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Performance Investigation of an Advanced Robust Biomass Gasifier Operation for Drying Process at Hilly Region in India

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Abstract

This work presents a pilot-scale performance study intended at evaluate the achievability and operatability of biomass gasifier specially designed for hilly regions. The operations were carried out with forest wood blocks with around 35% moisture content. The gasifier was designed for 360 kWth downdraft modes operating with air at 15°C as gasifying agent. The designed gasifier system was installed in a green tea processing factory for supplying thermal energy for panning of green leaves. This system has replaced their conventional open wood firing rotary kiln furnace which was an in efficient combustion due to the ambient conditions. A performance study conducted on the gasifier system for their factory's thermal demand had shown firewood saving of 35% over conventional panning operation. The economics of installation–cum–operation of the gasifier was also found to be acceptable enough the operation results are discussed.

Keywords: Biomass gasification; Green tea leaves drying; Hilly region

Introduction

Gasification is an established technology for power generation where the process facilitates to overcome many of the limitations of the conventional combustion systems with highest efficiency which converts solid fuels into a clean gas that can be used as a substitution for meeting the factory's thermal demand. It is a green energy revolution that bestowed a big boost to the all-scale industrial sector. The gasification of biomass has a extensive history, remarkably its application in Europe during World War II. Given the current monetary, socio-economic and alarming environmental issues associated with fossil fuels depletion, promotion on the biomass-based thermochemical processes had embarked on to receive attention. This is evidenced by reviews in the literature [1-5].

Compared with combustion, gasification is more efficient at producing thermal and electrical energy generation. This technology also presents the advantage of a strong adaptability allowing the use of different biomass feed materials. These characteristics made biomass gasification suitable for solving environmental and energy supply problems for providing thermal energy in scarce regions using local biomass resources [6]. Gasification process is an incomplete combustion of a carbon-based biomass in a partial air environment where the dried feedstock continues to move downward and the volatile matter in feedstock gets pyrolyzed as it enters the pyrolysis zone which temperature ranges from 250 to 550°C [7]. Products that come out of this sub-process are volatile gas (CO, CO_2, CH_4, H_2 and tar), char and water vapor. The char, tar and volatile gas will then mix with the injected air and partially burn at the gasification zone. Un-burnt gas vapours flows further down until it is gasified and cracked completely in the reduction zone. This gas is called producer gas and has the same composition as volatile gas but the quantities of combustible gas (CO, CH_4 and H_2) are improved. The producer gas leaves the system through the bottom of the gasifier. This can then be used to serve thermal applications and if the gas quality and quantity is sufficiently good.

However, the fixed feedstock specifications and operation requirements such as low moisture and narrow size distribution [8,9] limit the reliability and diffusion of gasification technology. Most modern, high efficiency gasifiers are designed to operate within a range of parameters to ensure that performance meets emissions and efficiency specifications and a range of acceptable moisture content for the fuel is usually specified. If fuel outside this specification range is used the gasifier may shut down the operation automatically. However, low moisture content is not suitable for all biomass gasification system. Not all modern biomass gasifier systems require low moisture content fuel, however. Some are designed to handle fuel at much higher moisture content, e.g., as 'green' (freshly harvested) chips. These systems typically make use of some of the heat of combustion to dry the fuel as it approaches the combustion zone [10]. But, this designed downdraft biomass gasifier for tea manufacturing industry at hilly region can able to accept and operate with moisture content of the biomass up to 40% and the ambient operation condition experienced during the performance study was around 15°C.

Many biomass gasifiers are designed to operate on very low moisture content feedstock, perhaps 10-20%. Most studies on downdraft gasifiers involve woody biomass materials as feedstock is pre-prepared by cutting into desired shapes such as chips or briquettes which is cumbersome process with intense man power and energy usage. The effect of particle size on the gasification performance with a pilot-scale 25 kg/h capacity downdraft fixed bed gasifier device was experimented using pruning's of peach tree at five different size fractions below 1, 1–2, 2–4, 4–6 and 6–8 cm were tested for gasification. The lower heating value of the gas got decreased slightly with respect to particle size. At smaller particle size, more hydrocarbons were noticed in the producer gas. H_2 and CO_2 contents augmented with the decrease in particle size [11]. The demonstration of technological reliability for

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large scale downdraft gasifier in industrial platform directly depends on pilot scale tests [12-14]. Simple economic analysis shows gasifier integrated to tea dryer technology may be economically favorable option with an annual saving of 21,067$ in a medium scale tea factory (990 t per year made tea) if 28% of total thermal energy requirement was substituted by biomass gasification. The energy consumption was found as 19.01 MJ kg^{-1} of made tea (3% w.b.) based on calorific value of producer gas (HHV = 4.39 MJ Nm^{-3}). Specific energy consumption of the tea dryer was approximately 6.274 MJ kg^{-1} of water removed [15].

In green tea industry sector, the important factor that focuses on the higher cost of production is the high energy consumption during processing. In other countries, 1 kg of "made" tea requires approximately 0.75-0.94 kWh of electrical energy and 22.0-22.7 MJ of thermal energy [16], whereas in India, to produce 1 kg of "made" tea 0.55-0.66 kWh of electrical energy and 14.4-18.0 MJ of thermal energy are used [17], which is 40% less than the average energy consumption by the tea industry over other countries. [18] has quoted the figures of 0.7 kWh of electrical energy and 10.8 MJ of thermal energy to produce 1 kg of "made" tea in India. In tea processing, 90% of the energy requirement is related to thermal energy in the form of hot air and most of this energy is obtained from locally available fuel wood. The high energy consumption is mainly due to the high volume of production and in part due to the low efficiency of equipment such as boilers, heat exchangers, furnaces and the inefficient use of electrical energy in the withering process of operation under hilly conditions.

Due to inflation in the cost for fuel oil and electricity, fuel wood has become the main energy source in the tea industry located mostly at hilly stations and this dependence is creating concern because local forests depletion are being lost at an alarming rate [19]. More than eighty percent of the thermal energy is produced conventionally by combustion of forest fuel wood. The tea industry at The Nilgiris is the largest green tea producers in South India which consumes forest fuel wood. This account for 33% of the total industrial fuel wood consumption and 70% of this fuel wood is collected from forest resource marking gradual depletion. Forest firewood which is the main source of energy for the tea industry is now becoming expensive and scarce as the wood has now been re-discovered for furniture making and acclaimed by experts as the timber of the future with its eco-friendly properties. A shortage of forest firewood for the tea industry is expected in the near future. The diminishing forest ecosystem in the country and rising carbon dioxide levels in the atmosphere for which the whole nation is paying "externally" are also important factors that should be taken into account. A reduction in the use of fuel wood adopting gasification would help to reduce the extent of these existing problems.

The prime objective of this investigating was focused on:

- The specific energy requirements for the green tea leaves processing at a factory located at hilly region.
- The focus of cost effectiveness of the gasifier technology to harness those resources and to compare it with conventionally available methods.
- The further developments in the gasifier technology adopted had occurred locally.
- The effects of operating and design parameters on the thermal performance of the gasifier to meet the demand of thermal energy requirement in a green tea leave panning process methodology.

Experimental

Study area

This pilot scale investigation was carried out at a village located at a distance of 25 kilometers from The Nilgiris, Tamil Nadu, India. This place is located at 11.50°N 76.61°E – around 2500 m above from mean sea level. The altitude of the Nilgiris results in a much cooler and wetter climate than the surrounding plains, so the area is popular as a retreat from the summer heat. During summer the temperature remains to the maximum of 25°C and reaches a minimum of 10°C. During winter the temperature reaches a maximum of 20°C and a minimum of 0°C. The ambient operation condition experienced during the performance study was around 15°C.

Biomass feedstock

Forest fire wood (Figure 1) is the main source of energy for tea industry and for other process heating in industries. In hilly region, the share of biomass as compared to the total energy consumption was about 70% of which fuel wood accounted for 85% of the total biomass consumption. The moisture content of the biomass available for gasification was around 35-40%. The specification and properties of biomass feedstock used for gasification is shown in Table 1.

Green tea process description

The factory produces green tea and panning is an important step during the process of operation in green tea manufacturing. Panning operation is carried out to roast the fresh green leaves and reduce its moisture content to 58 % for further processing in rolling and drying sections. In a conventional system, the panning rotary drum (Figure 2) is heated from the bottom by burning the firewood directly beneath the drum as shown in Figure 3. This conventional method of firing is expected to be suboptimal due to its open combustion of firewood and manual feed of firewood. Most number of times, it was noticed that the flame goes either uncontrolled or subdued during the process of panning operation. A wide variation in combustion process was also noticed. Further, the heat loss from the combustion furnace was also quite rapid due to the outer ambient chill weather conditions. In place

Figure 1: Forest Firewood blocks for gasification.

Sl. No.	Particulars	Specifications
1.	Feedstock	All types of forest fire wood
2.	Moisture content	35-40%
3.	Size	Length=250-300 mm and Diameter=50-100 mm
4.	Bulk density	500-550 kg/m^3
5.	Gross calorific value	3300-3500 kcal/kg
6.	Ash content	2-3%
7.	Volatile Matter	33-35%
8.	Fixed carbon	25-27%

Table 1: Details of biomass feedstock.

Figure 2: Panning process in rotary drum.

Figure 3: Open combustion of fire wood below rotary drum.

of open combustion, it was suggested to adopt a gasifier system that produces flammable gas by the gasification of properly sized firewood. This process integration is expected to give a better control over combustion and thereby achieving a possible reduction in firewood consumption.

Gasifier design

The multi-condition flexible operatability high temperature biomass gasifier is a rectangular shaped which can be operated on all types of firewood that produces tar free gas while removing ash and particulate in the proficient manner. This system can handle high bulk density biomass which operates on stratified downdraft mode under slightly above atmospheric pressure for flexible rating (Figure 4). The gasification zone temperature is maintained 1200°C and above at very high temperatures to achieve tar-free gas. This reactor can accommodate any type of biomass feed even with higher bulk density above 1000 kg/m^3 also comparable to woody biomass such as large wood blocks up to 300 mm length and 100 mm diameter even on higher moisture biomass up to 40%. It works under pressure below 30 cm of water column. The maintenance of char bed porosity, prevention of load to the char bed, uniform distribution of air for partial combustion and augmented performance is achieved adopting air nozzle duct at the centre of the gasifier and rotating grate mechanism. The grate is rotary mechanism which is designed to minimize char ash generation and thus achieving very high gasification efficiency. This system is fully insulated to achieve maximum thermal efficiency as well as cold gas efficiency with tar-free gas. The pressure drop across grate can be uniformly maintained which will make possible to gasify smaller particles of biomass. The load above the reduction zone is totally minimized that helps in efficient agitation of char bed avoiding clinker formation. The design claims are intended for very high temperature reactions inside the gasification zone of the biomass gasifier. The approach of this work was purely adopted on the basis of engineering calculations. The pilot model gasifier (Figure 5) was designed for 360 kWth downdraft modes operating with air at around 15°C as gasifying agent. The designed gasifier system was installed in a green tea processing factory at The Nilgiris, Tamil Nadu, India for supplying thermal energy for panning of green leaves.

Gasifier integration for panning process

The factory produces green tea adopting panning process which is an important operation in green tea manufacturing. Panning operation is carried out to short retention roasting of the fresh green leaves to attain a reduction in its moisture content up to 58% for further processing in rolling and drying sections of the industry. In a conventional system, the panning drum is heated by burning the firewood directly beneath the drum (Figure 3). This method is expected to be suboptimal due to its open combustion of firewood and manual feed of firewood.

Before adopting gasification integration to process, it was noticed that the flame goes either uncontrolled or subdued which results in reduction in process efficiency. A wide variation in combustion process was noticed and further, the heat loss from the combustion furnace was also quite high. In place of open combustion, it was suggested to integrate with gasifier system that produces rich flammable gas by the

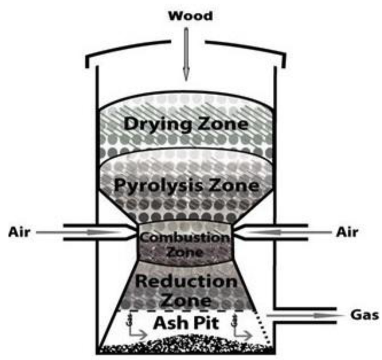

Figure 4: Downdraft gasifier process.

Figure 5: Downdraft gasifier installed for green tea drying.

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gasification of properly sized firewood that is expected to give a better control over combustion and thereby possible reduction in firewood consumption. Gasification is the process of heating the solid biomass (firewood) with sub stoichiometric air supply to release volatile matters and partially combusted gas. The resulting producer gas is a mixture of CO, H_2 and CH_4 which will be used as a gaseous fuel and burnt in the furnace. An in-house burner design was developed and constructed for flaring of the generated producer gas as shown in Figure 6. In the present investigation, the firewood is loaded into the gasifier in semi-continuous mode of feeding and the producer gas generated in the reactor is taken through pipes to the burners where it is burnt uniformly to heat the panning drum (Figure 7).

Results and Discussion

The intent during the production of green tea is to preserve the healthy, natural and active substances of the fresh leaves so they may be released into the cup at the time of infusion. After picking, the green leaves are spread out in the hot air to wither. Once they have become soft and pliable, they are traditionally pan-fried in woks. This prevents the leaves from oxidizing (usually called fermenting) as it occurs during the production of black tea. The subsequent rolling gives the leaves their style: twisted, curly or balled as well as increased durability. Rolling also helps to regulate the release of the natural substances and flavor during the steeping. In the final step, the leaves are dried by firing whereby the natural fragrances and flavors are stabilized; the leaves keep their green color. The resulting green tea is high in nutrients and minerals; their health benefits are the subject of a great number of medical studies.

Drying is the most expensive process in the manufacture of green tea. The capital investment on the driers is also the highest among the different processing machines. Objective of drying are to arrest the fermentation process and to remove the moisture and to produce tea with good keeping qualities. Before going to the different types of drying systems it is essential to know the basis of drying. Drying a solid matter indicates removal of water from the solid materials by evaporation. During the early stages of drying, the solid is so wet that a continuous film of water exists over the entire surface. The water removed during in this period is mainly superficial water. During this period the rate of drying under a given set of air conditions is constant and independent of the moisture content. This period is known as the constant rate of drying and the temperature of the solid during this period approaches the wet bulb temperature of the air. The magnitude of the constant rate depends on the area exposed to the drying medium, the difference in temperature between the gas stream and the wet surface of the solid and the air velocity. The average firewood consumption through conventional system is about 125-130 kg/h. The pre-heating time duration is 1½ hours. The temperature distribution in the panning drum is not uniform due to distributed and uneven burning of firewood. There was no restriction on the type, size and quality of firewood used. The moisture content of final panned leaf is around 61%. Firewood Consumption in pre-heating of Panner is not considered in both the cases Conventional and Gasifier system.

Figure 6: Gasifier burner design.

Figure 7: Producer gas flaring burners below rotary kiln.

Panning process

Non-fermented and very light fermentation: This tea retains quite a bit of their original flavor. Green tea falls in this category. Most green teas like Dragon Well stop the fermentation process through pan frying while a few will stop the fermentation process through steaming. White tea undergoes very light fermentation during the withering process. Sometimes this non-fermented and very light fermented tea will be scented with Jasmine petals to give the tea an aroma of Jasmine. Examples of Non-fermented and very light fermented tea: Green Tea, Steaming Green (Sencha), Jasmine scented Green tea, Yellow Tea, White Tea.

Drying with existing conventional

Drying is done to “finish” the tea for sale. This can be done in a myriad of ways including panning, sunning, air drying, or baking. Baking is usually the most common. Great care must be taken to not over-cook the leaves. The drying of the produced tea is responsible for many new flavor compounds particularly important in green tea. After the tea leaves are plucked, they must be dried to prevent fermentation, which stops any enzyme activity that causes oxidation. In India, green teas are often pan-fired in very large woks, over a flame or using an electric wok. The tea leaves must be stirred constantly for even drying. Withering is also used, which spreads the tea leaves on racks of bamboo or woven straw to dry in the sun or using warm air. Again, the leaves must be moved around to ensure uniform drying.

The principle involved in the conventional driers is that fermented leaf is subjected to a blast of hot air in such a manner that the hottest air first comes in contact with the tea having the least moisture content. In these driers, the fermented leaf falls on a series of moving perforated trays on which it is passed and re-passed through a moving stream of hot air. The perforated trays are mounted on an endless chain and arranged in a tier of six or eight units which alternate in the direction of motion. The design is such that at each stage of the drying operation, the leaf is subjected to a different temperature. As the leaf passes from tray to tray, it progressively comes into contact with higher temperatures. When the air takes up moisture, the dry bulb temperature falls. A final moisture content of between 2.5 and 3.0% should be the aim. If the tea is dried below 1.0%, it loses some quality. Tea dried to 3.5% moisture content and above does not keep well. The optimal inlet temperature for processed leaf is 100 ± 5°C. The exhaust temperature should be maintained at 54.4 ± 2.7°C (130 ± 5°F). If the exhaust temperature is less than 49°C (120°F), the post fermentation process will continue for a considerable time and will soften the liquor. This condition is referred to as "stewing". If the exhaust temperature is greater than 57.2°C (135°F) the rate of moisture removal is too rapid and results in case hardened tea in which the particles are hard on the outside but incompletely dried within; such teas yield harsh liquors and do not keep well. So it is of paramount importance to ensure that temperatures are kept under control to the extent possible.

Drying with gasifier integration

Gasification is the process of heating the solid biomass (wood) with sub stoichiometric air supply to release volatile matters and partially combusted gas, namely, CO. The resulting producer gas is a mixture of CO, H_2 and CH_4 which will be used as a gaseous fuel and burnt in the furnace. In the present case, firewood is loaded into the gasifier in batches and the producer gas generated in the reactor is taken through pipes to the burners where it is burnt uniformly to heat the panning drum.

Cumulative comparisons

The performance data were noted for 7 weeks (05.03.2013 to 22.04.2013) and discussed. Experimental investigations were carried out on phase wise manner to explore the possibilities of studying the performance enhancements integrating biomass gasifier for drying applications in a hilly condition gasifier operations, In the Phase-1, the performance investigation was carried out for conventional methodology (without integrating gasifier) as shown in Table 2 and in Phase-2 and Phase-3, the performance investigation was carried out for gasifier integrated process as shown in Tables 3 and 4. The cumulative values of the performance investigation undertaken in Phase-2 and Phase-3 were noted (Table 5).

The comparison between the operational parameters of the conventional panning and gasifier operated panning system were noted (Table 6). The panning rate was higher in gasifier system compared to that in conventional system as can be seen from the following chart as shown in Figure 8. This step is the crucial technique for quality. Panning has four important goals: to get the proper color, smell and taste of Green Tea by completely destroying the activity of enzymes in fresh leaves and stop the enzymatic oxidation of polyphenols; to give off grassy smell in order to release the aroma; to evaporate part of the water in the fresh leaves to soft the leaves and enhance toughness to make the next step rolling easier; to promote the transformation of inclusions, and promote the formation of green tea. The drying of the produced tea is responsible for many new flavor compounds particularly. At the same time improve its appearance.

Phase-1 Study (conventional investigation):

- The average firewood consumption through conventional system was about 125-130 kg/h.
- The pre–heating time duration was 1½ hours.
- The temperature distribution in the panning drum is not uniform due to distributed and uneven burning of firewood.
- There was no restriction on the type, size and quality of firewood used.
- The moisture content of final panned leaf was around 61%.

Phase-2-3 Study (gasifier integrated investigation):

- The average firewood consumption by the gasifier system was 145 kg/h.

No	Parameter	Unit	5th – 11th March 2013	12th – 18th March 2013
1	Total firewood gasified per day	kg	1000	1260
2	Gasifier operation per day	min	465	610
3	Firewood feed rate	kg/h	130	124
4	Panned green leaves per day	kg	5 372	8692
5	Moisture content (initial)	%	68	68
6	Moisture content (final)	%	61	61
7	Moisture evaporation	kg	964	1560
8	Panning operation per day	min	405	620
9	Panning rate of green leaves	kg/h	796	841
10	Moisture evaporation rate	kg/h	143	151
11	Specific wood consumption	kg wood/kg Leaves	0.162	0.147
12	Specific moisture removal	kg moisture/ kg wood	1.1	1.217

Table 2: Average values of Phase-1 (conventional investigation).

No	Parameter	Unit	19th – 25th March 2013	26th – 1st April 2013
1	Total firewood gasified per day	kg	713	910
2	Gasifier operation per day	min	300	420
3	Firewood feed rate	kg/h	143	130
4	Panned green leaves per day	kg	3852	6108
5	Moisture content (initial)	%	67	72
6	Moisture content (final)	%	61	62
7	Moisture evaporation	kg	593	1 607
8	Panning operation per day	min	240	365
9	Panning rate of green leaves	kg/h	963	1004
10	Moisture evaporation rate	kg/h	148	265
11	Specific wood consumption	Kg wood/kg Leaves	0. 148	0. 129
12	Specific moisture removal	kg moisture/ kg wood	1. 036	2. 032

Table 3: Average values of Phase-2 (gasifier integrated investigation).

No	Parameter	Unit	2nd – 9th April 2013	19th – 15th April 2013	16th – 22nd April 2013
1	Total firewood gasified per day	kg	1570	1900	1700
2	Gasifier operation per day	min	660	780	645
3	Firewood feed rate	kg/h	143	146	158
4	Panned green leaves per day	kg	8120	11607	9240
5	Moisture content (initial)	%	68	70	68
6	Moisture content (final)	%	58	60	57
7	Moisture evaporation	kg	1933	2902	2364
8	Panning operation per day	min	570	680	600
9	Panning rate of green leaves	kg/h	855	1024	924
10	Moisture evaporation rate	kg/h	204	256	237
11	Specific wood consumption	kg wood/kg Leaves	0.167	0. 142	0. 17
12	Specific moisture removal	kg moisture/ kg wood	1. 424	1. 753	1. 496

Table 4: Average values of Phase-3 (gasifier integrated investigation) .

No	Parameter	Unit	Cumulative
1	Total firewood gasified per day	kg	6793
2	Gasifier operation per day	min	2805
3	Firewood feed rate	kg/h	145
4	Panned green leaves per day	kg	38927
5	Moisture evaporation	kg	9399
6	Panning operation per day	min	2455
7	Panning rate of green leaves	kg/h	951
8	Moisture evaporation rate	kg/h	230
9	Specific wood consumption	kg wood/kg Green Leaves	0.153
10	Specific moisture removal	kg moisture/ kg wood	1.586

Table 5: Cumulative values of Phase-2 to Phase-3 (gasifier integrated investigations).

No	Parameter	Unit	Panning System (Conventional)	Panning System (Gasifier)	% Variation from Conventional
1	Green Leaf Panning Rate	Kg/h	823	951	+ 15. 6
2	Moisture Evaporation Rate	Kg/h	148	230	+ 55. 4
3	Firewood Firing Rate	Kg/h	126	145	+ 15. 0
4	Specific Moisture Evaporation Rate	kg H_2O/kg wood	1. 175	1. 586	+ 35. 0
5	Specific Wood Consumption	kg wood/kg Green Leaf	0. 153	0. 153	0

Table 6: Comparison between the operational parameters of the conventional panning and gasifier operated panning system.

- Pre–heating time duration was found to be less than conventional system at 30-35 min from fully loaded condition of gasifier.
- The temperature distribution across the panning drum was even at around 300°C.
- Smaller size firewood [less than 100 mm diameter] was used during study.
- The moisture content of the final panned leaf was around 60%.
- Moisture Evaporation rate was certainly on the higher side compared to that achieved in conventional system.

Conclusion

Wood firing rate has obviously gone–up in the gasifier system due to controlled combustion and utilization in an effectively designed system meant for giving higher heat output. The wood firing rate was 15% more achieved compared to the conventional open firing system. Green leaf charging rate was increased by 15.6% which depicted a positive trend. Moisture removal rate has gone up tremendously by 55.4% when gasifier panning was resorted to in place of conventional panning arrangement. Ultimately, the efficiency parameter defined as moisture evaporation rate per kg of wood fired has increased by 35%. This is equivalent to saying that the wood savings is 35% for the same quantity of moisture removal when gasifier was used. Thus, the gasifier

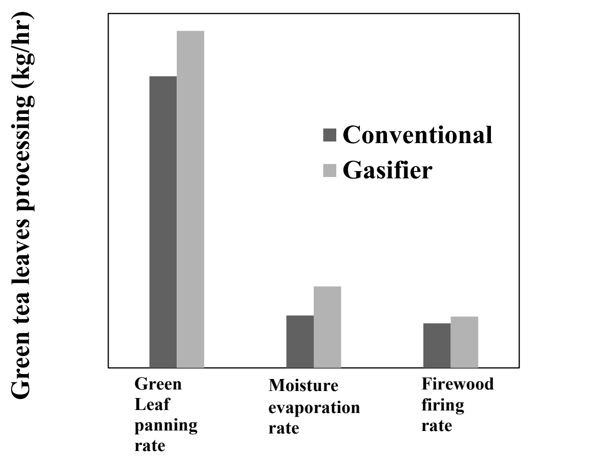

Figure 8: Comparison chart between the operational parameters of the conventional panning and gasifier operated panning system.

system seems to be offering both the benefits of increased panning rate of green leaves and simultaneous reduction in specific fuel wood consumption for evaporating moisture. This performance study of the designed gasifier for a hilly condition operation will be a boon at all-scale industrial sector focused for all the chill ambient weather condition countries.

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