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Utilization of Agro-Residue Wastes Through Clean Combustion for Sustainable Energy Solutions in Jaggery Production

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Abstract - India is an agriculture-based economy and most of the crops are grown due to suitable weather conditions therefore, various crop residues having significant energy potential are available in abundance. Some of the agro-residues and agro-processing wastes are consumed during the processing of refined product particularly, for generating heat while some remains unconsumed, estimated to be more than 300 million ton/yr. Jaggery is one such activity where the requirement of heat is met by the bagasse, which is a by-product of the sugarcane itself. However, traditional jaggery making is an energy-intensive process that utilizes the bagasse to produce heat in an open-hearth furnace leading to huge emissions of harmful pollutants into the environment. These emissions need to be assessed and technical interventions are required to reduce the levels of pollutants that are being released from traditional plants leading to sustainable utilization of agro-residues. In this article, an attempt has been made to estimate the thermal efficiency and annual emissions of CO and PM2.5 from different jaggery making units viz. varying in the number of pans. Further, emission reduction potentials from traditional jaggery plants have been calculated and compared to the proposed modified plant having improved combustion characteristics. The result obtained, indicates that the emissions of CO and PM2.5 from the traditional jaggery making units could be reduced up to 91.23 - 95.36% and 97.10 - 98.47%, respectively.

***Keywords*:** Jaggery plant; Thermal efficiency; Bagasse consumption; Emission savings; Crop residues.

1. Introduction

Jaggery, a traditional Indian sweetener, is produced by continuous heating and boiling of sugar cane juice in open pans. India is the leading producer of jaggery and holds more than 70% of global jaggery production. The daily jaggery production from a plant varies from place to place, and there are several factors including but not limited to the type of plant, plant size, number of pans, distance from the market and so on, as these plants are part of the unorganized sector [1]. The number of pans in a jaggery unit varies from one to four, and its overall performance increases, as the number of pans in a jaggery plant increases [1]. However, some of the authors have also reported that the performance of three-pan units is better compared to four-pan units [2].

However, the traditional open-hearth furnaces are constructed by local semi-skilled labourers which consume an enormous amount of fuel varying from 3 to 4 kg of bagasse per kg of jaggery production, having very poor thermal performance and combustion characteristics [1,3]. The thermal performance and emission characteristics of jaggery plants can be improved through various technological interventions being proposed by the number of authors [4–13]. These interventions include the use of solar energy for juice boiling and bagasse drying [4], freeze pre-concentration [6], changes in pans design [4,10,14], waste heat utilization [9], modifying furnace design [1,15], controlled fuel feeding and inlet air flow rate [9] as well as, the integration of these technologies [13].

In 2018, India produced 585.47 MT of agricultural wastes, out of which wheat, rice and sugarcane contributed to more than 80% [16] and approximately 24% of the agricultural residue was burnt in the open fields [17]. The stubble burning releases various harmful pollutants such as fine and ultrafine particulate matter (PM2.5 and below), carbon monoxide (CO), oxides of nitrogen (NOx), volatile organic compound (VOCs), non-methane volatile organic compound (NMVOCs), semi-volatile organic compound (SVOCs), and polycyclic-aromatic-hydrocarbons (PAHs) [17–19]. The prolonged exposure to these pollutants stimulates several health problems such as respiratory diseases, coughing, bronchospasm, irregular heartbeat, reduction in pulmonary and lung function, hypoxia, ischemia, cardiovascular disease, etc. and results in a huge burden on the economy of the country [17,20–24].

The utilization of agro-residues for bioenergy applications is one of the most discussed technological methods of waste management. Apart from heat generation through direct combustion, bagasse could be a precious commodity to produce fibre composites, bioethanol, activated carbons, paper making, etc. which can generate additional revenue to the jaggery plant owner, if it is sold in the market. On the other hand, the heat required for jaggery production can be fulfilled by utilizing the processed agro-residue (pellets, briquette, etc.) being burnt in the open field. Therefore, there is an urgent need to replace the traditional open-hearth furnace with a more scientifically designed modified furnace that can burn the processed agro-residue thereby, reducing not only the fuel consumption but also burning it cleanly similar to gas burner [25] and reducing the burden on the environment [1].

From the available literature, it is found that the penetration of technology has been very limited for the jaggery industry and the modifications were restricted to pans, crushing units, juice clarification and utilization of waste heat and use of solar energy. But scientific interventions for the design and improvements in the traditional open-hearth furnace were found to be very limited, as a result, the thermal performance and emission characteristics, remain poor even today.

Therefore, the objective of the present work is to evaluate the bagasse consumption, thermal performance and emission characteristics of the traditional jaggery industry, for sustainable utilization of agro-residues.

2. Materials and Methods

The schematic of a traditional three-pan jaggery plant is shown in Fig. 1. The first process in the jaggery making process involves the crushing of sugarcane harvested from the fields to obtain the juice which is stored in a settling tank. The bagasse left after the crushing of sugarcane is first dried in the open fields and, thereafter combusted in the open-hearth furnace to fulfil the thermal energy requirement for the jaggery making process. These furnaces are very inefficient due to the lack of availability of proper air-fuel ratio leading to incomplete combustion which further results in the emission of harmful pollutants and excess fuel consumption.

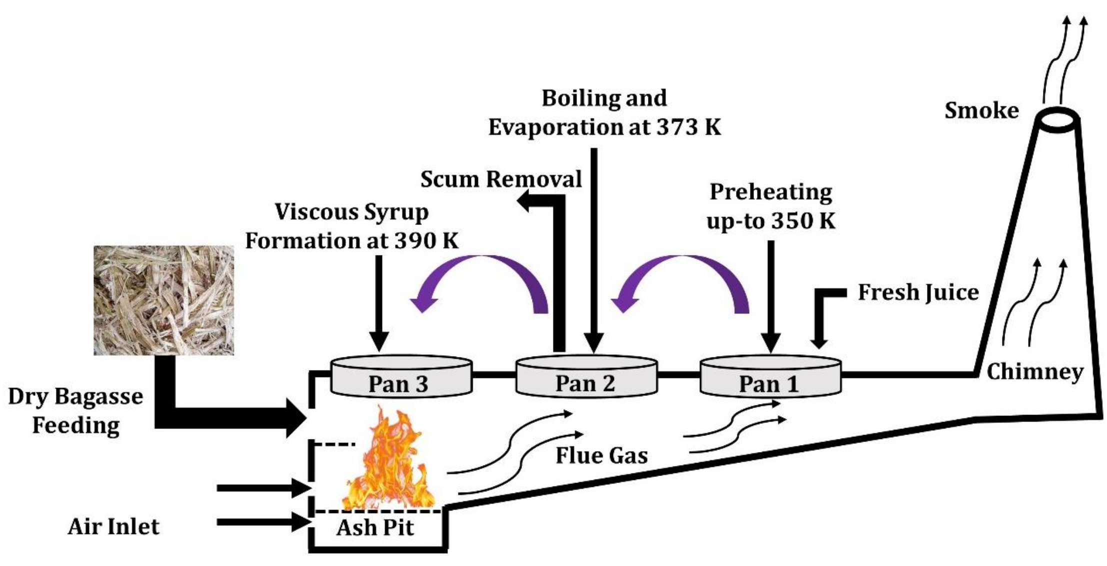


Fig. 1: Schematic of traditional three pan jaggery plant

The emission of pollutants from the jaggery making plants significantly contribute to air pollution and is hazardous for both human health and the environment. The annual emissions of CO, CO_2, and PM2.5 from traditional and modified jaggery plants have been estimated. A total of six plants have been considered in this study as shown in Table 1. The data of bagasse consumption for four jaggery plants have been taken from the already published literature, while data for the traditional three-pan jaggery plant has been collected in the present study to ensure the reliability of the published work. Further, a plant has been proposed to have a modified combustion device to lower the emission of pollutants.

Table 1: Details of different plants considered in this study

S. No.	Name	Type	Reference
1.	Plant 1	Traditional 3-Pan	[26]
2.	Plant 2	Traditional 3-Pan	Present study
3.	Plant 3	Traditional 4-Pan	[26]
4.	Plant 4	Traditional 4-Pan	[12]
5.	Plant 5	Modified 4-Pan	[12]
6.	Plant 6	Proposed Plant	Present study

The data for the traditional 3-pan jaggery plant was collected at Tatiri village in Baghpat district of Uttar Pradesh, India. A platform balance of 100 kg capacity was used to perform the weighing activities. The thermal efficiency of the different jaggery plants was calculated by estimating the heat utilized in the jaggery making process which can be calculated by using the following equations [11]:

$$\text{Heat utilized} = \left[m_w C_{pw}(T_{bw} - T_{wo}) + m_w L_w\right] + \left[m_j C_{pj}\left(T_{sj} - T_{ji}\right)\right] \quad (1)$$

$$\text{Heat input} = m_b \times CV_b \quad (2)$$

$$\text{Thermal Efficiency}(\eta) = \frac{\left[m_w C_{pw}(T_{bw} - T_{wo}) + m_w L_w\right] + \left[m_j C_{pj}\left(T_{sj} - T_{ji}\right)\right]}{m_b \times CV_b} \times 100 \quad (3)$$

where, m_w is the mass of water evaporated from sugarcane juice (kg); C_{pw} is the specific heat of water (kJ/kg.K); T_{bw} is the boiling temperature of water (K); Two is the initial temperature of water (K); L_w is the latent heat of vaporization of water (kJ/kg); m_j is the mass of jaggery produced; C_{pj} is the specific heat of jaggery (kJ/kg.K); T_{sj} is the striking point temperature of jaggery; T_{ji} is the initial temperature of jaggery (K); m_b is the mass of bagasse consumed and CV_b is the calorific value of bagasse.

Table 2: Different parameters used for calculation of thermal efficiency [11,12].

S. No.	Parameter	Value
1.	Juice content in sugarcane	65 % (by weight)
2.	Jaggery content in sugarcane	12.5% (by weight)
3.	Specific heat of water	4.186 kJ/kg.K
4.	Latent heat of evaporation of water	2270 kJ/kg
5.	Specific heat of jaggery	2 kJ/kg.K
6.	Calorific value of bagasse	16000 kJ/kg
7.	Boiling temperature of water	373 K
8.	Striking temperature of jaggery	391 K

3. Results and Discussion

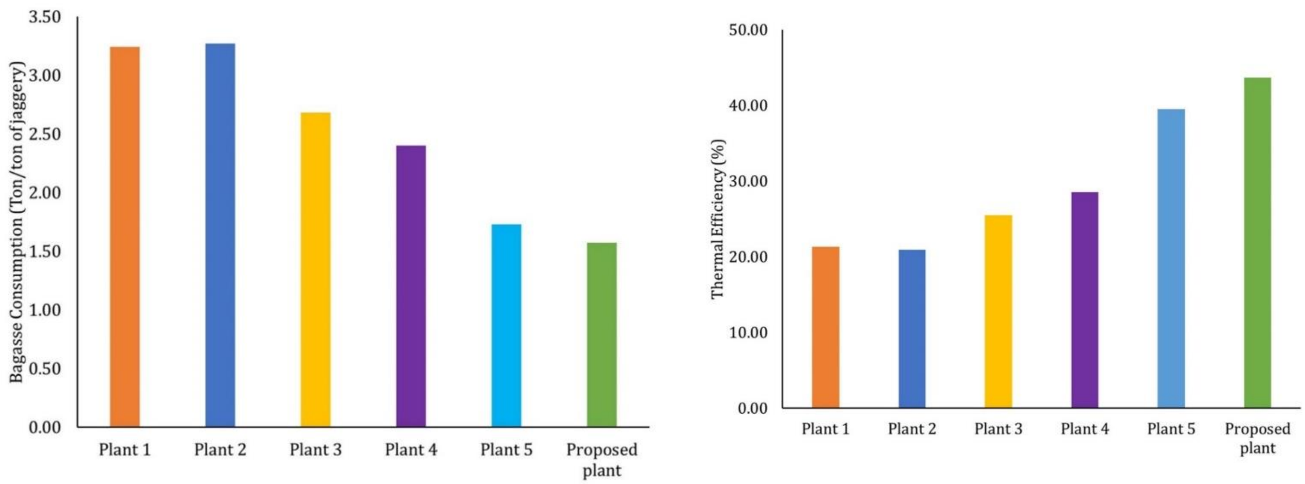
The majority of jaggery plants are being fabricated by semi-skilled workers without having much knowledge of combustion mechanism, air-to-fuel ratio and heat transfer, leading to incomplete burning of fuel in the furnace, which is responsible for the release of harmful pollutants into the environment. It is evident from the previously published literature that the intensity and type of pollutants released from the traditional jaggery plants are similar to that of the traditional open fire stoves being used by more than 40% of the global population [1,25]. The emission characteristics of the traditional stoves using agro residues are available in the literature and have been used in this study to estimate the annual of CO, CO_2, and PM2.5 for different multi-pan jaggery plants. The emission factors of traditional and proposed plants used for the determination of annual emissions are shown in Table 3.

Table 3: Emission factors of traditional and proposed jaggery plant [1,27]

S. No.	**Type of plant**	**CO (g/kg-fuel)**	**PM 2.5 (g/kg-fuel)**
1.	Traditional	65.6	6.3
2.	Proposed	6.4	0.2

The annual emissions from a jaggery plant proposed in this study have also been calculated if the traditional furnace in the jaggery plant is replaced by a developed combustion device while utilizing pellets as fuel. Further, the emission reduction potentials of CO, CO_2 and PM2.5 from the proposed plant have also been calculated as compared to the multi-pan jaggery plants. The bagasse consumption per ton of jaggery production in multi-pan traditional and modified plants is shown in Fig. 2(a). The bagasse consumption for traditional 3-pan and 4-pan jaggery plants were found to be in the range of 3.24 – 3.27 ton/ton of jaggery and 2.40 – 2.68 ton/ton of jaggery, while the values were 1.73 ton/ton of jaggery and 1.57 ton/ton of jaggery for the modified 4-pan and proposed plant, respectively.

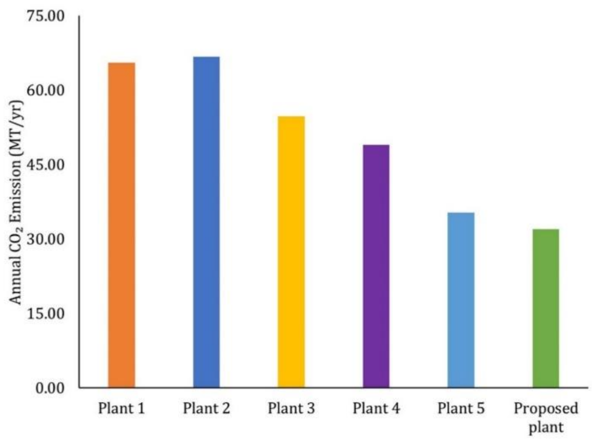
The thermal efficiencies of the different plants were also calculated as shown in Fig. 2(b). The values of thermal efficiencies for traditional three-pan and four-pan jaggery plants were estimated to be in the range of 20.92 – 21.30 % and 25.51 – 28.49 %, while these were found to be 39.53% and 43.68% for modified and proposed plants respectively. Therefore, the proposed jaggery plant was found to be the most efficient having the highest thermal efficiency and lowest bagasse consumption among all the jaggery plants. It has been estimated that the farmers could be able to generate an additional income of 0.99 – 2.04 billion USD annually from the bagasse savings in the traditional multi-pan jaggery making plants while utilizing the proposed plant. The reduced bagasse consumption in a proposed plant may enable the use of fresh bagasse saved from traditional jaggery plants in other valuable products such as the paper and pulp industry etc. This may further enhance the market value of fresh bagasse obtained from sugarcane juice in raw form.



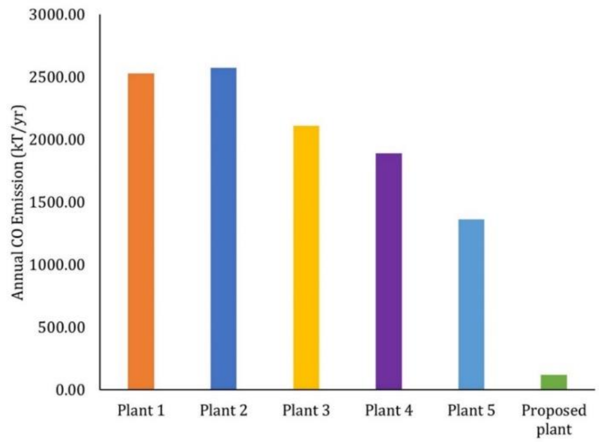
(a) (b)

Fig. 2: (a) Bagasse consumption per ton of jaggery (b) Thermal efficiency in different jaggery plants.

The annual emissions of CO_2, CO and PM2.5 for different plants are shown in Fig. 3. The emission of CO_2 from the traditional three-pan and four-pan jaggery units were found to be in the range of 65.48 – 66.71 MT/yr and 48.96 –54.67 MT/yr, while for the modified and proposed plants, these values were 35.29 MT/yr and 31.94 MT/yr, respectively, as can be seen from Fig. 3(a). The annual CO emission from traditional three-pan and four-pan jaggery making units were ranged between 2526.91 – 2574.14 kT/yr and 1889.28 – 2109.70 kT/yr, while it was found to be 1361.86 kT/yr and 119.47 kT/yr for the modified and proposed plants, respectively as shown in Fig. 3(b). On the other hand, the annual emissions of PM2.5 from traditional three-pan and four-pan jaggery plants were found to be in the range of 242.68 – 247.21 kT/yr and 181.44 – 202.61 kT/yr, while the values were 130.79 kT/yr and 3.79 kT/yr for modified and proposed plants, respectively as can be seen from Fig. 3(c).



(a)



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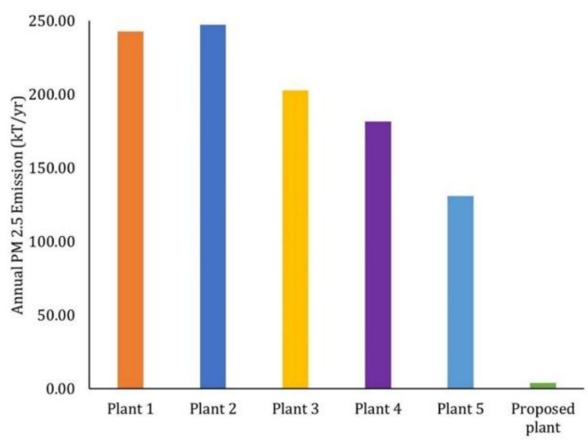

(c)

Fig. 3: Annual emissions of a) CO_2, b) CO and c) PM2.5 from different jaggery plants.

The emission reduction potentials of CO_2, CO and PM2.5 from the proposed plant as compared to the multi-pan traditional and modified jaggery plants is presented in Fig. 4(a-c). It is visible from Fig. 4(a) that the emission of CO_2 could be lowered in the range of 51.23 – 52.13% and 34.77 – 41.59% for traditional three-pan and four-pan jaggery plants, while for plant 5 the saving can be 9.51%, respectively. The savings in the emission of CO_2 from the proposed plant are directly linked to the bagasse consumption per ton of jaggery production. The values of emission reduction potentials for CO and

PM2.5 were found to be in the range of 95.27 – 95.36% and 98.44 – 98.47% for traditional three-pan plants, while these values ranged between 93.68 – 94.34% and 97.91 – 98.13% for traditional four-pan plants, respectively as shown in Fig. 4(b-c). Further, the saving potentials of CO and PM2.5 for the proposed plant could be 91.23% and 97.10% respectively, as compared to plant 5. The significant reduction in emissions from the proposed plant was attributed to the savings in bagasse consumption as well as the lower emission factors of the modified combustion device due to the improved combustion characteristics.

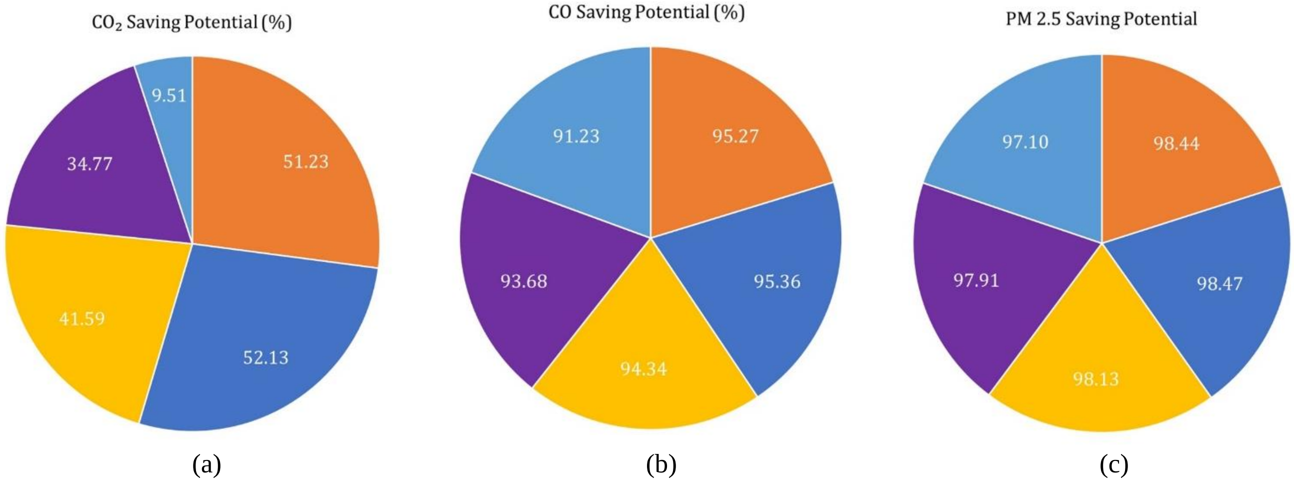

Fig. 4: Emission reduction potentials of a) CO_2, b) CO and c) PM2.5 from proposed jaggery plant.

4. Conclusion

This article estimates the thermal performance, emission characteristics, bagasse consumption and emission reduction potential of CO and PM2.5 for different jaggery making units viz. varying in the number of pans. It was concluded from the field study that there is a huge scope of improvement in the multi-pan traditional jaggery plants which could result in savings of bagasse consumption as well as the emissions of harmful pollutants. The bagasse consumption in traditional 3-pan and 4-pan jaggery making plants was found to be in the range of 2.40 – 3.27 kg/kg of jaggery produced and can be reduced by 34.58 – 51.98% while utilizing processed biomass such as pellets in the proposed jaggery plant.

Further, there is a huge potential for bagasse savings through improved combustion and furnace modifications, as proposed in this study as compared to the traditional jaggery industry in the country, which is equally applicable elsewhere. Therefore, the surplus bagasse resulting from reduced consumption due to the proposed modifications in the traditional plants can be utilized in different industries for other value-added products including the pulp and paper industry. At present, the bagasse price is around USD 100/ton in the Indian market, which may generate significant revenue, if utilised in other industries for other products. It is further estimated that the bagasse savings may lead to additional earnings to farmers of around 0.99 – 2.04 billion USD, annually.

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