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Converting pruned tea plants into biomass pellets: A sustainable energy source

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ABSTRACT

India has experienced a 22.4% rise in coal consumption over the past five years, intensifying concerns over depleting fossil fuel reserves, greenhouse gas emissions, and public health risks. To address these challenges, agro-waste, particularly pruned tea plant biomass from northeastern India, offers a sustainable alternative. This study presents a novel approach to converting pruned tea plant waste into biomass pellets, a renewable and eco-friendly fuel. The process involves drying, grinding, optimizing binder concentration, and pelletizing the biomass. The resulting pellets exhibited desirable properties, including low moisture content (<5%), a calorific value of 14-15.5 MJ/kg, and reduced emissions of hydrocarbons (5 ppm), carbon monoxide (0.05%), carbon dioxide (0.32%), and nitrogen oxides (7 ppm). Characterization through proximate and ultimate analyses confirmed their efficiency as clean fuel. These findings highlight the potential of tea plant biomass pellets as a cost-effective, portable, and sustainable energy source, promoting eco-friendly energy solutions and reducing dependence on fossil fuels.

Keywords: agro-waste, calorific value, biomass pellet, sustainable

INTRODUCTION

According to the International Energy Agency (IEA), India was the third-largest consumer of primary energy in 2023, with a consumption of 39.02 exajoules (EJ), following China (170.74 EJ) and the USA (94.28 EJ) (Adeleke et al., 2024). Globally, fossil fuels contribute about 313.6 EJ (78.4%) of the energy count, making them the fuel with the highest consumption compared to other fuels. Whereas renewables can contribute up to ~77.2 EJ i.e. 19.3%, and the remaining 9.2 EJ (2.3%) is from nuclear energy. Increased energy consumption has led to the depletion of fossil fuels (Pradhan et al., 2018). Worldwide energy consumption is given in **Figure 1**. Due to its negative impacts on the environment, such as global warming, biomass is now used as an alternative fuel to reduce emissions of pollutant gases (Najjar et al., 2018; Saidur et al., 2011).

Biomass is an organic waste obtained from various human activities, such as agricultural waste, forestry residues, bagasse, municipal waste, food waste, industrial waste, etc. The energy obtained from the above-mentioned biomass is known as biomass energy," which is sustainable and obtained from renewable resources. The biomass is processed into biomass pellets, which fall under solid fuel (Ozyuguran et al., 2018). India generates 750 million metric tons of biomass in a year, of which agricultural residues and waste contribute 230 million metric tons which has a capacity to generate 28 GW of electricity. The bagasse obtained from the sugar mills alone can generate 14 GW of electricity. This shows that biomass can provide a firm source of energy for about 32% of the primary energy needs of the country's population, depending on the ministry of new and renewable energy (Jayappa Veeresh et al., n.d.; Özyuğuran & Yaman, 2017; Pappu et al., 2007). Agricultural residues are easily found as huge biomass and are a very cheap source of renewable energy (Jayappa Veeresh et al., n.d.). These can be pruned residues, which are usually left unused and burned, and can be utilised to control environmental burdens. It can be beneficial for farmers as well by reducing their costs through the sale of agro-waste (Lu et al., 2014). Despite knowing its residual effects on environmental aspects and human health, it is still carried out not only in India but also worldwide. Nearly 15.9% of the residue is burned in India (Rajabi Hamedani et al., 2019). The Northeast (NE) region of India is rich in tea plants (Camellia sinensis), especially in Assam, where the bulk of tea waste is generated as it covers the largest tea land in the world (Najjar et al., 2018). Tons of tea waste are produced from the pruning of tea bushes in the form of leaves, buds, and stems. The sum of pruning litter depends upon the types of pruning (light,

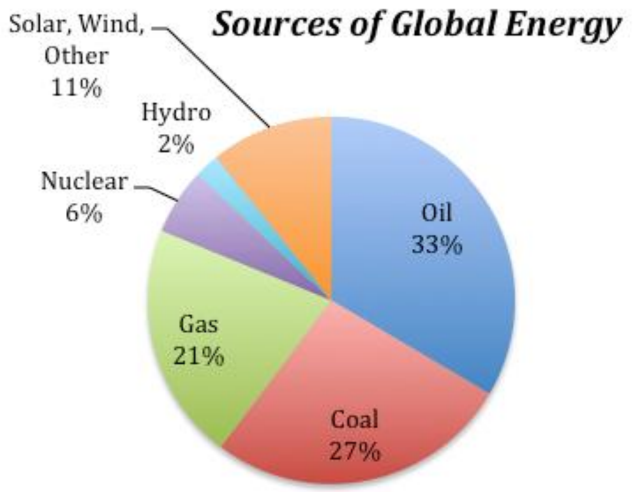

Figure 1. Energy consumed worldwide (https://www.e-education.psu.edu/earth104/node/1345)

Figure 2. Schematic representation of production of tea biomass pellets (Source: Authors' own elaboration)

medium, and heavy pruning) it has undergone (Ravindra et al., 2019). Yearly, India generates nearly 857,000 metric tons of tea, making up about 27.4% of total world production. Out of which 190,400 tons are tea factory waste (Najjar et al., 2018). Biomass is known as carbon neutral due to its contribution to an almost zero count of carbon dioxide in the atmosphere (Kumar et al., 2015; Shuma & Madyira, 2017). The amount of CO_2 released is almost the same as the CO_2 used up by biomass plants during photosynthesis. This is the reason "biomass" as a renewable resource is a highly discussed topic today (Shuma & Madyira, 2019). But there are some disadvantages, like being hard to handle, difficulties in transportation, needing more storage space, and low combustion with excess smoke and ash content in straight use of biomass due to their inhomogeneous structure and low bulk density, which leads to low volumetric energy. The above-mentioned properties are known as "poor handling properties" of biomass feed stock. The above-mentioned disadvantage can be overcome through pelletization and briquetting methods (Purohit & Chaturvedi, 2018).

Biomass is densified into pellets due to its advantages in comparison to unprocessed fuels or raw biomass, as it generates very little particulate matter and gases during combustion. Meyer hardness is a single pellet study commonly used to check pellet strength (Pramanik et al., 2016). These highly dense pellets have a very low moisture content (< 10%) and high energy conversion efficiency (~75%). Because of its regular geometry and standard size, there is an improvement in handling, transportation, and boiler feeding of the pellets (Pradhan et al., 2018). It can be stored for a long period of time so that the pellet stock will be available whenever needed. The transportation and storage costs are also very low compared to other fuel supplies (Jiang et al., 2016; Tauro et al., 2018). These agro-waste pellets are used in the boilers of power industry to produce heat and electricity (Nilsson et al., 2011). Binders are added to the raw biomass to improve the pelleting process and pellet quality, so that the energy consumed during the process should be very low (Greinert et al., 2019). Therefore, this is the reason why researchers have developed an interest in pelletization and briquetting. In comparison with other renewable energy sectors, the pellet sector is growing fast. In the past decade, 20% of the annual growth rate of biomass pellet production has increased. India produces a bulk amount of agricultural and forestry biomass waste, which is used as fuel for domestic, commercial, and industrial activities (Purohit & Chaturvedi, 2018). In this present study, the pellets were prepared from the tea-pruned biomass waste with two different binders at various concentrations. These pellets were characterised by their proximate, ultimate, compression analysis, smoke emission test and calorific values.

MATERIALS AND METHODOLOGY

Tea-pruned biomass was collected from the garden located at Karsingsa, Papum Pare District, Arunachal Pradesh. Starch was extracted from rice, and guar gum (GRM1233) was purchased from Hi-Media.

Tea waste biomass was used as the raw material. A schematic representation of tea biomass pellets is described in **Figure 2**. Pruned leaves and stems were kept in the sunlight for drying. The dried material was ground into powder using equipment (a Dynamics miller). Two different types of binders (starch and guar gum) were used. For each binder, three different concentrations of 5%, 10%, and 15% were made separately. And another three concentrations with the mixture of both starch and guar gum were prepared in the ratios of 1:1 (5%), 1:3 (10%), and 1:5 (15%) (guar gum: starch), respectively, and mixed thoroughly with the tea waste powder. Powdered tea waste was then subjected to a pelletizing device (a Dynamics pelletizer). It was pressed in such a way that it produces cylindrical shaped pellets with an approximate diameter of 8 mm (millimeters) and a length of 20 mm. The moisture content was maintained between 13% and 15% to give a better result, as the strength of the pellets depends on it.

Proximate analysis was done to determine the moisture, volatile matter, fixed carbon, and ash contents of the biomass pellets (done by ASTM D5142 protocol) (Xia et al., 2019). Ultimate analysis (done by ASTM D5373 protocol) was done to determine the carbon, hydrogen, oxygen, nitrogen and Sulphur content. The oxygen content was calculated by equation 1 (Cavalaglio et al., 2020).

Figure 3. Biomass samples of different binder concentrations (Source: Authors' own elaboration)

$$O\% = 100 - ash\% - C\% - H\% - N\% \quad (1)$$

Where O-oxygen, C-carbon, H-hydrogen, N-nitrogen.

Compression strength was measured the crushing strength of the cylindrical pellet kept horizontally. It was done by compressing the pellet using hydraulic device (Asian Universal Testing Machine ATEUTM20T). The maximum compressing force applied to crush the pellet was recorded in the device. The hardness/tensile strength was calculated by equation 2 (Greinert et al., 2019).

$$\sigma t = 2F/\pi dl \quad (2)$$

Where σt is the tensile strength, F is the maximum compressing force, d is the diameter of the pellet, l is the length of the pellet.

High heating value (HHV) according to equation 3 (Liu et al., 2014).

$$HHV = 0.312\, FC + 0.1534\, VM \quad (3)$$

Where FC=fixed carbon, VM=volatile matter.

Smoke emission test was done by the furnace at 250°C and the gases were measured GC TDC (gas chromatography thermal conductivity detector) (Purwanto et al., 2010).

RESULTS AND DISCUSSION

From the various combinations with different concentrations, nine pellet samples (**Figure 3**) are obtained. The pellets obtained were cylindrical in shape, measuring 20 mm in length and 8 mm in diameter. The outer surface was smooth with no cracks and a shiny appearance for the guar gum pellets. For starch, a combination of starch and guar gum pellets has a dull appearance with no cracks. The three parameters were kept at optimum conditions (temperature of 100 °C, moisture content of 10%, and pressure of 200 MPa).

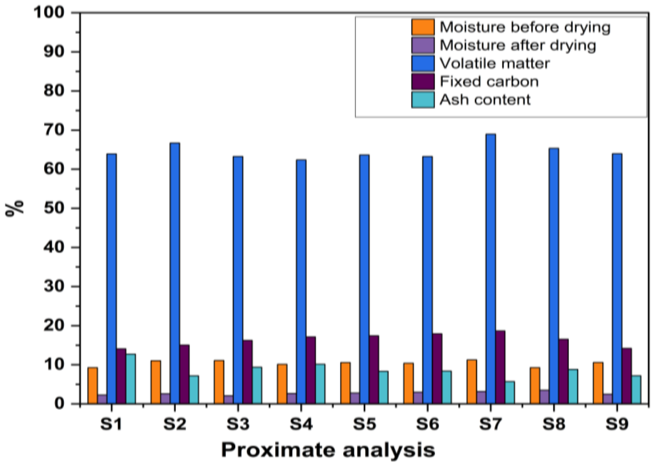

Figure 4. Proximate study of tea pruned biomass pellets (Source: Authors' own elaboration)

When the parameters have some changes, the obtained pellets have some deformities. For example, when the moisture content was less than 10%, the pellets were easily breakable and turned into powder. When the moisture content was more than 10%, pellets were bent, and cracks were also found. The temperature and the pressure are also equally important, as they have the capacity to trigger the natural binders present in biomass. These natural binders, along with added binders, promote the cohesion of the particles (particle density increases with an increase in temperature). The pressure increases with the molecular contact of the particles. Therefore, the quality of the pellets obtained is good (Cavalaglio et al., 2020; Purwanto et al., 2010; Siyal et al., 2021).

In proximate analysis (**Figure 4, Table 1**), there are four major parameters:

1. Moisture content,
2. Ash content,
3. Volatile matter, and
4. Fixed carbon.

The pellets that are commercially available contain 10-12% moisture content. The obtained moisture content before drying is between 9 and 11%, and after drying it is between 2.5% and 3.5%. So, this shows the moisture content is less than 5%, and similarly low moisture content is obtained due to the length of the drying process. The moisture content of the pellet determined the quality of the pellet as well as its heating value. The moisture content present in the vapours during the combustion process decreases the heating efficiency and performance of the pellet. A higher moisture content decreases the burning carbon rate. This action leads to incomplete combustion of volatile matter and deposits unburned carbon, which smokes. The ash content in a fuel represents the mineral content left after the combustion process. The compounds that are commonly present in the ash are silica oxides, aluminum oxides, potassium oxides, sodium oxides, and iron oxides. These are the solid residues that are responsible for the formation of slags and fouling layers in the inner parts of boilers and influence the combustion rate during the pyrolysis and gasification processes. Ash is a non-flammable material, but high ash content reduces the HHV.

Table 1. Proximate study of tea pruned biomass pellets

Analysis Proximate Analysis (%)	Samples								
	1	2	3	4	5	6	7	8	9
Moisture before drying	9.29	11.06	11.12	10.13	10.58	10.42	11.25	9.28	10.61
Moisture after drying	2.3	2.6	2.1	2.7	2.8	3.0	3.2	3.5	2.5
Volatile matter	63.9	66.71	63.26	62.38	63.66	63.26	68.97	65.35	63.96
Fixed carbon	14.09	15.04	16.24	17.15	17.42	17.92	18.66	16.54	14.21
Ash content	12.72	7.19	9.38	10.16	8.35	8.4	5.72	8.82	7.22

The pellets are made of biomass pellets (agrowaste), and they can also be reused as organic fertilizer for the agriculture fields. For the guar gum (samples 1-3), the 10% concentration sample shows a moderate level of ash content compared to 5% and 15%. For starch (sample no. 4-6), 5% indicates a high ash content, while 10% and 15% indicate a moderate level. For the combination of binders, 5% shows the least ash content, and the other two concentrations have a moderate level of ash content. Therefore, according to the ash content, sample 7 (5%:1 ratio) has the best out of all the other samples. The reason for the high ash content in other samples is due to an insufficient or excess amount of binder added to the biomass. Volatile matter is the organic compounds (hydrocarbons, methane, carbon monoxide, nitrogen, and unburned gases) present in the pellets, which result in good HHV by releasing vapours during the combustion process. The high volatile content also makes the ignition process much easier. For the samples, the volatile matter content varied from 63% to 68%. The highest value of volatile matter was obtained at sample 7 (5% with a 1:1 ratio). Fixed carbon (FC) is also known as solid carbon. These FC and carbon contents from the ultimate analysis are not the same. FC is the carbon that remains after the burning of volatile matter during the combustion process. FC has a greater influence on HHV because the higher the FC content, the higher the combustion value. For the sample, the value of FC ranges from 14 to 18%, with the highest value obtained for the sample being 7 (5% with a 1:1 ratio) (Cavalaglio et al., 2020; Purwanto et al., 2010; Sukarta et al., 2018).

Ultimate Analysis

The ultimate analysis (**Figure 5, Table 2**) mainly focuses on C, N, H, and O content. The sulphur content is less than the detectable limit or in a trace amount. C, H, N, and O are the major compounds that are present in the biomass. Carbon is the most essential element present in carbonaceous fuels. Nitrogen is also present, but the proportion varies from plant to plant. C and H content have some influence on ash content and HHV. When the C and H content is high, the HHV and ash content are also high. The main purpose of the ultimate analysis is to measure the pollutants that are going to be released into the environment after the combustion process. The results obtained from the samples do not show much difference. The nitrogen content was around 2%, the carbon content was 43-44%, the hydrogen content was 6%, and the oxygen content was 36-40%. Sulphur was found to be in trace amounts. During the combustion process, a very small or negatable amount of NOx and SOx will be released into the environment; however, the emissions from biomass pellets are significantly lower compared to conventional fossil fuels, thereby reducing environmental impact (Cavalaglio et al., 2020; Sukarta et al., 2018).

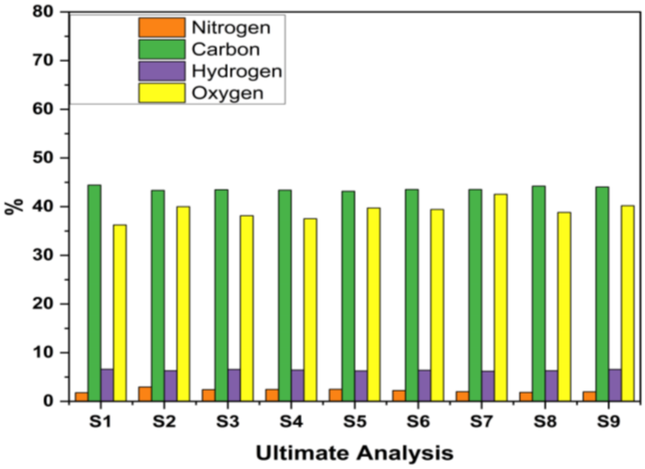

Figure 5. Ultimate study of tea pruned biomass pellets (Source: Authors' own elaboration)

Compression analysis and HHV study

A compression analysis (**Figure 6, Table 3**) was done to check the deformation properties of the pellet. An external force is applied so that the strength of the pellet can be measured. Through this analysis, the reason for the deformation of the pellets can be identified. Sample 9 (15% with a ratio of 1:5) shows the least force of 1200 N, and the tensile strength of the sample was found to be 4.77 MPa. The highest force was resisted by the sample 8 (10% with the 1:3 ratio); the force was recorded at 2200 N, and the tensile strength was found to be 8.75 MPa. For starch samples alone, the maximum force was recorded for sample 4 (5%) and the tensile strength was 7.56 MPa. For guar gum, sample 1 (5%) recorded a force of 1800 N and a tensile strength of 7.16 MPa. So, according to the analysis reports, the highest force was

Table 2. Ultimate study of tea pruned biomass pellets

Analysis Ultimate Analysis (%)	Samples								
	1	2	3	4	5	6	7	8	9
Nitrogen	1.78	2.96	2.42	2.46	2.5	2.25	1.99	1.85	1.97
Carbon	44.44	43.35	43.48	43.4	43.17	43.52	43.54	44.22	44.05
Hydrogen	6.6	6.3	6.57	6.45	6.27	6.4	6.19	6.28	6.56
Oxygen	36.24	40	38.15	37.53	39.73	39.43	42.56	38.83	40.2
Sulfur	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace

Table 3. Compression and HHV study of tea pruned biomass pellets

Analysis	Samples								
	1	2	3	4	5	6	7	8	9
Compression force (N)	1800	1500	1600	1900	1800	1800	1800	2200	1200
Tensile strength (TS)(MPa)	7.16	5.97	6.36	7.56	7.16	7.16	7.16	8.75	4.77
HHV (according to proximate analysis) (MJ/Kg)	14.19	14.92	14.77	14.91	15.2	15.29	15.15	15.18	15.49

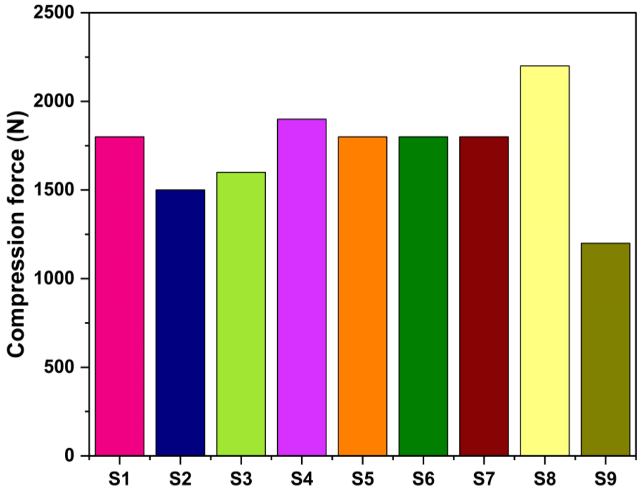

Figure 6. Compression study of tea pruned biomass pellets (Source: Authors' own elaboration)

recorded for sample 8, which has a good strength and will not deform during rough transportation and storage (Cavalaglio et al., 2020; Liu et al., 2014). These results indicate that the tensile strength and resistance to compression force are key indicators of the mechanical stability of the pellets. Pellets with higher tensile strength, such as sample 8, demonstrate better resistance to deformation during rough transportation and storage, suggesting enhanced durability. However, this study focuses on measuring short-term mechanical properties and does not explore the long-term durability of the pellets under real-world conditions, such as prolonged storage, repeated handling, or exposure to environmental factors like humidity. Future studies will investigate these aspects to provide a more comprehensive understanding of the correlation between mechanical properties and long-term durability.

High heating value (HHV) (**Figure 6, Table 3**) is a measurement of heat measured during the combustion of biomass pellets in which the pellet is completely burned. Usually, the HHV is measured in a bomb calorimeter, but the HHV can also be calculated by the elemental composition, and the value will be mentioned in MJ/kg. HHV mainly considers the two main elements C and H combined in a biomass with low ash content to have HHV, and vice versa. Therefore, for this work, the obtained value was between 14 and 15.5 MJ/kg. The values were calculated by using FC and VM values from proximate analysis. There was not much difference in the HHV obtained. Therefore, the results of sample 7 were better as compared to all the samples because the results were moderate in strength analysis and the HHV, along with the ash content, were also less than 5% (Liu et al., 2014; Özyuğuran & Yaman, 2017; Purwanto et al., 2010; Sukarta et al., 2018).

Smoke emission analysis

Smoke emission was done for sample 7 because, based on the obtained results, sample 7 was found to be the best. The results obtained from the smoke emission were HC (hydrocarbon) at 5 ppmv, CO (carbon monoxide) at 0.05 vol%, CO_2 (carbon dioxide) at 0.32 vol%, and NO_x (nitrogen oxides) at 7 ppmv. The pollutant that will be released into the environment was measured in a trace amount, which will be a more environmentally sustainable option (Purohit & Chaturvedi, 2018).

CONCLUSION

To develop an alternative solution for the current solid fuel consumption demand, an investigation was done on the tea-pruned biomass (agro-waste) turned into biomass pellets. In this study, the optimisation of binders with tea-pruned biomass waste turned into pellets was performed. Nine samples of different biomass pellets were obtained. These pellets were subjected to characterization (proximate, ultimate, HHV, smoke emission, compression, and tensile strength analysis). The results obtained were satisfactory, particularly sample 7, which was the best among the other samples. Therefore, only sample 7 was subjected to smoke emission analysis. The pollutants released during combustion were found to be lower compared to conventional fossil fuels, making biomass pellets a more environmentally sustainable option. While biomass combustion does generate emissions, its overall environmental impact is lower than that of fossil fuels when considering a life-cycle perspective. In conclusion, biomass pellets can serve as a viable alternative to solid fuels like coal, especially considering the rising costs of fuels such as liquefied petroleum gas (LPG) and coal. It can also serve as an excellent alternative fuel for both industrial and domestic use, particularly in hilly and mountainous regions, where fuel storage and transportation can be managed more efficiently.

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Ethical statement: The authors stated that the study did not require approval from an ethics committee. The research did not involve any human participants, animal subjects, or sensitive data. The study was solely based on plant-based materials (pruned tea plants) and involved no ethical concerns.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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