Characteristic properties of pine needle biochar blocks with distinctive binders

Hemant Kumar Sharma[1,*], Akanksha Kumain[2] and T. K. Bhattacharya[2]

[1]ICAR-Central Institute of Agricultural Engineering, Nabi Bagh, Bhopal 462 038, India
[2]G.B. Pant University of Agriculture and Technology, Pantnagar, U.S. Nagar 263 145, India

Biochar beehive blocks are an unpolluted renewable and sustainable source of energy. Pine needle is abundantly available in the form of biomass world over. In the present study biomass of pine needles was transformed into biochar using a biochar production machine. The biochar beehive blocks were produced with different binding agents, e.g. soil, cattle dung, cement and lime in 30%, 40% and 50% weight proportion. Block-making procedure increases the bulk density of loose biomass up to 30–100% with increase in calorific value, reduction in storage space requirement and transportation cost as compared to loose biomass. The developed biochar blocks were 12.7 cm in diameter, 8 cm in height and weighed 600 g. The average moisture, volatiles, ash and fixed carbon contents were 5%, 36%, 25% and 40% respectively. The results of the study showed that the maximum shatter resistance and water absorption resistance as 83% and 76% for B50C50 and B50L50 respectively, while the maximum calorific value was 29 MJ/kg for B70S30. Based on process optimization using RSM, a biochar block with a binding ratio of 40% proved to be optimal. The production cost of biochar blocks for soil or dung was ₹6.30/kg, while for cement or lime blocks it was ₹10.30/kg. The use of pine needle biomass reduces the hazard of bushfire and helps achieve effective self-employment by preventing rural farmers from migrating from the countryside.

Keywords: Biochar, beehive briquettes, binders, calorific value, pine needles.

IN 2011–12, India was the fourth leading consumer in the world of Crude Oil and Natural Gas, after the United States, China and Russia in 2011–12 (ref. 1). Currently, conventional commercial sources of energy, i.e. coal, oil, natural gas, hydro and nuclear power comprise 85–90% of the principal energy incorporation in the country. The renewable energy sources account for nearly 10% of the aggregate energy mandate in India. Biomass is considered as a renewable, sustainable and carbon-natural energy source[2,3]. Presently, several studies are being carried out to find the suitability of different biomass potential fuel sources on different routes[4,5].

Pine needle is the abundantly present biomass of pine forests world over. Pine (*Pinus roxburghii*) or chir pine forests are mainly found in the hilly regions and cover a large area in the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand in the Himalayan region of India. About 7.62 Mha land is under pine forest in the Himalayan expanse covering India, Nepal and Bhutan. The reserve pine forestry in Uttarakhand includes an area of about 0.343 M ha (ref. 6). In Uttarakhand alone, about 2.058 million metric tonne pine needle waste is available annually[7].

From April to May every year, pine needles, release a thick layer of dry leaves on the forestland, causing fires and delaying the growth of cattle-feed grass. Pine needles are difficult to integrate with forest waste because they cannot be used as animal feed; they do not decompose like other types of biomass. However, they can be a good source of biomass and environment-friendly renewable energy source. Various thermal conversion processes such as combustion, gasification, liquefaction, hydrogenation and pyrolysis can be used to transform biomass to different energy products[8,9]. Among various processes briquetting, gasification and pyrolysis are advantageous with an energy conversion efficiency of 88%, 52% and 74% respectively[10,11].

Biochar is a carbon-rich source of biomass (like wood, manure or plant waste), produced when the biomass is heated in a closed container in which less air available. The thermal performance of biochar is superior as its emissions are very low. Two types of blocks, viz. biomass and biochar blocks are a renewable and sustainable source of energy. Biomass blocks are mass-produced by densifying loose biomass in a block-making machine, however, charcoal blocks are formed from charcoal and binding agents. Block-making is a procedure of densification of slack biomass to expand its fuel-plus-handling characteristics. It increases the calorific value, and decreases transportation charge and storage space associated with raw biomass. By block production, bulk density of slack biomass can be augmented from 40–200 kg/m^3 to 600–1200 kg/m^3. Due to its unvarying size, high density and enhanced fuel characteristic properties, these blocks have been used in the industries and native cooking applications as renewable fuel. Block-making is also pursued as a substitute for the burning of forestry

*For correspondence. (e-mail: hemant.sharma2495@gmail.com)

and agricultural waste, thus decreasing environmental pollution and loss of carbon to the atmosphere[12].

Biochar block burns with a small flame and with less smoke. It is clean and more suitable for slow cooking. Biochar blocks cook with even heat and are long-lasting. They are also smokeless, odourless and sparkless. The block-making technique may help in generating employment in rural areas of developing countries. This technology is pollution-free and eco-friendly. Indirectly it is a way to utilize waste biomass energy available on the farm to generate electricity/thermal heat.

Materials and methods

To produce pine needle biochar blocks, a manually operated block-making machine designed and developed in the Research Workshop, Department of Farm Machinery and Power Engineering, College of Technology, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India was used (Figure 1). The ergonomically designed machine can produce four blocks simultaneously.

The height of the machine was 90 cm and the handle to compress the blocks was 150 cm long for mechanical advantage. The height of moulds was 17 cm and diameter was 12.7 cm. The diameter of the blocks produced in the machine was 12.7 cm and height of blocks was 8 cm. The number of holes in the blocks was seven, each of 1 cm diameter. The specifications of the blocks produced were according to those made using a manual mould with 21 spikes[13,14]. The cost of the manually operated block-making machine was ₹10000.00.

Pine needle biomass is the raw material used for making the blocks. Different blends of biomass and binders with water can be used. The raw materials were selected on the basis of local availability and feasibility for the average entrepreneur. The pine needles are sharp leaves occurring in the bunch, 20–35 cm long and are noticeably yellowish-brown in colour after drying. The initial moisture contents of the samples collected were in the range 23–26%. The biomass samples were then dried under direct sunlight for a duration of seven days. Thereafter, the average moisture content of the biomass sample was in the range 7.78–10%.

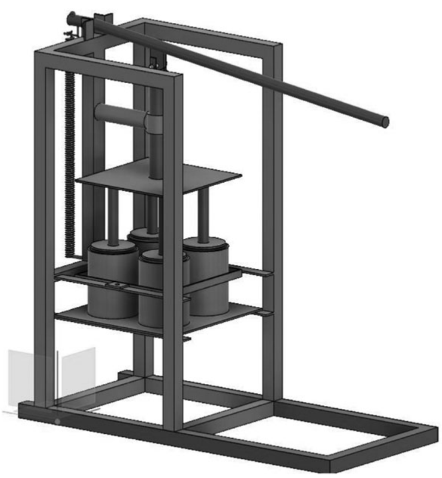

Figure 1. Manually operated block-making machine.

Biochar is as the high carbon content product obtained after biomass like wood, manure or plant waste is heated at moderately low temperatures (<700°C) in a closed container with little or no air[15]. The pine needles are converted into biochar in a production unit called biochar drum.

The block-making procedure requires additional binding material to hold the blocks together, block formation, storage and transportation. Binders play a significant role in the block production. Several types of binding materials has been used by different researchers such as organic binders, inorganic binders and compound binders. For the process of biochar block-making, four types of binding materials were used, viz. soil, cattle dung, cement and lime.

Soil is an inorganic binder that has advantage over organic binding materials. Clay soil is the earliest known binder that has been used in block production; hence it is called civilian block binder. Soil binder is widely available, low cost and has the advantage of good hydrophilicity. Cattle dung is an organic binder used by several block producers. The cattle dung binder has good binding performance and also the blocks made using cattle dung binder show high compressive strength. The organic binders decompose easily at high temperature. Cement is an inorganic binder with advantages like robust adhesion, non-polluting, low cost and good hydrophilicity. Cement is used in the industrial blocks and is widely available. Lime is also an inorganic binder used in industrial blocks. It is a local resource, low cost and non-polluting binder with good thermal stability. The use of inorganic binders in the production of blocks was reported to not only reduce the emission of harmful gases in the environment, but also improve the utilization of energy[16,17].

In Figure 2, there are four columns of small blocks containing binder ratio 20%, 30%, 40% and 50% respectively. The 10% binder ratio in the biochar was not feasible to form as blocks. After sun-drying for 48 h, these combinations were tested. According to observations, 30–50% binder level was determined for the production of blocks. Maximum binder level was kept 50% for better heating properties. For proper mixing and preparation of the dough, 30% water of the total weight was added to the mixture.

For the production of biochar blocks and in order to evaluate their performance in terms of physical properties, chemical properties and thermal properties, several combinations of the composition were analysed (Table 1).

The optimization of binder levels was done in each group as the four different types of binders were not mixed together to produce blocks. DESIGN-EXPERT Version: 11.1.2.0 was used for optimization of treatments.

Optimal design is a choice when central composite (CC) and Box–Behnken (BB) designs do not fulfil the necessary requirements. In the central composite design and Box-Behnken design, the points were selected using factor setting outside the range of the factors in the factorial part. The Box-Behnken design is rotatable (or nearly so) but it contains regions of poor prediction quality. Due to the point assortment process and the fact that there were many statistically corresponding sets of design points, it was possible to achieve slightly changed designs for identical factors and model statistics. The input variable in the optimal design was the binder ratio in each binder type. The responses for the variables were the dependent parameters of composition of biochar blocks like density, degree of densification, shattering resistance, water resistance, proximate results and heating properties.

Properties of blocks

The size of the blocks was determined by measuring their average length and diameter. Weight of the blocks was determined by measuring the average weight of the prepared block samples using an electronic weighing balance.

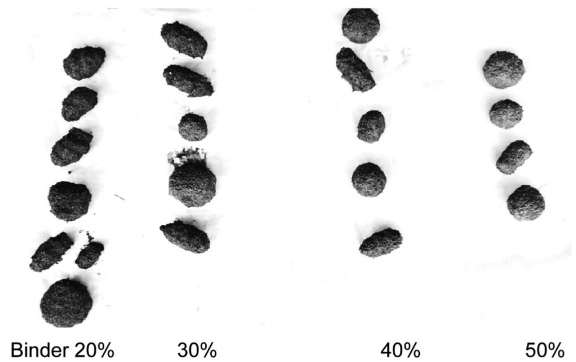

Figure 2. Composition of biochar and binders in different ratios.

Table 1. Composition of raw material treatments

Treatments	Composition	No. of replications	Description
T1	B70S30	3	Biochar 70% + soil 30%
T2	B60S40	3	Biochar 60% + soil 40%
T3	B50S50	3	Biochar 50% + soil 50%
T4	B70D30	3	Biochar 70% + dung 30%
T5	B60D40	3	Biochar 60% + dung 40%
T6	B50D50	3	Biochar 50% + dung 50%
T7	B70C30	3	Biochar 70% + cement 30%
T8	B60C40	3	Biochar 60% + cement 40%
T9	B50C50	3	Biochar 50% + cement 50%
T10	B70L30	3	Biochar 70% + lime 30%
T11	B60L40	3	Biochar 60% + lime 40%
T12	B50L50	3	Biochar 50% + lime 50%

The bulk density of the samples was determined using ASTM E873-82 (2013)[18]. An empty, a cylindrical-shaped container of known volume was weighed to determine its mass and then the container was filled with sample and weighed again. Bulk density was estimated as

$$\text{Bulk density (kg/m}^3) = \frac{\text{Mass of the sample (kg)}}{\text{Volume of the container (m}^3)}. \quad (1)$$

The shattering test includes determination of stability of the relative size of the blocks as well as their friability. It indicates the hardness and capability of the blocks to endure cracking when handling. According to the standard test method of drop shatter analysis[19], sample blocks of known weight and length were dropped twice from a height of 1.83 m on a concrete floor. The weight of the shattered blocks was noted and the percentage loss of material was calculated. The shattering resistance of block was calculated by

$$\%\text{ Weight loss} = \frac{W_1 - W_2}{W_1} \times 100, \quad (2)$$

$$\%\text{ Shattering resistance} = 100 - \%\text{ weight loss}, \quad (3)$$

where W_1 is the mass of block sample before shattering (g) and W_2 is the mass of block sample after shattering (g).

Water absorption test is a measure of water absorbed by the blocks when completely immersed in water. The blocks were immersed in water for 60 sec at room temperature[20]. The proportion of water absorbed by each block was calculated and the water absorption resistance determined using the formula

$$\%\text{ Water gained by the block} = \frac{W_1 - W_2}{W_1} \times 100, \quad (4)$$

$$\%\text{ Water absorption resistance} = 100 - \%\text{ water gained}, \quad (5)$$

where W_1 is the mass of block sample before the test (g) and W_2 is the mass of block sample after the test (g).

Degree of densification is defined as the percentage increase in the density of raw materials using the briquetting procedure. This indicates the ability of the biomass to get bounded, and is determined using the formula given below[21]

$$\text{Degree of densification (\%)} = \frac{\text{Density of the block} - \text{Density of raw material}}{\text{Density of raw material}}. \quad (6)$$

The compressive strength is the ability of the blocks to resist breaking under a compressive force. The compressive strength is measured using a universal testing machine. The block samples were placed directly on the platform of the machine plunger to be pressed. The machine applies a compressive force on the surface of blocks until failure is encountered on them. The compressive strength is calculated as

$$F = \frac{P}{A}, \tag{7}$$

where F is the compressive strength (MPa), P the maximum load applied to the sample (N) and A is the cross-sectional area of the sample (mm^2).

Moisture is defined as the amount of liquid per unit mass of the wet solid. According to the standardized test method for moisture analysis[22], 1 g of the sample was retained in a hot-air-oven at 105°C for 1 h. Next, the oven-dried sample was weighed. Moisture content was estimated as

$$\text{Moisture content (\%)} = \frac{W_2 - W_3}{W_2 - W_1} \times 100, \tag{8}$$

where W_1 is the weight of the empty crucible (g), W_2 the weight of the empty crucible + sample (g) and W_3 is the weight of the empty crucible + sample after drying (g).

Volatile matter determines the percentage of the gaseous products which is released under the specific conditions of the test in the analysis of the sample free from moisture content. As per the standard test method for volatile matter analysis[23], the oven-dried sample enclosed in a crucible with a lid was placed in a muffle furnace, and maintained at 950° ± 20°C for 7 min. Therefore, the crucible was first cooled in the surrounding air and then in a desiccator, and weight loss was calculated

$$\text{Volatile matter (\%)} = \frac{W_3 - W_4}{W_2 - W_1} \times 100, \tag{9}$$

where W_1 is the weight of the empty crucible (g), W_2 the weight of the empty crucible + sample (g), W_3 the weight of the empty crucible + sample after oven-drying (g) and W_4 is the weight of the empty crucible + weight after heating in muffle furnace (g).

Ash content was determined by weighing the residue remaining after burning the coal under rigidly controlled conditions of sample weight, temperature, time, atmosphere and equipment specifications. According to the standardized test method for ash content analysis[24], the remaining sample residue after volatile matter test, was heated in the muffle furnace at 700° ± 50°C for 4 h. The ash content in each sample of the block was estimated using the formula

$$\text{Ash content (\%)} = \frac{W_5 - W_1}{W_2 - W_1} \times 100, \tag{10}$$

where W_1 is the weight of the empty crucible (g), W_2 the weight of the empty crucible + sample, after volatile matter (g) and W_5 is the weight of the empty crucible + ash left in the crucible (g).

According to the standard test method[25], the fixed carbon is a calculated value, it is the resultant of the summation of the percentage moisture, ash and volatile matter subtracted from 100. All percentage will be on the same moisture reference base. The fixed carbon was determined using the standard formula

$$\text{FC(\%)} = 100 - \{\text{MC(\%)} + \text{VM(\%)} + \text{AC (\%)}\}, \tag{11}$$

where FC is the fixed carbon, MC the moisture content, VM the volatile matter and AC is the ash content.

The calorific value of blocks is determined using the bomb calorimeter, according to the standard test method for calorific value[26]. The bomb calorimeter consists of a solid cylindrical, stainless-steel bomb inside which the combustion of fuel takes place. Less than 1 g of fuel sample is placed in the crucible, a fuse wire is used to ignite the fuel and the bomb filled with oxygen gas at 25–30 atmospheric pressure. The electrode was connected to electrical supply and initial water temperature was noted. After combustion of the fuel sample, the increase in water temperature was noted for determination of calorific value. The calorific value determined by the formula

$$\text{Calorific value (kcal/kg)} = \frac{W \times \Delta T}{M}, \tag{12}$$

where M is the Mass of fuel placed in the crucible (g), W is the water equivalent of the bomb calorimeter or heat capacity (cal/°C), $\Delta T = t_2 - t_1$, where t_1 is the initial temperature of water in the calorimeter (°C) and t_2 is the final temperature of water in the calorimeter (°C).

To determine the heat capacity of the bomb calorimeter, wherever nichrome fuse wire and cotton thread are used simultaneously, pure benzoic acid is used in the bomb. In this case, cotton thread was also used along with nichrome fuse wire. The heat capacity for nichrome fuse wire is 333.68 cal/g and for cotton thread it is 4180 cal/g (ref. 27)

$$W = \frac{M \times H + (E_w) + (E_t)}{\Delta T}, \tag{13}$$

where W is the water equivalent of the bomb calorimeter (2283.32 cal/°C)[27], M the mass of the test sample, ΔT the rise in temperature, E_w the correction of heat of combustion for nichrome fuse wire and E_t is the correction of heat of combustion for cotton thread

$$E_w = M_w \times H_w,$$

where M_w is the mass of nichrome fuse wire and H_w is the heat capacity per gram of nichrome fuse wire

$$E_t = M_t \times H_t,$$

where M_t is the mass of cotton thread and H_t is the heat capacity per gram of cotton thread.

The thermal efficiency test was done according to IS 13152 (Part 1): 1991 (ref. 28) by the water-boiling test. The thermal efficiency of the stove is defined as the ratio of the heat completely utilized to that hypothetically produced by burning a given quantity of the blocks. A known amount of water was used to heat a known quantity of block fuel. The amount of water and quantity of fuel was determined by the burning capacity rate.

The thermal efficiency η was estimated as

$$\eta(\%) = \frac{\text{Heat utilized}}{\text{Heat produced}} \times 100. \quad (14)$$

Heat utilized (kJ) = $(n - 1)(W \times 0.896 + w \times 4.1868)(t_2 - t_1) + (W \times 0.896 + w \times 4.1868)(t_3 - t_1)$
Heat produced (kJ) = $4.186[(X \times C_1) + (xd/1000 \times C_2)]$.

$$\eta(\%) = \frac{(n-1)(W \times 0.896 + w \times 4.1868)(t_2 - t_1) + (W \times 0.896 + w \times 4.1868)(t_3 - t_1)}{4.186[(X \times C_1) + (xd/1000 \times C_2)]},$$

where w is the mass of water in the vessel (kg), W the mass of the vessel complete with lid and stirrer (kg), X the mass of the fuel consumed (kg), C_1 the calorific value of the fuel (kcal/kg), x the volume of kerosene (ml), C_2 the calorific value of kerosene (kcal/kg), d the density of kerosene (g/cm^3), t_1 the initial temperature of water (°C), t_2 the final temperature of water (°C), t_3 the final temperature of water in the last vessel at completion of test (°C) and n is the total number of vessels used (specific heat of aluminium = 0.896 kJ/kg°C).

The burning capacity rate was determined according to the standard method[28]. A known weight of block sample was burnt completely until the constant-weight ash was formed. The loss in weight at a specific time was calculated as the burning rate.

$$\text{Burning capacity rate} = 2\,(M_1 - M_2) \times \text{CV (kcal/h)}, \quad (15)$$

where M_1 the initial mass of the fuel with stove (kg), M_2 the mass of the stove after burning of the fuel for half an hour (kg) and CV is the calorific value of the fuel (kcal/kg).

Production cost of blocks

The cost of manually operated biochar block-making machine was evaluated according to the standardized practice described in IS 9164: 1979 (ref. 29).

Fixed cost. The depreciation cost was estimated on the basis of decrease in the worth of the machine with wear and time. The depreciation was estimated using the straight-line method

$$D = \frac{P - S}{L}, \quad (16)$$

where D is the depreciation cost, average/yr (Rs), P the purchase price of the machine (Rs), S the residual value of the machine (Rs) = 5% of the purchase price and L is the useful life of the machine = 5 years.

The yearly charges of interest were determined on the basis of the rate of interest actually payable. The interest was 12% of the average purchase price of the machine. The average purchase price was estimated as

$$A = \frac{P + S}{2}, \quad (17)$$

where A is the average purchase price (Rs), P the purchase price of the machine (Rs) and S is the residual value of the machine (Rs).

The amount paid annually for insurance and taxes was calculated on the basis of 2% of the average purchase cost of the machine. The housing price was estimated according to 1.5% of the average purchase amount of the block-making machine.

Variable cost. This is related to the operation of the machine. The material cost involves cost of raw materials needed for the production of the blocks. This is based on a survey of the local market price.

Cost of biochar per kg = Rs 4.67 (ref. 30)
Cost of soil per kg = Rs 2.0
Cost of dung per kg = Rs 2.0
Cost of cement per kg = Rs 10.0
Cost of lime per kg = Rs 10.0

The repair and maintenance cost is useful to keep a machine in working condition and avoid any breakdown due to wear and accident. It is 6% of the initial cost of the machine.

The cost to operate a machine on an hourly basis includes the wages/labour charges of an operator. The labour charges are Rs 275.00 for 8 h of working per day[31].

Total cost. The sum of fixed cost and variable cost per hour gives the total cost.

Results and discussion

Figure 3 shows the pine needle biochar blocks produced with the manually operated block-making machine. Table 2 lists the characteristic properties of biochar blocks.

Table 2. Characteristic properties of biochar blocks

Treatment	Avg. length (cm)	Avg. weight (g)	Density (kg/m^3)	Degree of densification (%)	Shattering resistance (%)	Water resistance (%)	MC (%)	VM (%)	AC (%)	FC (%)	Calorific value (MJ/kg)	Compressive strength (MPa)
B70S30	8.5	481	441.1	42.1	41.1	2.1	3.8	30.9	22.6	42.7	28.9	0.18
B60S40	8.5	615	567.8	70.4	52.5	28.7	4.9	19.7	18.8	56.7	26.7	0.25
B50S50	8.5	630	581.6	73.5	74.7	74.6	4.6	23.9	33.2	33.5	21	0.37
B70D30	8	568.3	560.8	40.2	44.1	15.9	8.7	9	26.5	55.8	25.4	0.12
B60D40	8	588.3	580.6	40.3	67.7	48.6	10	3.0	34.5	42.5	23.7	0.14
B50D50	8	603.3	595.3	39	76.8	67.4	8.4	16.8	32.2	42.6	22.4	0.29
B70C30	8.5	561.7	521.6	43.5	31.9	11.1	4.0	56.3	32.5	7.3	22.5	0.29
B60C40	8.5	606.7	536.4	50.3	49.5	51.9	5.7	56.9	24.5	12.9	19.4	0.30
B50C50	8.5	651.2	605.2	56.3	82.5	75.2	5.9	50.2	41.7	2.2	18.7	0.52
B70L30	8	500	493.4	54.5	44.1	4.7	3.6	62.1	22.3	12.1	25.2	0.16
B60L40	8	570	562.4	73.4	57.3	38	3.4	56.5	26.9	13.2	22.7	0.30
B50L50	8	686.7	679.9	92.7	81.6	75.7	3.5	53.6	33.9	9.0	19.1	0.54

MC, Moisture content; VM, Volatile matter; AC, Ash content; FC, Fixed carbon.

Table 3. Burning capacity rate of biochar and thermal efficiency blocks

Sample	Burning capacity rate (kcal/h)	Thermal efficiency (%)
B70S30	1879.97	15.53
B70D30	1760.61	12.76
B70C30	1687.76	11.24
B70L30	1746.07	10.23

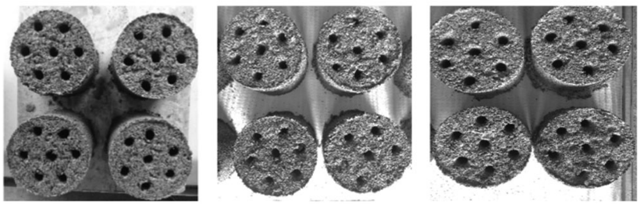

Figure 3. Pine needle biochar blocks produced by manually operated block-making machine.

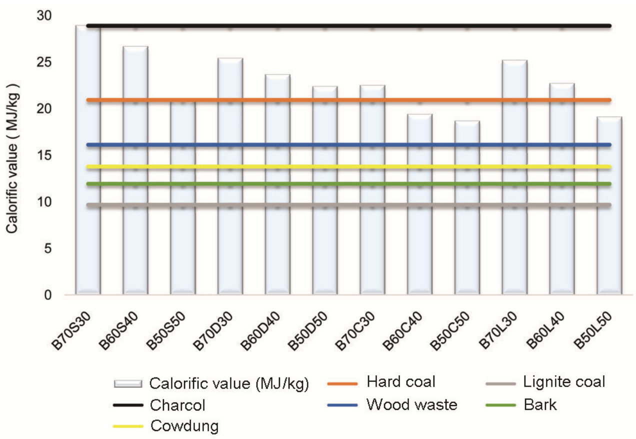

Figure 4. Comparison of calorific value of biochar blocks with different fuels.

Proximate analysis initiated that the moisture content of pine needles reduced to <10 wt% after sun-drying, which is suitable for making pine-needle biochar. The results of proximate analysis of raw materials such as pine needle biomass and pine needle biochar used in block making procedure are compared with each other. The pine needle biochar has better fuel characteristics properties as compared to pine needle biomass. The pine needle had 2.16% ash content whereas pine needle biochar had 6.64% ash content. The pine needle had 17.75% fixed carbon and biochar 63.3%. The pine needle had a higher value of volatile matter compared to biochar. The volatile matter in pine needle was 71.43% and in biochar it was 25.44%. The high value of volatile matter produces more tar. On comparison with other biomass resources (crop residue: 63–80%, wood: 72–78%, peat: 70%, coal: up to 40%), charcoal had the least percentage of volatile matter (3–30)[32].

The pine needle had higher moisture content compared to biochar. The moisture content in biochar was 4.65% and in pine needle 8.66%. The calorific value of pine needle was less than that of the biochar. The calorific value of pine needle was 19.27 MJ/kg and that of biochar 29.31 MJ/kg.

Blocks were prepared for the selected compositions of biochar and binder. To produce a block weighing 600 g, the mass of raw material was fixed at 600 g.

The average height of biochar blocks was between 8 and 8.5 cm, while the diameter of the blocks was uniform (12.7 cm). The average weight of biochar blocks was in the range 480–680 g. Since the density of lime is more than that of soil and cement, the degree of densification for the composition of biochar with lime (B50L50) was maximum and was determined at 92.67%. With an increase in the percentage of the binder, the bulk density of briquettes also increased due to the fact that binders have a higher bulk density compared to that of biochar.

The results show that the biochar blocks have moisture content in the desired range. The reported moisture content range in biochar blocks is 8–10% (ref. 13), whereas it is 5.56–10.29% for beehive blocks[14]. Higher moisture content produces high smoke and slow burning of blocks.

Table 4. Optimization of treatments of composition of biochar with soil, dung, cement and lime

Binder	Ratio	Density	Degree of densification	Shattering resistance	Water resistance	Moisture content	Volatile matter	Ash content	Fixed carbon	Calorific value	Compressive strength	Desirability
Soil	40%	547	65.7	59.5	42.4	4.5	23.8	25.6	44	24.7	0.3	0.5
Dung	40%	578.6	40	62.8	43.7	9.1	9	31.3	46.8	23.8	0.2	0.5
Cement	40%	557.7	51.1	57.7	52.3	5.5	54.4	32.	8.1	19.7	0.4	0.5
Lime	40%	610.8	80.2	67.4	51.9	3.5	55.8	29.6	11	21.3	0.4	0.5

Table 5. Cost analysis of biochar block preparation

Parameter			Cost
Fixed cost	Initial cost of block making machine (₹)		8000.00
	Depreciation (₹/h)		0.3167
	Interest at 12% of average purchase price (₹/h)		0.2100
	Insurance and taxes at 2% of initial cost (₹/h)		0.0067
	Housing charges at 1.5% of initial cost		0.0050
Variable cost	Material cost for block production of (50 : 50) blocks; material capacity is 24 kg/h, i.e. 12 kg biochar + 12 kg binder		
	Cost of biochar (₹/h)		56.0
	Cost of soil (₹/h)		24.0
	Cost of dung (₹/h)		24.0
	Cost of cement (₹/h)		120.0
	Cost of lime (₹/h)		120.0
	Repair and maintenance cost at 6% of initial cost		0.0150
	Labour charges (two persons; ₹/h)		70.0
Total fixed cost (₹/h)			0.5384
Total variable cost (₹/h)			
Biochar : soil			150.0
Biochar : dung			150.0
Biochar : cement			246.0
Biochar : lime			246.0
Total cost (₹/h)			
Biochar : soil			150.5
Biochar : dung			150.5
Biochar : cement			246.5
Biochar : lime			246.5
Cost of block		₹/kg	₹/block
Biochar : soil		6.30	3.20
Biochar : dung		6.30	3.20
Biochar : cement		10.30	5.20
Biochar : lime		10.30	5.20

The average volatile matter in charcoal was reported to be 3–30% (ref. 32). The determined volatile matter in the blocks was in the range 3.02–62.08%. The fixed carbon is the solid combustible residue which remains after the block is burnt and volatile matter is expelled. The higher value of fixed carbon indicates that the block requires longer combustion period.

The results also indicate that lower the biochar content in the briquettes, higher is their shattering resistance. This is due to the fact that higher content of binders could produce briquettes which are more cohesive. With an increase in the binder level, the compressive strength, shattering strength and water absorption resistance of the biochar blocks also increase, whereas calorific value of the blocks decreases with an increase in the binder level. The minimum binder-level blocks have maximum biochar properties by virtue of which there is an increase in the calorific value of the blocks.

The results also show that the minimum mixture of the binder is suitable for higher calorific value of the fuel. As the amount of binder in the composition increases, there is a decrease in the calorific value of fuels. The additional value of binder converted into more ash content and less calorific value. Therefore, the calorific value of 30%

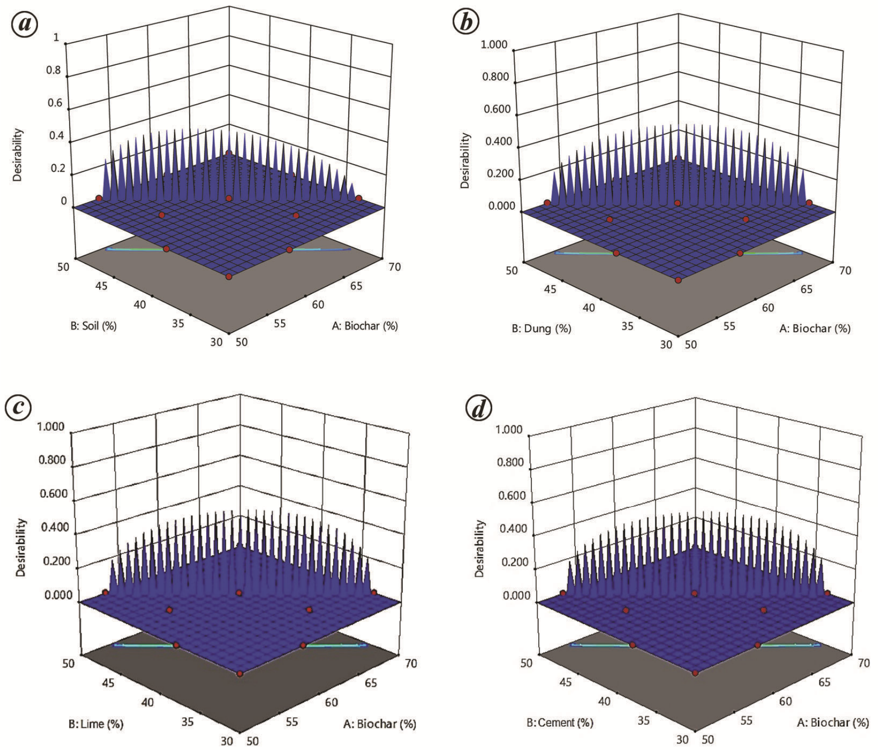

Figure 5 *a–d*. Response surface curve of optimal biochar and binder ratio.

binder composition blocks was higher than the other compositions. The calorific value of block composition with soil as a binding agent had higher calorific value compared to the same level of other binders. The soil has organic matter that helps retain the heat capacity[33]. The produced biochar blocks with distinctive binder were compared with the commercially available fuels on the basis of calorific values. The commercially available hard coal, lignite coal, charcoal, wood waste, bark and cow dung have a calorific value of 20.92, 9.67, 28.87, 16.11, 11.92 and 13.77 MJ/kg respectively[34].

Figure 4 shows the calorific value of biochar blocks, the horizontal lines represent the calorific value of different fuels with respect to their colour coding. The calorific value of charcoal was greater than that of biochar blocks, except for the B70S30 block. The calorific value of biochar blocks was significantly better than the above-listed fuels. The calorific value of the prepared blocks was significantly better than those of commercial fuels such as hard coal, lignite coal, wood wastes, bark and cattle dung. Charcoal has a calorific value of 28.87 MJ/kg, which is similar to that of the B70S30 block.

Experiments on the burning capacity rate of biochar blocks were carried out by selecting blocks representing the highest calorific value among each binder group. Four samples were selected having a higher calorific value. Table 3 shows the burning capacity rate of selected biochar blocks. The water boiling test was performed to determine thermal efficiency. The results indicate that thermal efficiency of the stove using the composition biochar with soil (B70S30) is maximum, whereas thermal efficiency of the stove using the composition biochar with lime (B70L30) is less than that of soil.

The optimization of the binder level was performed in each binder group. Table 4 list the optimal composition of biochar and binder for the production of biochar blocks. The results show that biochar 60% and binder 40% is suitable for the production of blocks with adequate strength and heating properties.

Figure 5 *a–d* shows the response surface curve for optimal biochar and binder ratio. The 50% desirability of binder ratio was found to be maximum at biochar 60 and binder 40 coordinate of the plot.

Table 5 shows the cost analysis of producing biochar blocks. The selling price per block in the local area is Rs 25. The cost of production is Rs 3.20 for each soil and dung binder block and Rs 5.20 for each cement and lime binder block.

Conclusion

The use of pine-needle biomass reduces forest fires and other hazards in the hilly regions. Here, a manually operated biochar block-making machine was developed to produce four blocks simultaneously of height 8 cm and weight 600 g. The maximum degree of densification and compressive strength was 93% and 0.54 MPa respectively, for B50L50 blocks. The prepared blocks were durable and shatter-proof. The maximum shattering resistance and water absorption resistance of biochar blocks were 83% and 76% for B50C50 and B50L50 blocks respectively. The average moisture, volatile matter, ash and fixed carbon were 5%, 36%, 25% and 40% respectively. The maximum calorific value was 29 MJ/kg for B70S30 and minimum calorific value was 19.1 MJ/kg for B50L50. The average heat-retaining capacity of biochar blocks was up to 3 h. These blocks are suitable for cooking, heating purposes and produce very low-smoke fuel. The cost of production of biochar blocks for soil or dung was ₹6.30/kg, while it was ₹10.30/kg for cement or lime. The block-making process will help generate self-employment and prove effective in preventing migration of rural farmers from the hilly regions.

1. EIA, Energy Information Administration Federal Agency, Washington DC, USA, 2011; https://www.eia.gov/
2. Goyal, H. B., Seal, D. and Saxena, R. C., Bio-fuels from thermochemical conversion of renewable resources: a review. *Renew. Sustain. Energy Rev.*, 2008, **12**(2), 504–517.
3. Kaygusuz, K., Biomass as a renewable energy source for sustainable fuels. *Energy Sources, Part A*, 2009, **31**(6), 535–545.
4. IEA, Wind energy Annual Report, International Energy Association, 2006; www.ieawind.org
5. Efika, C. E., Wu, C. and Williams, P. T., Syngas production from pyrolysis–catalytic steam reforming of waste biomass in a continuous screw kiln reactor. *J. Anal. Appl. Pyrol.*, 2012, **95**, 87–94.
6. Singh, R. D., Gumber, S., Tewari, P. and Singh, S. P., Nature of forest fires in Uttarakhand: frequency, size and seasonal patterns in relation to pre-monsoonal environment. *Curr. Sci.*, 2016, **111**(2), 398–403.
7. Uttarakhand Renewable Energy Development Agency (UREDA), Department of Renewable Energy, 2010; ureda.uk.gov.in/
8. Haykiri-Acma, H. and Yaman, S., Interpretation of biomass gasification yields regarding temperature intervals under nitrogen–steam atmosphere. *Fuel Process. Technol.*, 2007, **88**(4), 417–425.
9. Font, R., Conesa, J. A., Moltó, J. and Muñoz, M., Kinetics of pyrolysis and combustion of pine needles and cones. *J. Anal. Appl. Pyrol.*, 2009, **85**(1–2), 276–286.
10. Mahmood, R., Parshetti, G. K. and Balasubramanian, R., Energy, exergy and techno-economic analyses of hydrothermal oxidation of food waste to produce hydro-char and bio-oil. *Energy*, 2016, **102**, 187–198.
11. Mandal, S., Bhattacharya, T. K. and Tanna, H. R., Energy harnessing routes of rice straw. *Curr. Sci.*, 2017, **113**(1), 21–23.
12. Mandal, S., Kumar, G. P., Bhattacharya, T. K., Tanna, H. R. and Jena, P. C., Briquetting of pine needles (*Pinus roxburgii*) and their physical, handling and combustion properties. *Waste Biomass Valorization*, 2019, **10**(8), 2415–2424.
13. Mandal, S., Arvind, K., Singh, R. K. and Ngachan, S. V., Evaluation of composition, burn rate and economy beehive charcoal briquettes. *Int. J. Agric. Eng.*, 2012, **5**(2), 158–162.
14. Mandal, S., Kumar, A., Singh, R. K., Ngachan, S. V. and Kundu, K., Drying, burning and emission characteristics of beehive charcoal briquettes: an alternative household fuel of Eastern Himalayan Region. *J. Environ. Biol.*, 2014, **35**(3), 543.
15. Lehmann, J. and Joseph, S., *Biochar for Environmental Management: Science and Technology*, No. 631.422 B615bi, GB: Earthscan, London, 2009.
16. Zhang, G., Sun, Y. and Xu, Y., Review of briquette binders and briquetting mechanism. *Renew. Sustain. Energy Rev.*, 2018, **82**, 477–487.
17. Kaur, A., Roy, M. and Kundu, K., Densification of biomass by briquetting: a review. *Int. J. Rec. Sci. Res.*, 2017, **8**, 20561–20568.
18. ASTM E873-82 (2013), Standard test method for bulk density of densified particulate biomass fuels. ASTM International, West Conshohocken, PA, USA, 2013.
19. ASTM D440-86 (2002), Standard test method of drop shatter test for coal. ASTM International, West Conshohocken, PA, USA, 1986.
20. NAIP, Value chain on biomass based decentralized power generation for agro enterprises. Final Report, National Agricultural Innovation Project, ICAR-Central Institute of Agricultural Engineering, Bhopal, 2014.
21. Birwatkar, V. R. *et al.*, Physical and thermal properties of biomass briquetted fuel. *Indian J. Sci. Technol.*, 2014, **2**, 55–62.
22. ASTM D3173-03 (2008), Standard test method for moisture in the analysis sample of coal and coke. ASTM International, West Conshohocken, PA, USA, 2008.
23. ASTM D3175-07, Standard test method for volatile matter in the analysis sample of coal and coke. ASTM International, West Conshohocken, PA, USA, 2007.
24. ASTM D3174-02, Standard test method for ash in the analysis sample of coal and coke from coal. ASTM International, West Conshohocken, PA, USA, 2002.
25. ASTM D3172-07a, Standard practice for proximate analysis of coal and coke. ASTM International, West Conshohocken, PA, USA, 2007.
26. ASTM E711-87 (2004), Standard test method for gross calorific value of refuse-derived fuel by the bomb calorimeter (withdrawn 2004). ASTM International, West Conshohocken, PA, USA, 1987.
27. Parray, Studies on suitability of some surfactants for e-diesel and performance evaluation of a CI engine on formulated fuels. M Tech thesis, Department of Farm Machinery and Power Engineering, G. B. Pant University of Agriculture and Technology (GBPUAT), Pantnagar, 2012.
28. IS 13152-1, Solid bio-mass chulha, Part 1: portable (metallic). Bureau of Indian Standards (BIS), MED 4: Non-Conventional Energy Sources, New Delhi, 1991.
29. IS 9164, Guide for estimating cost of farm machinery operation. BIS, New Delhi, 1979.
30. Mandal, Optimization of process parameters for conversion of pine needles to bio oil, biochar and product gas through batch and continuous pyrolysis, Ph D thesis, Department of Farm Machinery and Power Engineering, GBPUAT, Pantnagar, 2018.
31. Labour Bureau, Government of India, Wages in rural area, November 2018.
32. Rominiyi, O. L., Olaniyi, T. K., Azeez, T. M., Eiche, J. F. and Akinola, S. A., Synergetic effect of proximate and ultimate analysis on the heating value of municipal solid waste of Ado Ekiti metropolis, Southwest Nigeria. *Curr. J. Appl. Sci. Technol.*, 2017, 1–12.
33. Abu-Hamdeh, N. H. and Reeder, R. C., Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. *Soil Sci. Soc. Am. J.*, 2000, **64**(4), 1285–1290.
34. Ramachandra, T. V., *Renewable Energy and Energy Conservation Technologies*, Karnataka Environment Research Foundation, 2000.

ACKNOWLEDGEMENTS. H.K.S. thanks the Department of Farm Machinery and Power Engineering, G.B. Pant University of Agriculture and Technology, Pantnagar for his entire research work. H.K.S. also thanks Dr K. C. Pandey, Project Coordinator of ICAR-All India Coordinated Research Project on Energy in Agriculture and Agro-based Industries (AICRP on EAAI) for his guidance and support.

Received 31 January 2020; accepted 13 February 2020

doi: 10.18520/cs/v118/i12/1959-1967