the ISO 14,040 standard guidelines. TRACI, version 3 was used to predict GHG emission and global warming potential for the pine needle-based energy centre[12]. Table 3 describes the GHG conversion statistics used in this study for different inputs. This study is based on only GHG emissions from the pyrolysis of pine needles. Therefore, we did not consider GHG emissions from the construction work required for biomass storage and setting up the plant. We also assumed that the transport of raw pine needles from the hills to the plant was carried out by road using a

Table 4. GHG (CO_2) emission of the proposed energy centre due to different operations

Conversion route	Biomass collection and transport	Bio-oil/briquettes conversion process	Total
Bio-oil route	2.15E-03	73.03 E-03	75.18 E-03
Briquetting route	2.15E-03	50.71 E-03	52.86 E-03
Charring route	2.15E-03	0	2.15 E-03

diesel vehicle, with an average travel distance of 40 km on the basis of a survey conducted in the Bhowali region of Uttarakhand. The diesel consumption/t/km was assumed to be 0.050 l (ref. 13). The GHG emission intensity for diesel fuel was 0.450 t CO_2-eq. per tonne of diesel fuel. Thus, the GHG emission for transportation purposes was calculated to be 1.4E-03 t CO_2-eq. Similarly, for the bailing of 1 t pine needles, we require 2 litres of diesel fuel which produces 0.75E-03 t CO_2-eq. The briquetting of 1 t pine needles requires 265 MJ (73.6 kWh) electricity, which is equivalent to 50.71 E-03 t CO_2-eq. On the other hand, the pyrolysis of 1 t pine needles requires 106 kWh of electricity. Thus, total GHG emissions from the pyrolysis process are calculated as 73.03 E-03 t CO_2-eq. If we compare these conversion routes, the biochar route produces the lowest GHG emissions. In addition, soil carbon sequestration has been found to reduce GHG emissions by 1.8 Pg CO_2-eq. annually[14]. Table 4 shows the total GHG emissions of different pathways for the conversion of pine needles into energy. If we consider GHG emissions from the burning of raw pine needles in the forests on the basis of the biomass empirical formula and molar mass, it will produce 164.79 t CO_2-eq. per tonne of biomass, along with severe damage to flora and fauna[16]. Therefore, it can be concluded that the proposed energy centre is not only energy-efficient but can also successfully mitigate global climate change.

Pine needle-based energy centre is a viable solution for the utilization of pine needles as an energy source as well as to reduce forest fires. Analysis carried out in this study shows that energy efficiency of 87.2% can be achieved in the energy centre by combining three conversion technologies, viz. briquetting, charring and pyrolysis. Among the three routes of conversion, CO_2 emissions were at their lowest in the charring route.

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