Journal of Environmental Management 301 (2022) 113792

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Technological advancements in jaggery-making processes and emission reduction potential via clean combustion for sustainable jaggery production: An overview

S.K. Tyagi [a,*], S. Kamboj [a], Himanshu [a], N. Tyagi [a], R. Narayanan [b], V.V. Tyagi [c]

[a] Department of Energy Science and Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, 110016, India
[b] School of Engineering and Technology, Central Queensland University, QLD, 4670, Australia
[c] School of Energy Management, Shri Mata Vaishno Devi University, Katra, (J&K), 182320, India

ARTICLE INFO

Keywords:
Technological advancements
Sustainable jaggery production
Emission reduction potential
Cleaner combustion
Freeze pre-concentration

ABSTRACT

Jaggery is a kind of unrefined non-centrifugal sugar (NCS) used mainly in Asia, Africa, Latin America, and the Caribbean. Traditionally, jaggery is produced by concentrating sugarcane juice in open pans with the help of bagasse combustion. However, due to thermal energy loss with flue gases and an unscientific approach in plant construction, jaggery plants have a poor thermal efficiency of less than 25%, poor emission characteristics, and a high bagasse consumption rate. Advanced jaggery-making techniques use solar energy and heat pumps for jaggery production. However, these techniques are in the early stage of development, and the literature indicates that these techniques should be used in conjuction with traditional ones to improve the performance of jaggery making plants. This literature review describes advances in jaggery-making methods, critically analyzed them, and provides a qualitative comparison of these methods. Further, gaps in the existing literature are identified and reported for future research direction.

In addition, efforts have been made to quantify and estimate the emissions reduction and bagasse consumption potentials from the traditional jaggery industry to make this rural industry a sustainable and profitable business for rural entrepreneurs. The comparison with the recently developed clean combustion device exhibits that the harmful emissions from the jaggery industry could be reduced drastically viz. 95%–98% of PM2.5; 92%–95% of CO, and 52–60% of CO2, while saving more than 35% of bagasse consumption. Implemented at a national scale, it may reduce nearly 3% of all harmful emissions in the country, which is equally applicable elsewhere.

Authors credit

S K Tyagi: Conceptualization, Data collection and analysis Reviewing and Editing, Supervision. Sachin Kamboj: Conceptualization, Writing - Original Draft preparation, Visualization. N Tyagi: Data collection from the jaggery plant. Himanshu: Writing - Original Draft preparation, Formal analysis, Methodology. R. Narayanan: Writing- Reviewing and Editing. V. V. Tyagi: Writing- Reviewing and Editing.

1. Introduction

The jaggery industry is a traditional and small-scale rural-based cottage industry that has played an important role in creating jobs and contributing to the rural Indian economy. Jaggery is an unprocessed and non-centrifugal traditional Indian sweetener produced through evaporation or freezing of water from sugarcane juice (Kumar and Kumar, 2021; Singh et al., 2013). It is manufactured in many countries and is known by various names in different countries: gur (India and Pakistan), panela (Peru and Colombia), hakura (Srilanka), kokuto (Japan), rupadura (Brazil), Naam taan Oi(Thailand), and jaggery (the Philippines and Burma) (Asfaq and Chand, 2020; Kumar and Singh, 2020; Vera-Gutiérrez et al., 2019). India is the world's largest producer of jaggery, accounting for 70% of total jaggery production, followed by Colombia accounting for around 12% (Solís-Fuentes et al., 2019). India's major jaggery export partners are Nepal, USA, Benin, UAE, Sudan, Kenya, Kuwait, Oman, Russia, Canada, Philippines, and Bangladesh. The quality of the jaggery is determined by the processing method, clarifiers utilized and the variety of sugarcane used (Hariprasad et al., 2014;

* Corresponding author.
E-mail addresses: sudhirtyagi@yahoo.com, tyagisk@iitd.ac.in (S.K. Tyagi).

https://doi.org/10.1016/j.jenvman.2021.113792
Received 27 January 2021; Received in revised form 11 August 2021; Accepted 18 September 2021
Available online 1 October 2021

Vera-Gutiérrez et al., 2019). The high-quality jaggery is golden yellowish in color, low in moisture, and hard in texture (Said and Pradhan, 2013). However, the color of jaggery, the extent of inversion during storage, and moisture content also depend on the acid and chemical clarifiers employed during processing (Verma et al., 2019a, 2019b, 2019b). Consumption of jaggery offers many health benefits, such as blood pressure regulation, mitigates the impact of arsenic consumption on human health, acts as cytoprotective, boosts immunity, improves digestion, etc. (Jaffe, 2012; Patil, 2021; Singh et al., 2010).

Jaggery-making methods may be broadly classified into two categories: traditional and advanced. Another way to categorize jaggery-making techniques is the process by which water is removed from the cane juice: evaporation technique and freezing technique. However, this categorization provides no information about the maturity level of a technique. The traditional method uses open pans for cane juice heating while bagasse is burnt in a furnace to provide heat for juice heating. Advanced techniques, on the other hand, are those that use modern technology for jaggery production, such as heat pumps, steam jacket pans, and renewable (solar still and evacuated solar tubes) energy. Although technological advancements have aided in the improvement of the conventional jaggery-making procedure over the years, lack of automation, bagasse handling, poor furnace efficiency, and waste heat utilization are still issues that need to be addressed (Kumar and Kumar, 2018, 2021; Pandraju et al., 2021). It can also be determined from the existing literature that advanced techniques alone are incapable of converting cane juice to jaggery. As a result, it is recommended that advanced techniques should be used in conjunction with the traditional method to improve the overall performance of jaggery-making plants.

While conducting the literature survey, it was perceived that only a limited number of review articles related to jaggery production have been published in the past. For review purposes, we have referred to peer-reviewed journal articles. We have, however, included grey material on rare occasions where it was necessary. Nath et al. (2015) reviewed value-added jaggery products, Jaffe (2012) reviewed the health effects of jaggery consumption, Madhu et al. (2018) reviewed the use of various edible coatings to improve the shelf life of jaggery, Meshram and Deshmukh (2018) reviewed jaggery-making process, and Velásquez et al. (2019) reviewed process variables in jaggery production and their effect on the final product. Kumar and Kumar (2018) reviewed advances in the jaggery-making process and storage technologies. Selvi et al. (2021) reviewed advancements in jaggery-making, packing, and storage. Although this review article discussed freeze-pre concentration jaggery-making method briefly, it does not discuss the contribution from various researchers in the advancement of this method and its limitations. Also, there is no discussion related to the environmental aspect of jaggery production. Similarly, Kore and Lakade (Kore and Lakade, 2021) discussed modifications incorporated by various researchers in the traditional jaggery-making method. However, the limitations of the freezing process and the environmental issues of jaggery production methods were not discussed in this article.

The current article provides an unprecedented comprehensive review of the jaggery industry, covering technical advancements in traditional jaggery-making technique, advanced jaggery-making techniques (freeze-pre concentration, solar still, and evacuated solar tubes), as well as their limitations and qualitative comparison. Furthermore, for the first time, this article used layout to demonstrate the traditional jaggery-making process used in the production of various types of jaggery. It also discusses the environmental aspects of the traditional jaggery-making technique.

Therefore, the present study has focused on the following aspects:

(i) To review the technological advancement in jaggery production processes along with their limitations.
(ii) To evaluate emissions reduction potential from the traditional jaggery units via cleaner combustion.
(iii) To identify and report the research gaps and recommendations for future R&Ds.

2. Jaggery production

During the 2018–19 fiscal year, sugarcane production was 415 million tons (Indian Sugar Mills Association, 2019). Approximately 20–30% of total sugarcane produced goes into the jaggery-making industry (Singh et al., 2013). Sugarcane juice accounts for around 70% of jaggery production, with palms accounting for the remaining 30% (Rao et al., 2008). Jaggery is available in liquid, powder (granular), and solid forms. Around 80% of total jaggery production in India is prepared in solid form, while the remaining 20% is prepared in granular and liquid form (Rao et al., 2007). All three types of jaggery are made in much the same way. Once the juice reaches its striking point, liquid jaggery is extracted and filled directly into vessels; solid jaggery is filled in molds or wrapped in wet cloths after stirring. On the other hand, granular jaggery is prepared by mixing a small amount of sodium bicarbonate (baking soda) and orthophosphoric acid, followed by stirring and rubbing with wooden scrapers on a circular concrete slab. The sequence of processes involved in jaggery-making is shown in Fig. 1.

A typical jaggery plant/unit has a mechanical crusher, a power source (electric motor/or diesel engine), several pans, a concrete disk, a furnace with a bagasse feeding hole, and a chimney (see Fig. 2). The crushing capacity of the jaggery unit depends upon its size and varies from 1.5 tons to 8–8.5 tons per day, with a jaggery production capacity of 0.15 tons–1.1 tons per day, respectively (Yadav et al., 2018). In general, a jaggery unit with four pans and a cane crushing capacity of 7–10 tons per day requires 8–10 labors for 24 × 7 operation. The number of pans in jaggery units varies from 1 to 4. Jaggery units with one pan are prevalent in the Kolhapur region of Maharashtra and some parts of Punjab. In Karnataka, two pan jaggery units are prevalent; in Maharashtra and Punjab, single and four pan units are frequent; and in western Uttar Pradesh and Uttarakhand, three and four pan units are common (Shanthy and Baburaj, 2015). When utilized for large volumes of jaggery production, three pan jaggery units have higher efficiency, lower operating costs, and higher profitability (Shanthy and Baburaj, 2015). The schematic view of a typical four-pan jaggery unit is represented in Fig. 2.

Jaggery has 50 times more minerals than white sugar (Gopalan et al., 1989), and one ton of jaggery is equivalent to 0.66 tons of white sugar in terms of sweetening ability (Dhawan, 1967). The nutritional values of solid, liquid and granular jaggery are given in Table 1. The granular (powdered) jaggery is more stable than the solid jaggery because of higher crystallization during its production as compared to the former (Verma et al., 2019c). Some manufacturers add sucrose during granular jaggery production to ensure the uniform particles size (Pawar et al., 2017). The crystallization process of jaggery impacts its texture and shelf life. Crystallization is influenced by stirring time, cooling rate, and reducing sugar (RS) in the viscous syrup, and a temperature of 80–85 °C is sufficient to achieve sufficient crystallization (Verma et al., 2020). Moreover, the slow cooling rate of syrup favors crystallization, while RS in the syrup has dominating control on the crystallization and negatively impacts it.

Jaggery demand is anticipated to rise in emerging and undeveloped nations as a result of urbanization, rising middle-class income, and population expansion. India exported about 0.314 million tonnes of jaggery worth USD 230 million in 2018–19, a figure that is anticipated to rise at a pace of around 6% yearly in the future years (Ministry of Commerce and Industry, 2019), while total worldwide demand is expected to reach 180 million tons by 2020–21 (APEDA, 2020). Therefore, to satisfy the rising demand for jaggery, production must be increased, which may be accomplished by expanding the number of jaggery units, increasing their production capacity, and enhancing their thermal and mechanical performance.

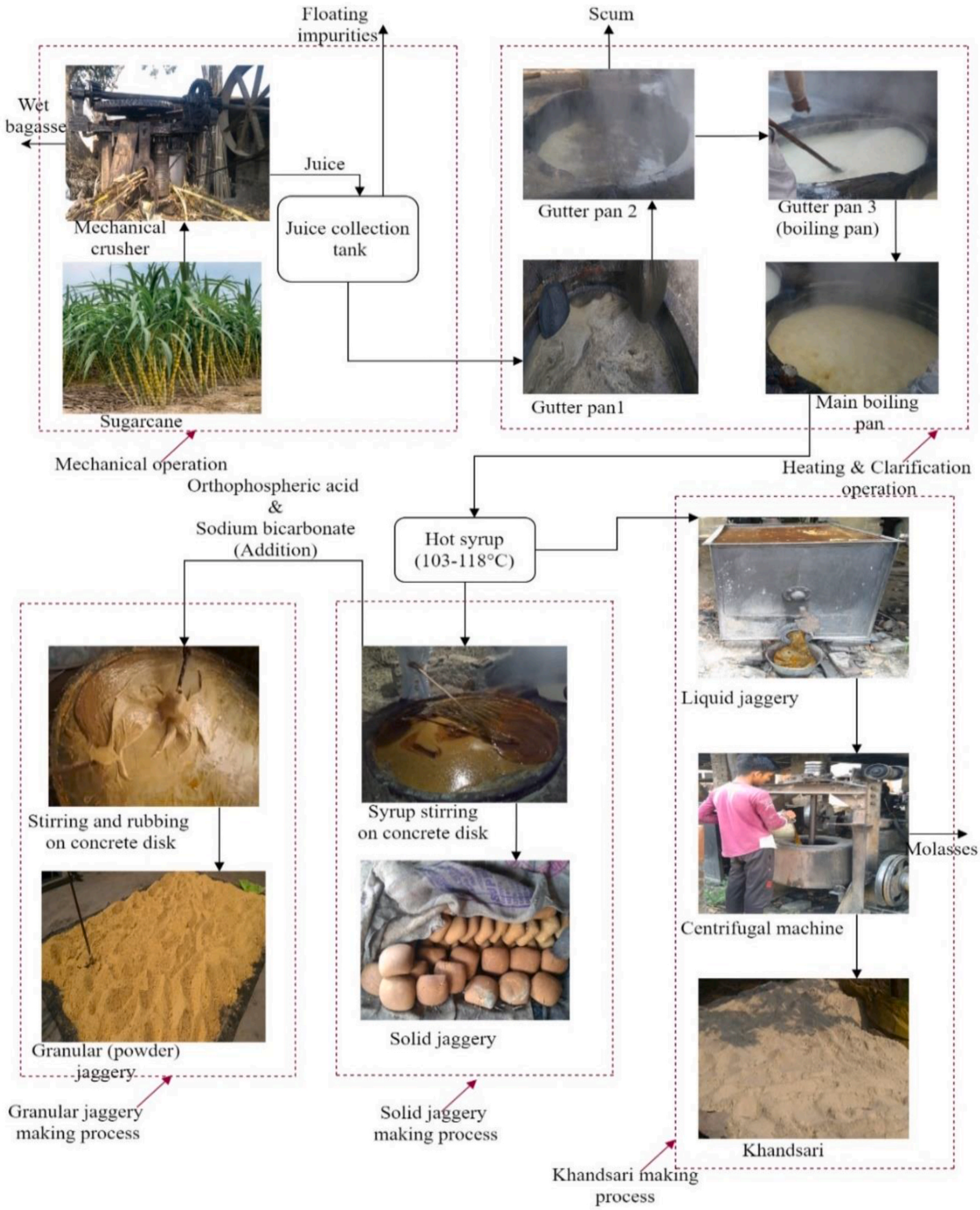

Fig. 1. Typical jaggery (solid, granular, and liquid), and khandsari making process.

3. Operation of traditional jaggery unit

After harvesting the sugarcane from the fields, it is transported to the crusher site and weighed. After weighing, some of the sugarcane is transferred to the crusher while the rest is stored for later crushing for a continuous (24 × 7) operation of the plant. However, storing sugarcane for more than 72 h is not recommended since it causes the inversion of sucrose into glucose and other harmful substances (Jayamala et al., 2009). During the crushing process, the sugarcane produces two useful products: sugarcane juice and bagasse. The fresh bagasse is strewn in a field where it is sun-dried and then used as fuel to heat the juice for jaggery manufacturing. Crusher is either powered by a diesel engine or an electric motor. In rural locations, power is usually only available for a portion of the day, forcing jaggery owners to rely on diesel engines, which contributes to global warming. Additionally, bagasse combustion to generate heat for juice boiling has the potential for negative environmental consequences (Lopes Silva et al., 2014). The juice, on the other hand, is sent to a settling-cum-collection tank and kept at ambient

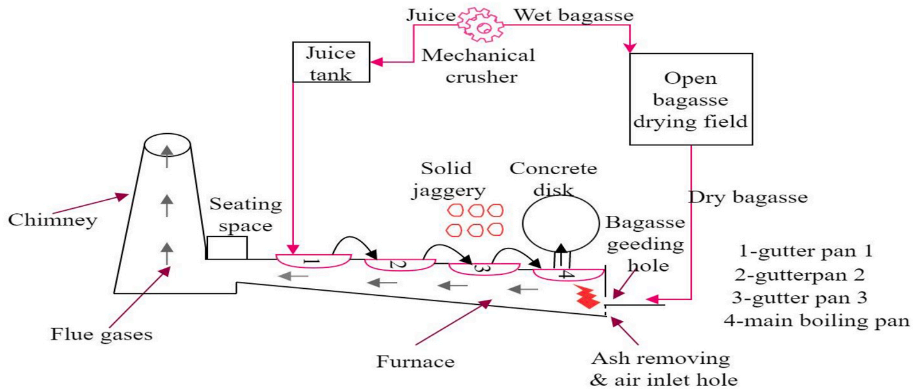

Fig. 2. Schematic diagram of a typical four-pan jaggery-making unit.

Table 1
Nutritional values of jaggery per kg (Kumar and Singh, 2020; Nagarajan et al., 2019; Nath et al., 2015; Rao et al., 2007; Said and Pradhan, 2013; Singh et al., 2013).

Particular	Type of jaggery		
	Solid	Granular	Liquid
Sucrose	720-780 gm	800-900 gm	400-600 gm
Fructose	15-70 gm	NA	NA
Glucose	15-70 gm	NA	NA
Minerals			
Magnesium	0.7–0.9 gm	NA	NA
Potassium	10.56 gm	NA	NA
Calcium	400–1000 mg	9 mg	300 mg
Phosphorus	200–900 mg	40 mg	30 mg
Sodium	19–30 mg	NA	NA
Iron	100–130 mg	120 mg	85–110 mg
Manganese	2–5 mg	NA	NA
Zinc	2–4 mg	NA	NA
Copper	1–9 mg	NA	NA
Vitamins	A-38 mg, B1-0.1 mg, B2-0.6 mg, B5-0.1 mg, B6-0.1 mg, C-70 mg, D2-65 mg, E−1.11 gm	NA	B-140 mg
Protein	2.80 gm	4 gm	5 gm
Calories	3830 kcal	3830 kcal	3000 kcal
Water	15-70 gm	10-20 gm	300-350 gm

†NA- Not available.

temperatures, where heavier particles such as sand, dirt, and so on settle to the bottom of the storage tank, while light impurities float on top and are removed with a strainer. The collected juice is then transferred to the gutter pans via pipe conduits for heating, while clarifiers are added to remove the impurities that are collected as scum. Heating and clarification of juice take place in gutter pans while boiling of the juice takes place in boiling (also called gutter pan 3 at times) and main boiling pan. The striking temperature (ST) for the jaggery-making process varies with sugarcane variety, agro-climate, and the type of jaggery namely liquid, granular and solid jaggery, and ranges between 103 and 118 °C (Hossain and Singh, 2018; Singh et al., 2013; Venkata Sai and Reddy, 2020; Verma et al., 2019a). The striking temperature is the temperature at which heated cane juice becomes viscous and suitable for conversion into jaggery, and beyond it, its color changes to red. In practice, to find whether syrup has attained ST or not, a small amount of syrup is dropped in the water, and if the syrup solidifies then, it has achieved ST otherwise, it has not.

After prolonged heating, clarification, and boiling to its striking temperature, the juice converts into syrup and is transferred to a wooden/aluminum mold or earthen pot or a circular concrete disk for further processing. Once the syrup is cooled down to some extent, it becomes viscous and stirred continuously using shovels until it is converted into semi-solid jaggery paste that is stuck on the circular concrete disk with a temperature varying from 80 to 85 °C. The hot semi-solid jaggery paste is then either cut into small pieces or encapsulated in wet fabric pieces to form the desired forms. Once this semi-solid paste becomes solid, the cloth is removed and jaggery pieces are put in open for drying. The shape and weight of jaggery pieces are subjected to jaggery unit location and are often made in balls varying from a few hundred grams to several kilograms (Kumar, 2015). These balls of various shapes are packed in suitable low-density polyethylene bags, jute bags, etc., stored for a shorter/or longer duration and later sold in the local market. The performance of a jaggery unit can be measured in terms of several parameters such as crushing efficiency (mechanical performance), thermal efficiency, bagasse consumption per kg of jaggery production (thermal performance), and emissions (environmental performance).

4. Technological advancements

The jaggery units have been suffering due to poor thermal and mechanical performances, storage issues, and utilization of wastes and lack of clear policies in place. Several researchers, however, have attempted to improve the performance of the jaggery industry to make the business profitable through several technical and policy interventions. This section discusses the various technological modifications suggested by several researchers in different subsystems of the jaggery plant to improve its overall thermal, mechanical, and environmental performance. These subsystems include the crusher, fuel drying, juice clarification, heating pans sizing and design, furnace designs, combustion mechanism, waste heat recovery, and so on. Table 2 summarizes various notable modifications and technological intervention(s) in jaggery-making units suggested/incorporated by various researchers.

4.1. Sugarcane crushing & dry bagasse

During the crushing process, the sugarcane is fed into the crusher's rollers from one side, which extracts the juice on the same side, while bagasse is generated as a byproduct on the other side. Sugarcane has traditionally been crushed using animal power such as bullocks, camels, and so on. However, in the last 2-3 decades, animal-powered crushers have been supplanted by diesel engines and/or electric motor-powered crushers (Sardeshpande et al., 2010). Until now, sugarcane is manually fed into the crusher for juice extraction, which demands a lot of focus and hard work and is prone to many mishaps. To limit the risks of an accident, it is preferable to create an automatic sugarcane feeding system, together with safety measures, that can cut feeding costs and assure consistent feeding without disrupting the crusher's continuous

Table 2
Review of notable technical innervations and modifications in the jaggery-making process.

Modification(s)/ interventions	Remarks	Reference
Modifications in pan(s)	Carried out the experimental study by installing the fins at the bottom of the gutter and boiling pans and achieved a higher thermal efficiency of 29.5%.	Anwar (2010a)
	Used CFD simulation tool to design a fire-tube pan to replace existing fined flat pan, whereby improved thermal efficiency by 11.4%.	La Madrid et al. (2017)
	Reviewed and discussed the various technological interventions in jaggery-making plants including thermal performance, shelf-life, drying and storage of jaggery, and suggested some modifications for future works.	Kumar and Kumar (2018)
	Used steam jacket pan for jaggery-making and achieved a thermal efficiency of 26%	Pandraju et al. (2021)
	Experiments were carried out by placing fins at the bottom of the boiling pan and internal copper tubes in the gutter pan, yielding a thermal efficiency of 72.34%.	Kumar and Kumar (2021)
Freeze pre-concentration system (FCS) use	Proposed heat pump-based freeze pre-concentration system and estimated sucrose loss while water was removed in form of ice. For the production of 1000 kg jaggery, 1338 kg of dry bagasse can be saved when this technique is coupled with bagasse burning.	Rane and Jabade (2005)
	Use reversible heat pump for freeze pre-concentration and this system saved up to 77% of total bagasse generated.	Rane and Uphade (2016)
	Implemented integrated approach of freeze pre-concentration system and bagasse combustion to produce jaggery. This system saved 1344 kJ of energy per kg of juice.	Srinvas et al. (2019)
	For the production of jaggery, freeze pre-concentration and solar energy were used. This technique can reduce energy usage by at least 91.30%.	Marie et al. (2020)
Modification in bagasse feeding hole and inlet air hole	Proposed a mass and energy balance procedure for jaggery furnace to evaluate its performance and recognition and quantification of losses. Further, controlled bagasse feeding reduces bagasse consumption by ~26%.	Sardeshpande et al. (2010)
	Evaluated thermal performance of two single-pan units having different chimney heights with controlled airflow in the furnace. The controlled flow of air in the furnace helps in increase in efficiency by ~10% while bagasse consumption varies between 1 and 1.5 kg per kg of jaggery.	Shiralkar et al. (2014)
	Conducted exergy analysis of a four-pan jaggery unit and showed that energy and exergy efficiency increase by 11% and ~4%, respectively with controlled bagasse feeding.	Khattak et al. (2018)
Waste heat recovery	Conceptualize and manufactured a waste heat recovery device for jaggery unit at lab scale with pebble bed for pre-heating of the air. Further, results were encouraging and both heat transfer coefficient and pressure drop of flue gases decreased with an increase in pebble size when flowing through the device.	Jangam and Shinde (2014)
	Utilized waste heat from furnace walls which resulted in a 54% decrease in the moisture content of bagasse and the net calorific value of the bagasse increased by 69%.	Shinde et al. (2019)
Use of Solar energy	Employed solar drier for air pre-heating and bagasse drying while solar collector was used to pre-heat the juice. With the application of solar energy, 0.236 kg of dry bagasse can be saved per kg of jaggery production.	Jakkamputi and Mandapati (2016)
	Evaluated 4-E (Energy-Exergy-Environment-Economic) performance of a jaggery unit through the implementation of freeze pre-concentration and solar energy along with bagasse combustion. This system reduced the exergy destruction by 76%.	Venkata Sai and Reddy (2020)

operation. Hasarmani et al. (2018) designed a solar photovoltaic system to power the electric motor used to crush sugarcane, which helped to reduce the industry's carbon footprint; such a system has a payback period of four years once government subsidies are applied.

Traditionally, the crushers feature three vertical cylindrical rollers; however, in certain places, two roller crushers are used. One of the rollers in a three-roller crusher is corrugated, while the other two have tiny cuts on its surface that not only help with feeding but also exert pressure on the sugarcane for juice extraction (Gbabo et al., 2013). Crushing rollers can be placed horizontally or vertically, with or without a gearbox, depending on the demand and technology available in certain locations. The number of rollers, their arrangement, and the pace of sugarcane feeding all have an impact on the percentage of juice extracted and bagasse obtained. The crushing efficiency of crushers is defined as the ratio of the weight of juice extracted to the sum of weights of juice extracted plus moisture and sugar content in wet bagasse. The crushing efficiency of vertically arranged three rollers crushers varies from 50% to 55% while, the crushing efficiency for horizontally arranged rollers varies from 55% to 60% (Gbabo et al., 2013; Kumar and Kumar, 2018). As a result, horizontal roller crushers are commonly utilized due to their increased efficiency, which may be linked to the weight and size of the rollers assisting in the efficient crushing of sugarcane. (Rao et al., 2007; Velásquez et al., 2019).

The addition of the fourth roller improves the effectiveness of dry crushing, and this type of crushing configuration may reach a crushing efficiency of up to 64% (Jayamala et al., 2009). Gbabo et al. (2013) achieved a crushing efficiency of up to 98% by combining a cane cutter with a roller crusher, compared to 56% for the roller crusher alone. Srinivas et al. (2020) used 11 criteria to select the best cane crushing method for jaggery production in terms of sustainability, economy, and environmental concerns. These criteria included water usage, energy required, working hours, CO_2 equivalent emissions, energy cost, machinery cost, crushing time, maintenance cost, level of automation, amount of juice extracted, and concentration of juice. They reported that the cost of the crushing roller system and the amount of juice extracted are the two prevailing factors in deciding the crushing method, and they also found that, among the various available alternatives crushing methods, the power-driven single horizontal crushing arrangement is the most appropriate and sustainable crushing method.

For numerous decades, sugar mills have utilized multiple crushers in conjunction with hot water to enhance crushing efficiency by extracting more juice from the sugarcane and reduce the waste of juice that would otherwise be lost with the bagasse. Similarly, multiple crushers, hot water or, steam can also be used in the jaggery plant to soften the outer part of the sugarcane, increasing juice extraction while reducing waste. This method can also be accomplished by incorporating extra subsystems for heating the water, such as using waste heat from the chimney before it is discharged into the atmosphere and/or employing a device for collecting steam generated from the juice boils pans. However, the complete system must be put in place with additional investments, thus extensive research in the form of payback duration, increase in crushing performance, and case studies are necessary using suitable techniques.

The freshly harvested sugarcane contains 60–65% of juice and 35–40% bagasse; however, this is affected by the variety of sugarcane (Sardeshpande et al., 2010). Fresh bagasse contains 40–50% moisture, which can be reduced to 8–20% by sun-drying (Anwar, 2010b; Kumar and Kumar, 2018; Rao et al., 2003; Shiralkar et al., 2014). Moisture content influences calorific value, combustion efficiency, and emissions of harmful pollutants up to some extent (Sahu et al., 2015). When the moisture content in bagasse is decreased to half of its original amount, the calorific value increases by 10% (Anwar, 2010b). Furthermore, as compared to other fossil fuels, the burning of bagasse produces less SO_2 and NO_x, but the emission of particulate matter (PM) is fairly important in the context of air pollution (Venkata Sai and Reddy, 2020). The development of efficient and cost-effective bagasse drying technologies is critical for bagasse drying to enhance combustion, ameliorate its calorific value, and bagasse saving. Dry bagasse is composed of lignin 20–30%, cellulose 40–45%, hemicellulose 30–35%, ash 3–4%, and traces of wax. Bagasse's composition also makes it an appealing feedstock for the manufacture of bioenergy and composite materials such as disposable packaging food containers, biodegradable tableware packaging, polyurethane foam; moreover, it is utilized as a raw material for the pulp and paper industries (Bezerra and Ragauskas, 2016; Loh et al., 2013). Bagasse drying using solar energy and heat use are described under the sections namely use of solar enegy and waste heat utilization.

4.2. Juice clarification

The clarification of juice is one of the essential operations to remove undesirable impurities and bagasse particles that influence the quality and shelf-life of the final product. Precipitation, coagulation, and flocculation processes govern juice clarification, which is accomplished through the combined action of heating and chemical treatment (Velásquez et al., 2019). Organic jaggery manufacturing is accomplished by the use of vegetable clarifiers with little or no chemical clarifiers (Pandey et al., 2016). The majority of organic clarifiers are locally available and/or grown by the proprietors of the jaggery production units. However, organic clarifiers are 25% more expensive than inorganic clarifiers, resulting in a greater cost of jaggery production with the former (Kumar and Kumar, 2018). Some of the organic clarifiers in their ascending order of clarification efficiency are Ricinus Communis (Castor seed), Kydia Calycina (Sukhlai), Grewia Asiatica (Bark of Falsa Tree), Bombax Malabaricum (Bark of Semal), Hibiscus Esculentus (Bhindi), Arachis Ypogea (Groundnut), Hibiscus Ficulneus (Deola) (Yadav et al., 2018).

The selection of a clarifier for the removal of dissolved and suspended impurities should be implemented carefully, as it may result in the formation of new non-sugar impurities (Patil et al., 2005). Further, while the use of excessive chemical clarifiers might give jaggery a better golden yellowish color, it can compromise against the quality and shelf life of the jaggery and in certain cases, can be harmful to human consumption. The use of hydros (Sodium hydrosulfite), super-phosphate, phosphoric acid, chemiflocks, and alum as clarifiers are mentioned in the literature (Hossain and Singh, 2018; Rao et al., 2007; Said and Pradhan, 2013; Verma et al., 2019a). The use of hydros improves the jaggery color from dark brown to yellowish, making it attractive. Some authors (Verma et al., 2019a) investigated the use of hydros and its effect on the color and quality of jaggery particularly, the polyphenols, flavonoids, minerals, and shelf-life. They concluded that the use of hydros causes minerals, polyphenols, and flavonoids loss, while jaggery produced with hydros is less susceptible to microbial growth. Furthermore, the amount of SO_2 and sodium in jaggery is proportional to the amount of hydros employed in its manufacturing. To produce optimal grade jaggery with SO_2 level less than 50 ppm and permissible self-life, a maximum of 35 gm of hydros per 1000 L of sugarcane juice can be added during clarification (Varshney, 2015). However, in practice, the amount of chemicals to be used is determined by labor experience and the intended color of jaggery, since it is the primary factor in determining the final price of jaggery in the market.

When used as a clarifier, calcium oxide (CaO) results in cleaner juice, darker jaggery color, and reduced bioactive content (Meerod et al., 2019); nevertheless, the use of CaO causes scale to build on the pans (Doherty, 2011), which is harmful to human health. The permissible limits for various constituents (by weight %) in jaggery as specified by the food safety and standards authority of India (FSSAI) are as follows: the moisture content should be less than 7%, sucrose should be minimum of 70%, total sugar content not less than 90%, reducing sugar not more than 20%, sulfate ash not more than 4%, extraneous matter and water-insoluble matter not more than 1.5% (FSSAI, 2017). Kumar and Chand (2015) employed a response surface method (RSM) to explore the application of activated charcoal for sugarcane juice clarification and process optimization and reported 77.55 °C temperature, 1.5 mm thick activated charcoal and 0.4 g/L of deola (Hibiscus Ficulneus) as optimum parameters.

Beeram et al. (2020) used a multi-criteria evaluation method to select appropriate and sustainable clarifiers based on 11 criteria concerning three sustainability dimensions: resources & environmental effects, techno-economic and process output parameters. They concluded that the initial investment and amount of organic clarifier are two important criteria for selecting an appropriate technique of clarification in terms of quality and shelf life. Further, the use of plant mucilage is an appropriate and sustainable method for clarification; however, inorganic clarifiers can be used in restricted quantities as recommended to be safer for human consumption. Fuentes et al. (Solís-Fuentes et al., 2019) compared the quality of jaggery produced using bagasse activated carbon (BAC) and BAC with ultrafiltration. They found that the jaggery obtained by BAC and the combination of BAC and ultrafiltration was of white color, as opposed to the usual golden yellowish color obtained from the traditional trapiche process. However, the clarification of sugarcane juice using a mix of BAC and ultrafiltration is a complex and costly process as compared to the clarification using BAC alone.

4.3. Modifications in the pans

Until the early 1980s, jaggery units were single pan, inefficient in operation, leading to higher fuel consumption and emission of hazardous pollutants into the environment (Kumar and Kumar, 2018; Venkata Sai and Reddy, 2020). However, as technology has advanced and environmental concerns have grown, technical advancements have prompted many unit owners to switch to a multi-pan system. The multi-pan jaggery plant offers several advantages over single pan plants, such as enhanced heat and mass transfer, reduced batch time, lesser consumption of fuel, and reduction in emission of harmful pollutants. Although the modern jaggery-making plants are quite advanced as compared to ancient times there is still much to be done in this rural industry for its sustainability with the least impact on the environment while fulfilling the ever-increasing annual demand of jaggery. (Gangwar et al., 2015; Kumar and Kumar, 2018; Venkata Sai and Reddy, 2020).

The heat transfer from flue gases to the juice through the boiling pans takes place by combined mode of radiation, convection and conduction, i.e. from flue gases to the pan by radiation and convection, within the pan via conduction and from the pan to juice again by radiation and convection. In the multi-pan furnaces, radiation is the dominating mode of heat transfer from the flame to the boiling pan, whereas convection heat transfer dominates for the gutter pans (Shiralkar et al., 2014). An efficient furnace for jaggery unit can be designed to enhance heat transfer rate by increasing the number of pans, modifying the pan shape, increasing flue gas velocity and the contact area between the pans and the flue gas, and changing the design (height and diameter) of the chimney to create the optimum draft. Nowadays, the juice boiling pans are available in various forms such as semi-spherical, semi-cylindrical, pyrotubular with different thicknesses having a flat bottom with and without fins (La Madrid et al., 2016; Velásquez et al., 2019). Anwar (2010a) modified the main and gutter pans by installing the parallel fins at the bottom of the pans, which improved the overall thermal efficiency of the jaggery plant by more than 9% and resulted in a 31% reduction in bagasse consumption. Similarly, Kumar and Kumar (2021) redesign the boiling pan with bottom fins, while the gutter pan was designed with internal copper tubes, and they also used an automatic bagasse feeding system. These changes resulted in a 72.34% thermal efficiency, a 1.39 kg bagasse consumption reduction per kg of jaggery, and an improved jaggery production rate of 0.61 kg/min. Pandraju et al. (2021) used a fire-tube type boiler to generate steam and steam jacket pan for jaggery-making purpose. This system has a thermal efficiency of 26%, helped in saving 36% bagasse, and reduced jaggery-making time per batch by 26% compared to the traditional open pan jaggery-making system.

4.4. Furnace modifications

The traditional furnaces in jaggery plants are constructed by semi-skilled laborers with limited and/or no knowledge about the stoichiometric air-fuel ratio. Consequently, it leads to incomplete combustion of fuel, resulting in the poor thermal efficiency of the furnace (Srinvas et al., 2019). The jaggery unit's furnace has two inlet holes on the feeding side. One of the holes facilitates sun-dried bagasse feeding and secondary air necessary for combustion, while another one for supplying primary air for gasification and ash removal. The hole on the other side of the furnace is attached to a chimney to accommodate the escape of flue gases by creating sufficient draft, which further ensures the supply of required air into the furnace. The primary air holes remain partially closed during the combustion and jaggery preparation, while these holes are opened fully for ash removal once the fire extinguishes.

Several parameters influence the inlet air flow rate and available draught, including chimney height, diameter, length of flue passage for gas and pressure loss due to friction along the passage, the temperature of the combustion zone, size of air inlet holes, and so on. For example, the excessive air flow rate into the furnace due to extra chimney height will reduce combustion zone temperature, resulting in the formation and emission of unburnt volatiles including particulate matter (PM) and the higher heat loss via the chimney along with the flue gas. Conversely, the lean air flow rate caused by the lower chimney height will result in incomplete combustion of bagasse and, as a result, the formation and release of carbon monoxide as well as other hazardous pollutants. Therefore, the chimney height has to be designed and optimized to ameliorate the combustion, resulting in reduced heat loss and pollutant emissions. In addition to chimney height, the holes provided for the air inlet at the feeding point can be made adjustable to have a variable diameter to control the airflow rates, resulting in better combustion of fuel, improved heat transfer, and emission characteristics.

According to Shiralkar et al. (2014), the use of dampers in the route of inlet air to regulate airflow rate can compensate for the increased chimney height, and it was concluded that controlled bagasse feeding and airflow rate could enhance the overall thermal efficiency by 10%. Singh et al. (2008) modified a two-pan furnace and compared the performance of a forced draught system to that of a natural draught system, concluding that the forced draught is superior to the natural draught because it can achieve the desired air-to-fuel ratio, resulting in improved combustion and emission characteristics. Also, with forced draft, the striking point of jaggery was obtained 10 min earlier than with natural draft, resulting in a 2.6% increase in the overall thermal efficiency and 8% reduction in bagasse consumption. Anwar (2014) investigated a single pan jaggery plant by designing, fabricating, and installing an efficiency booster device that directs the flame towards the bottom of the pan, and the device helped in reducing the batch time by 42%, improving the overall efficiency by 35%, and saving bagasse consumption by 26%.

Biomass combustion is an intricate thermochemical reaction involving fluid flow, heat and mass transfer simultaneously (Silva et al., 2017). Computational fluid dynamics (CFD) tools have recently been utilized extensively for the investigation of biomass fuel combustion, and the results may be used to improve these combustion processes (Chaney et al., 2012; Silva et al., 2017). Heat interaction between the flue gases and jaggery pans was studied using a CFD modeling tool by La Madrid et al. (La Madrid et al., 2016). They found that the temperature variation of flue gases along the furnace was in good agreement with the field data. Further, they concluded that the CFD tool may be used to evaluate the thermal performance and emission characteristics of the jaggery production units for different operating conditions. La Madrid et al. (La Madrid et al., 2017) further used a pre-validated CFD model to design the finned fire-tube heat exchanger, resulting in a 36.3% improvement in the overall thermal efficiency. Kulkarni and Ronge (2018) collected the detailed data from the field, in terms of furnace dimensions (diameter, height and length), inlet air holes (number of holes and diameter), dimensions of bagasse feeding hole, pan dimensions (top diameter, bottom diameter, thickness and height), dimensions of the cooling tray (length, width and thickness) and studied the performance of a single pan jaggery unit. They also measured the temperatures of flue gases and juice with respect to time and compared them with those obtained through simulation and found to be in good agreement with each other, with a minor deviation of 5.67% and 8.68%, respectively.

Most of the studies available in the literature are based on the quantitative performance of the jaggery units. However, the qualitative performance could also give a better understanding of resource consumptions and irreversibilities associated with various processes of a jaggery unit. Given this, Khattak et al. (2018) conducted an exergy analysis of a four-pan jaggery unit and concluded that the most notable exergy destruction occurs in combustion due to thermodynamic irreversibilities, while the biggest source of waste heat is found to be flue gas. Based on the experimental measurements of the base case, they evaluated the energy efficiency of the process and found that there is room for its improvement by ensuring complete combustion and proper utilization of fuel energy. However, the above results are based on some interruption in the fuel feeding rate, which was controlled and lowered, resulting in increased batch processing time, which would not be feasible otherwise unless an automatic feeder is used. These changes resulted in a bagasse saving of 28% compared to the baseline operation at the cost of additional processing time per batch, which also resulted in lowering the operating temperature of the furnace from 900 to 700 °C, thereby reducing the flue gas temperature. They also suggested that a minimum operating temperature of 700 °C is required to produce jaggery of satisfactory quality.

4.5. Waste heat utilization

The exhaust gas from the jaggery plant is at a very high temperature (700–900 K) and carries a high amount of energy, which may be utilized for various purposes to improve the overall performance of the jaggery plant. The flue gas temperature is significantly influenced by the inlet air flow rate, the moisture content in the bagasse, bagasse feeding rate, the number of pans used, design and dimensions of the furnace, and the combustion efficiency (Shiralkar et al., 2014). A large proportion of heat produced during combustion is lost in a jaggery unit through several processes, the majority of which occur within the furnace walls and flue gas. The waste heat from flue gas can be recovered in part and can be used either pre-heating of inlet air or bagasse drying, as well as for water heating. The waste-heat recovery strategies such as recuperation (Liu et al., 2014) for bagasse drying and air pre-heat can help jaggery plants run more efficiently. However, their economic viability for use in jaggery manufacturing units must be determined. Shinde et al. (2019) used waste heat from the walls of combustion chambers, which is only a fraction of total waste heat, to reduce the moisture content in bagasse, which resulted in a 54.4% reduction in moisture content and a 69% increase in the calorific value of bagasse.

4.6. *Use of solar energy*

The jaggery industry can also harness and use solar energy, which can result in reduced fuel consumption and lower emission of hazardous pollutants. The scientific community has already begun exploring the use of solar energy in the jaggery industry by some means, such as air pre-heating, bagasse drying, utilizing a solar still to concentrate the sugarcane juice at a medium temperature or using moderate temperature solar concentrators to boil it (Chaudhary and Yadav, 2020; Jakkamputi and Mandapati, 2016; Shanmugan et al., 2014). For instance, Shanmugan et al. (2014) designed and manufactured a solar still with a mirror booster that removed 7.3 L (73%) of water from 10 L of sugarcane juice and converted it into syrup over two days under clear sky conditions, with an overall efficiency of 36.53%. Later, the syrup was heated to produce a viscous syrup before being converted into jaggery on a gas burner in a stainless-steel pan. The final yield was 1.3 kg jaggery, and with a mix of solar thermal and conventional energy sources, this system may save up to 16.41 MJ of energy. However, the above arrangement seems to be complex and expensive, thus rural entrepreneurs may not be able to adopt such a typical arrangement due to many reasons, including financial and technical constraints. Further, the quality of jaggery produced from this method is doubtful due to the involvement of a juice heating mechanism over two days which makes the process lengthy and time-consuming. Also, the economic feasibility and sustainability of such lengthy production methods should be extensively assessed following the detailed techno-economic study and, finally, its acceptance by small and medium-scale jaggery producers.

Chaudhary and Yadav (2020) investigated the use of an evacuated tube collector-based solar cooking system for sugarcane juice concentration at a laboratory scale. They obtained 130 ml, 180 ml and 260 ml of concentrated syrup from 1 L, 1.5 L, and 2 L of fresh sugarcane juice, respectively. The time taken by each sample to obtain concentrated syrup was more than 4 h. Further, the results showed that using the heat transfer fluid (HTF), the maximum temperatures of 1 L, 1.5 L, and 2 L of fresh sugarcane juice were 137.1 °C, 141.3 °C, and 138.1 °C, respectively. They concluded that the system could maintain the temperature of juice above its boiling point even at low solar insolation and during the afternoon time. However, they have not processed this concentrated syrup further for making jaggery and/or any useful product; hence, the feasibility of the process and its sustainability can not be ascertained at this time. Jakkamputi and Mandapati (2016) used solar energy to pre-heat inlet air to 150 °C, resulting in a saving of 0.122 kg of dry bagasse per kg of jaggery produced in comparison to without pre-heating. However, we are skeptical about the economic viability of this process because jaggery production takes place only for 5–6 months a year. Further, the availability of solar radiation in the northern part of India also suffers greatly during that season, particularly from mid-December to starting of February, due to rain, cloud and fog, etc. (Rajput et al., 2014). Fig. 3 depicts a schematic representation of the utilization of solar energy for pre-heating of air, juice, and bagasse drying.

4.7. *Freeze pre-concentration of juice*

The concentration of sugarcane juice is accomplished by removing water from it, which is done either through evaporation by supplying heat to the juice (Jaffé, 2012; Jakkamputi and Mandapati, 2016; Kumar and Kumar, 2018; Rao et al., 2008; Sardeshpande et al., 2010; Shiralkar et al., 2014; Venkata Sai and Reddy, 2020) or through freezing by removing heat continuously from the juice (Rane and Uphade, 2016, 2017, 2018, 2017; Rane and Jabade, 2005; Srinvas et al., 2019; Venkata Sai and Reddy, 2020). In the freeze pre-concentration process, the water is converted into ice by cooling the sugarcane juice below the freezing point of water viz. from −1.5 to −4.6 °C. This turns a substantial proportion of the water into solid ice, which is separated from the juice after passing it through a strainer. Furthermore, the freeze pre-concentration process is constrained by the sugarcane juice's eutectic point (63 Brix at −13.9 °C), because beyond this point, both sucrose (sugar) and water freeze, making water removal impossible. Srinvas et al. (2019) assessed the optimum energy required for jaggery manufacture using a combination of heating and freeze pre-concentration. The energy required to elevate the sugar content of the juice from 20 to 70 Brix by evaporation alone is 1880 kJ/kg. The energy consumption was reduced to 535.1 kJ/kg of juice when the freeze pre-concentration (from 20 to 63 Brix) and evaporation (from 63 to 70 Brix) techniques were combined.

Rane and Jabade (2005) propose a unique idea of a heat pump-based Freezing Concentration System (FCS) for raising the concentration of cane juice in the jaggery production process from 20 to 40 Brix. The juice flows over the freezing surface, which works as both condenser and evaporator successively and then the juice is transferred to a boiling pan for further concentration. The system helped in saving 1338 kg of dry bagasse for the preparation of 1000 kg of jaggery. Rane and Uphade (2016) analyzed the performance of reversible heat pump-based freeze pre-concentration in terms of mass flow rate, heat duty, and inclusion estimation. The system has a low specific power consumption of 9–11 kWh/m^3 for water removal from juice, a practical coefficient of performance (COP)of 9–12, and can save up to 77% bagasse of the total bagasse generated. However, this system has an issue with sugar inclusion in ice, which can be mitigated to some extent by increasing juice speed up to 2 m/s and any increase in juice speed beyond this has an insignificant effect on sugar inclusion mitigation. Rane and Uphade (2017) designed a long-stroke reciprocating steam compressor prototype for efficient jaggery-making using a vapor recompression system. The prototype has a jaggery-making capacity of 0.6 kg/h and a water evaporation rate of 2.6 kg/h. Moreover, the system has a specific power consumption of 108.3 kWh/m^3 water removal and COP 78 (theoretical) for a sugar increment of 70 (from 20 to 90) Brix. Along the same line, Marie et al. (2020) employed freeze pre-concentrator and solar energy for jaggery-making. The authors concluded that theoretical energy demand by this process can be reduced by a minimum of 91.30% in comparison to the traditional jaggery-making method, depending upon the range over which freeze pre-concentrator is used. Further, Rane and Uphade (2018) investigated the application of a two-stage heat pump freeze pre-concentration system for the energy-efficient jaggery production process. One of the heat pumps was used as an evaporator to convert water from juice in ice, whereas the second heat pump was used as a condenser to melt ice that formed in the evaporator. The system achieved a COP of 14 at −8 °C, 3 °C, and 34 °C evaporation, condensation, and heat rejection temperatures, respectively. The system had a specific power consumption of 8.88 kWh/m^3 of water removal.

Another study was carried out by Venkata Sai and Reddy (Venkata Sai and Reddy, 2020) on a solar-powered jaggery industry with freeze pre-concentration with conventional and modified heating pans using 4E (Energy-Exergy-Environment-Economic) analyses through a

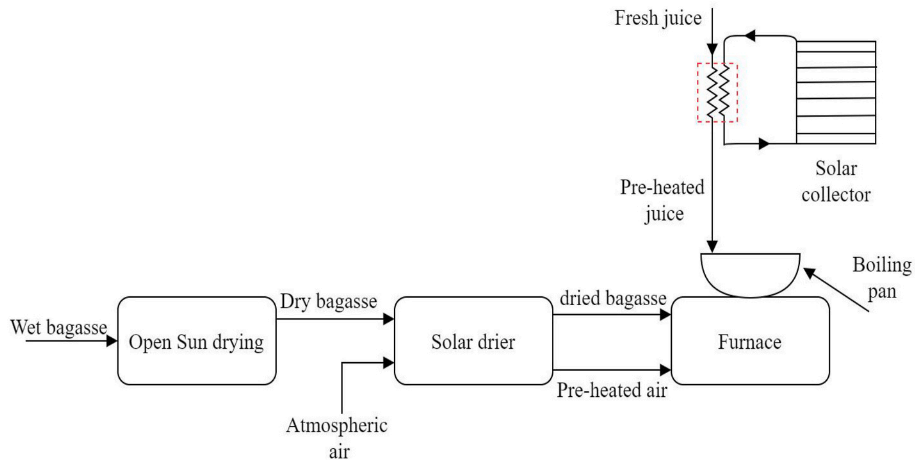

Fig. 3. Schematic diagram of modified jaggery plant with solar energy (Jakkamputi and Mandapati, 2016).

mathematical model developed for the study. With a payback time of 12 years at a jaggery selling price of USD 0.46/kg, these systems may help in saving ~38 tons of bagasse per year and reduction of ~123 tons of CO_2 emission per year., They also found that the modifications in the heating pan can reduce the exergy destruction up to 76%, while the destruction of bagasse exergy could be 400% more with dry bagasse combustion (DBC) as compared to the wet bagasse combustion (WBC). However, the latter seems to be unrealistic, as most of the plants use the dry bagasse in the country due to the high consumption rate of wet bagasse and excess air requirement for complete combustion compared to dry bagasse to produce the same amount of jaggery (Shiralkar et al., 2014; Venkata Sai and Reddy, 2020). The schematic diagram of the integrated jaggery preparation approach is shown in Fig. 4. Table 3 provides a qualitative overview of jaggery production techniques, as well as their advantages and disadvantages.

5. Emission reduction potential

In a typical jaggery plant, inadequate fuel combustion results in the production of numerous hazardous pollutants such as particulate matter (PM2.5) and carbon monoxide (CO). The emissions from the traditional jaggery plants are very similar to that of a traditional cookstove, as evident from the quantum of smoke being released in the open environment from both activities (Tyagi et al., 2021). The annual emissions of PM $_{2.5}$, CO and CO_2 from traditional jaggery plants have been calculated by using the values of annual jaggery production and bagasse consumption available in the literature for multi-pan jaggery plants (Anwar, 2010a; Sardeshpande et al., 2010; Shiralkar et al., 2014). However, the emission of harmful pollutants ($PM_{2.5}$, CO and CO_2) could be reduced drastically if the modified furnace having optimum air-to-fuel ratio, minimum heat loss to the surroundings while utilizing the processed agro-residues (bagasse) as the fuel in the jaggery production (Himanshu et al., 2021; Tyagi, 2018; Tyagi et al., 2021).

Further, a comparative study between the modified (proposed) and traditional jaggery plants is also carried out, and the emissions reduction potential for multi-pan arrangements has been presented, as given below:

The annual emissions of particulate matter ($PM_{2.5}$), carbon

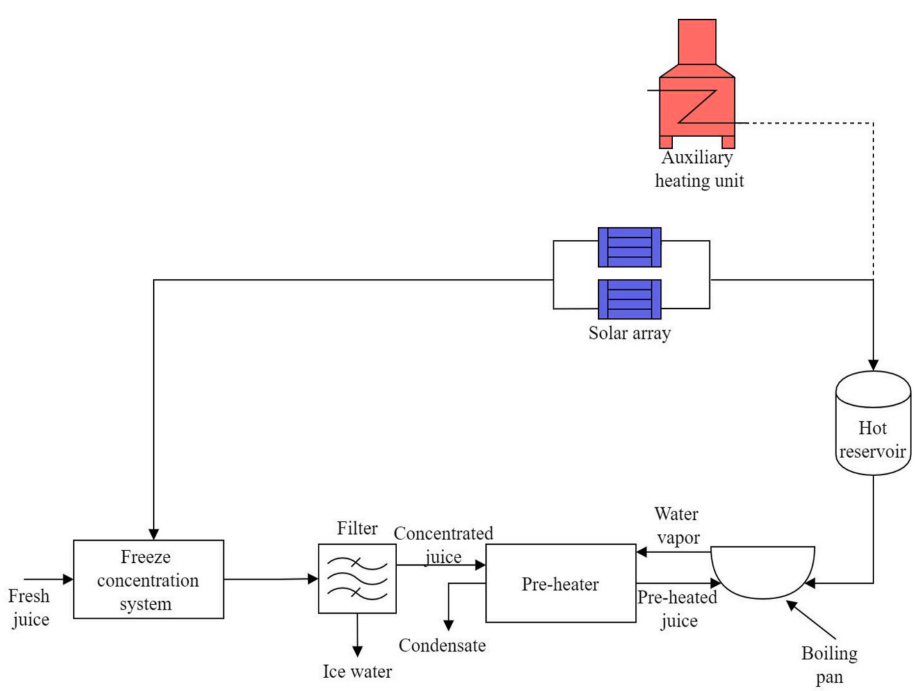

Fig. 4. Jaggery-making using integrated FCS, solar heating and bagasse combustion units (Venkata Sai and Reddy, 2020).

Table 3
Comparison of traditional and advanced jaggery-making techniques.

Jaggery-making technique	Advantage	Disadvantage
Traditional techniques		
Using open pans	• Fuel is freely available • Low initial investment is required • Can be constructed and operated by unskilled labor • Operation is well-understood due to being in operation for centuries • Renewable (solar) energy can be integrated for performance improvement	• Low overall and thermal efficiency due to unscientific approach in the construction of the plant • Poor emission characteristics, therefore, huge environmental load • The supply of dry fuel, which is essential for the smooth operation of plant, is dependent on weather conditions • Low production rate • Require a large number of workers for operation, which is one of the hurdles in achieving economic sustainability
Modern techniques		
Freeze-pre concentration	• Require only 1807.12 kJ energy per kg of juice while the traditional method requires 362.59 kJ to increase juice concentration from 20 to 63 Brix • High production rate • Can be powered with renewable/or conventional electricity • Helps in mitigating the environmental load of the jaggery-making process • Saving of bagasse generates extra revenue for plant operator • Less space is required for jaggery plant due to the reduction in the number and size of pans • Less number of laborers are required for bagasse drying and juice boiling/heating due to automated operation • Improved hygiene and quality of jaggery due to less/or no use of chemicals	• In the development phase for jaggery-making • Only useful in removing a fraction of water from juice • Therefore, require integration with conventional method/ renewable heating for jaggery production.
Solar still	Only tested at laboratory scale once, therefore, no significant practical information is available.	Effective only in increasing juice concentration, may require additional heating for final jaggery production.
Evacuated tube solar collector	Only tested at laboratory scale once, therefore, no significant practical information is available.	Effective only in increasing juice concentration, may require additional heating for final jaggery production.

monoxide (CO) and carbon dioxide (CO_2) from the multi-pan traditional and modified jaggery plants are shown in Fig. 5. The emission of $PM_{2.5}$ from the modified three- and four-pan jaggery units were found to be of 2.5 kT/yr and 2.07 kT/yr, while for the traditional units, these values are 244.94 kT/yr and 202.61 kT/yr, respectively, as can be seen from Fig. 5. Similarly, the emission of CO for traditional three- and four-pan jaggery plants was found to be 2550.53 kT/yr, and 2109.7 kT/yr, while it was found to be 85.53 kT/yr and 70.75 kT/yr for the modified plants, respectively. On the other hand, the annual emissions of CO_2 from traditional and modified jaggery plants were estimated to be 66.1 MT/yr and 54.67 MT/yr, and 22.37 MT/yr and 18.5 MT/yr respectively, for three- and four-pan jaggery plants, respectively.

Further, it was observed that the annual emissions of $PM_{2.5}$ and CO (which are hazardous to both the human and environment) could be reduced significantly viz. $PM_{2.5}$ from 95% to 98% and CO from 92% to 95% (three to four-pan) from the existing (traditional) plants through cleaner combustion (Tyagi et al., 2021). Since the improved combustion saves not only the emissions but also the fuel consumption, therefore, the emission of CO_2 could be reduced from 52 to 60% from this rural industry, as can be seen from Fig. 6(a). On the other hand, the annual emissions of $PM_{2.5}$, CO and CO_2, could be reduced from 2.22 to 2.66%, 2.27–3.34% and 1.10–1.47%, respectively, from all the sources at the National level, Fig. 6(b). Therefore, the results indicated that the emission characteristics of traditional jaggery plants can be improved significantly, and the fuel savings could be as high as 35% from the current level, using cleaner combustion (Tyagi et al., 2021).

6. Future research prospect and conclusions

This review shows that jaggery plants exhibit poor thermal and overall efficiency. However, technological inputs by various researchers have improved the thermal performance of these plants. Nevertheless, no efforts have been made to quantify the improvement in environmental performance owing to these technological interventions. Some advanced technologies such as heat pumps, solar still, evacuated solar tubes as so on, have been employed for jaggery production. However, these technologies are in the development phase, and except FPC, none of the technology has been implemented for jaggery production under real circumstances. Furthermore, advanced technologies alone are incapable of converting cane juice into jaggery; therefore, they need to be used in conjunction with traditional techniques for jaggery production. Furthermore, solar energy may contribute in several ways such as juice boiling, powering FCP, air pre-heating, and bagasse and jaggery drying. The most critical determinant in integrating modifications in conventional jaggery-making processes and transitioning to innovative jaggery-making technologies is cost. Therefore, short, and long-term benefits and costs of these changes need to be ascertained.

6.1. Future research prospect

The jaggery industry has a huge scope for improvement and scientific inputs may help in performance enhancement through cleaner combustion for reduction of pollutants and sustainable jaggery production. Based on the extensive literature survey, various research gaps are found and the following recommendations are made for future R&D:

- Design modifications in the crushers, storage tank, pan design, furnace design, bagasse combustion, the height of the chimney, etc. should be explored through modeling and simulation for improvements and safety in the jaggery units.
- Integration of advanced technologies such as freeze pre-concentration, solar dying, solar cooling, air-preheating, bagasse softening and re-crushing, etc. should be explored through modeling and simulation along with the financial viability.
- A detailed study for monitoring and evaluation of harmful pollutants on continuous operation (24 × 7) may be carried out.
- The desiccant-based drying systems could be tested for jaggery drying using solar photovoltaic and solar thermal technologies.
- The life cycle assessment (LCA) is found to be missing in the literature and may be taken into consideration for jaggery production.

6.2. Conclusions

It can be also concluded that the jaggery industry has a huge scope for improvement, and scientific inputs may help the farmers-cum-rural entrepreneurs in reducing the cost of jaggery production and emissions of hazardous pollutants being released into the environment. The analysis carried out in this study exhibits that the annual jaggery production is releasing around 244,940–202,610 tons of $PM_{2.5}$, around 2.11–2.55 million tons of CO, and around 54–66 million tons of CO_2 into

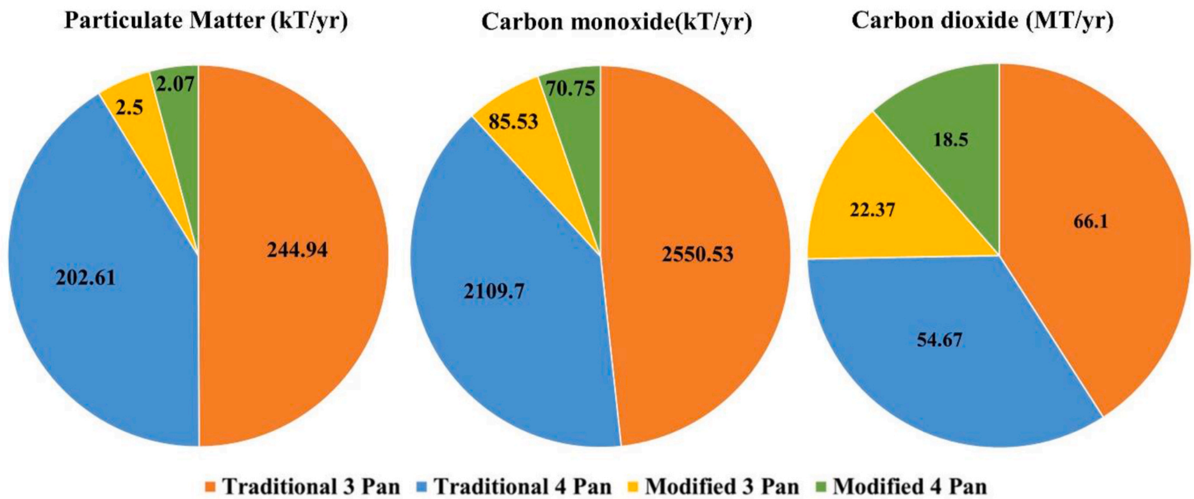

Fig. 5. Comparison of different pollutants from traditional and modified jaggery plants.

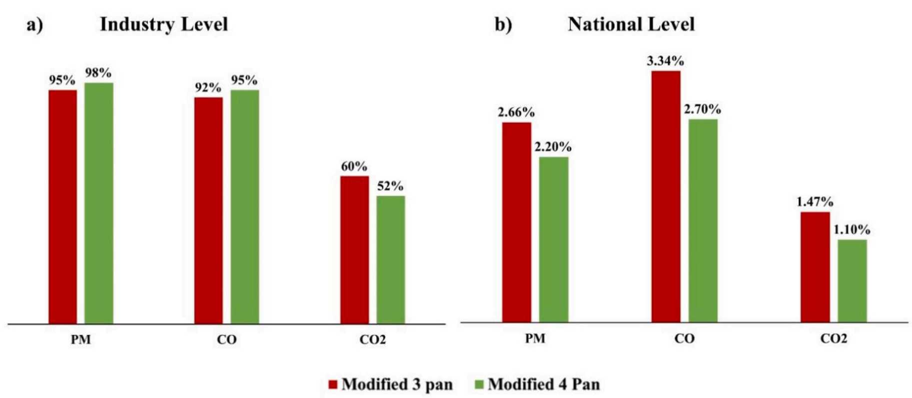

Fig. 6. Emission reduction potentials through cleaner combustion at (a) Industry and (b) National level.

the environment each year in the country. Further, the emission of different pollutants from this rural industry could be reduced significantly, viz. 2.2–2.66% of $PM_{2.5}$, 2.7–3.34% of CO and 1.1–1.47% of CO_2 from the country including, the domestic, industrial, agricultural, transportation, and residential sectors. Also, there could be an annual savings of 35% bagasse consumption, which may generate additional income for the rural entrepreneurs-cum-farmers in the country.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

One of the authors (SKT) acknowledges the financial support through the FIRP project (MI02090) from Industrial Research and Development (IRD), Indian Institute of Technology Delhi (IIT Delhi), for this R&D activity. Sachin Kamboj also appreciates the research exposure opportunity provided by IIT Delhi under the summer faculty research fellowship (SFRF) program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113792.

References

Anwar, S.I., 2014. Improving thermal efficiency of open pan jaggery furnaces - a novel concept. Indian J. Sugarcane Technol. 29, 32–34.

Anwar, S.I., 2010a. Fuel and energy saving in open pan furnace used in jaggery making through modified juice boiling/concentrating pans. Energy Convers. Manag. 51, 360–364. https://doi.org/10.1016/j.enconman.2009.09.033.

Anwar, S.I., 2010b. Determination of moisture content of bagasse of jaggery unit using microwave oven. J. Eng. Sci. Technol. 5, 472–478.

APEDA, 2020. Market Intelligence Report for Jaggery.

Asfaq, Chand, K., 2020. Effect of moisture absorber and high-density polyethylene bags on shelf life of edible coated jaggery cubes during storage. Sugar Tech. https://doi.org/10.1007/s12355-020-00849-.

Beeram, S., Morapakala, S., Deshmukh, S.S., Sunkara, P.R., 2020. Selection of suitable and sustainable clarificants and clarification method for non-centrifugal sugar production using MCE. In: Materials Today: Proceedings. Elsevier Ltd. https://doi.org/10.1016/j.matpr.2019.12.319.

Bezerra, T.L., Ragauskas, A.J., 2016. A review of sugarcane bagasse for second-generation bioethanol and biopower production. Biofuels, Bioprod. Biorefining 6, 246–256. https://doi.org/10.1002/bbb.

Chaney, J., Liu, H., Li, J., 2012. An overview of CFD modelling of small-scale fixed-bed biomass pellet boilers with preliminary results from a simplified approach. Energy Convers. Manag. 63, 149–156. https://doi.org/10.1016/j.enconman.2012.01.036.

Chaudhary, R., Yadav, A., 2020. Experimental investigation of solar cooking system based on evacuated tube solar collector for the preparation of concentrated sugarcane juice used in jaggery making. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-020-00601-8.

Dhawan, B.D., 1967. The traditional modern case of Indian sugar industry. Econ. Polit. Wkly. 2, 725–727.

Doherty, W.O.S., 2011. Improved sugar cane juice clarification by understanding calcium oxide-phosphate-sucrose systems. J. Agric. Food Chem. 59, 1829–1836. https://doi.org/10.1021/jf1043212.

FSSAI, 2017. Standards for Gur or Jaggery , Sodium Saccharin and Calcium Saccharin.

Gangwar, L.S., Solomon, S., Anwar, S.I., 2015. Policy Brief Technological and Policy Options for Modernization of Jaggery Industry in India.

Gbabo, A., Osunde, Z.D., Musa, S.D., 2013. Comparative study on cane cutter/juice expeller and roller model Sugarcane juice extraction systems Comparative study on cane cutter/juice expeller and roller model Sugarcane juice extraction systems. Intenational J ournal Curr. Sci. 7, 55–60.

Gopalan, C., Sastri, B.R., Balasubramanian, S.C., 1989. Nutritive Value of Indian Foods, second ed. National Institute of Nutrition, ICMR, Hyderabad.

Hariprasad, P., Vipin, A.V., Karuna, S., Raksha, R.K., Venkateswaran, G., 2014. Natural aflatoxin uptake by sugarcane (Saccharum officinaurum L.) and its persistence in jaggery. Environ. Sci. Pollut. Res. 22, 6246–6253. https://doi.org/10.1007/s11356-014-3851-2.

Hasarmani, T., Holmukhe, R., Ganer, N., 2018. Techno-economic sizing of renewable energy resources for energy improvements in jaggery making process. In: 2018 IEEE Punecon. IEEE, Pune, pp. 1–5. https://doi.org/10.1109/PUNECON.2018.8745390.

Himanshu, Pal, K., Jain, S., Tyagi, S.K., 2021. Development of advanced biomass cookstove and performance comparisons using the modified star rating methodology. Energy Eng. J. Assoc. Energy Eng. 118, 1237–1251. https://doi.org/10.32604/EE.2021.016489.

Hossain, M., Singh, N.G.I., 2018. Studies on the preparation of liquid jaggery from sugarcane (Sacharum officinarum L .) juice. Int. J. Food Sci. Nutr. 3, 179–182.

Indian Sugar Mills Association, 2019. Indian sugar mills association [WWW Document]. URL. https://indiansugar.com/Statics.aspx, 1.20.20.

Jaffé, W., 2012. Non Centrifugal Sugar: World Production and Trade. https://doi.org/10.13140/RG.2.1.3795.4081.

Jaffe, W.R., 2012. Health effects of non-centrifugal sugar (NCS): a review. Sugar Tech 14, 87–94. https://doi.org/10.1007/s12355-012-0145-1.

Jakkamputi, L.P., Mandapati, M.J.K., 2016. Improving the performance of jaggery making unit using solar energy. Perspect. Sci. 8, 146–150. https://doi.org/10.1016/j.pisc.2016.04.019.

Jangam, S.M., Shinde, N.H., 2014. Modelling of waste heat recovery device for jaggery units. Int. J. Eng. Res. Technol. 3, 446–449.

Jayamala, G.B., Gowda, M.C., Ramaya, H.N., Shankar, M., Krishnamma, P.N., 2009. Prospects of jaggery industry in Karnataka - a case study. Int. J. Appl. Agric. Res. 4, 203–214.

Khattak, S., Greenough, R., Sardeshpande, V., Brown, N., 2018. Exergy analysis of a four pan jaggery making process. Energy Rep. 4, 470–477. https://doi.org/10.1016/j.egyr.2018.06.002.

Kore, A.N., Lakade, S.S., 2021. Review on the overall development of jaggery plant to enhance thermal efficiency. Psychol. Educ. 58, 2172–2180.

Kulkarni, S.N., Ronge, B.P., 2018. CFD simulation and field data assessment of open Pan jaggery making furnace. Int. J. Mech. Prod. Eng. Res. Dev. 8, 647–652.

Kumar, A., Singh, S., 2020. The Benefit of Indian Jaggery over Sugar on Human Health, Dietary Sugar, Salt and Fat in Human Health. INC. https://doi.org/10.1016/b978-0-12-816918-6.00016-0.

Kumar, P., 2015. New approaches for jaggery production in Rajasthan. Indian J. Sugarcane Technol. 30, 6–11.

Kumar, R., Kumar, M., 2021. Thermoeconomic analysis of a modified jaggery making plant. Heat Transf 50, 4871–4891. https://doi.org/10.1002/htj.22107.

Kumar, R., Kumar, M., 2018. Upgradation of jaggery production and preservation technologies. Renew. Sustain. Energy Rev. 96, 167–180. https://doi.org/10.1016/j.rser.2018.07.053.

Kumar, U.P.K., Chand, K., 2015. Application of response surface method as an experimental design to optimize clarification process parameters for sugarcane juice. J. Food Process. Technol. https://doi.org/10.4172/2157-7110.1000422, 06.

La Madrid, R., Marcelo, D., Orbegoso, E.M., Saavedra, R., 2016. Heat transfer study on open heat exchangers used in jaggery production modules – computational Fluid Dynamics simulation and field data assessment. Energy Convers. Manag. 125, 107–120. https://doi.org/10.1016/j.enconman.2016.03.005.

La Madrid, R., Orbegoso, E.M., Saavedra, R., Marcelo, D., 2017. Improving the thermal efficiency of a jaggery production module using a fire-tube heat exchanger. J. Environ. Manag. 204, 622–636. https://doi.org/10.1016/j.jenvman.2017.09.035.

Liu, Y., Aziz, M., Kansha, Y., Bhattacharya, S., Tsutsumi, A., 2014. Application of the self-heat recuperation technology for energy saving in biomass drying system. Fuel Process. Technol. 117, 66–74. https://doi.org/10.1016/j.fuproc.2013.02.007.

Loh, Y.R., Sujan, D., Rahman, M.E., Das, C.A., 2013. Review Sugarcane bagasse - the future composite material: a literature review. Resour. Conserv. Recycl. 75, 14–22. https://doi.org/10.1016/j.resconrec.2013.03.002.

Lopes Silva, D.A., Delai, I., Delgado Montes, M.L., Roberto Ometto, A., 2014. Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. Renew. Sustain. Energy Rev. 32, 532–547. https://doi.org/10.1016/j.rser.2013.12.056.

Madhu, B., Patel, S., Jagannadha Rao, P.V.K., Sreedevi, P., 2018. Use of edible coatings to increase the shelf life of jaggery: a review. Int. J. Curr. Microbiol. Appl. Sci. 7, 2466–2479. https://doi.org/10.20546/ijcmas.2018.706.293.

Marie, L.F., Raj, S.P., Sai, P.V., Macleod, T., Srinivas, M., Srinivas Reddy, K., O'donovan, T.S., 2020. Solar thermal heating and freeze concentration for non-centrifugal sugar production: design and performance analysis. Energy Eng. J. Assoc. Energy Eng. 117, 323–342. https://doi.org/10.32604/EE.2020.011035.

Meerod, K., Weerawatanakorn, M., Pansak, W., 2019. Effect of liming process on physicochemical properties and phytochemical components of non-centrifugal sugar from different sugarcane cultivars. Agric. Res. https://doi.org/10.1007/s40003-019-00409-7.

Meshram, V.A., Deshmukh, D.A., 2018. The review on jaggery making process and preparing CFD model to analyse heat transfer. Int. J. Theor. Appl. Res. Mech. Eng. 7, 72–80.

Ministry of Commerce and Industry, 2019. Jaggery and Confectionary [WWW Document]. URL. http://apeda.gov.in/apedawebsite/SubHead_Products/Jaggery_and_Confectionary.htm, 1.20.20.

Nagarajan, K., Balkrishna, A., Gowda, P., 2019. Alternative and supplementary health model on traditional sugars. J. Nutr. Weight Loss Res. 4, 1–10.

Nath, A., Dutta, D., Kumar, P., Singh, J., 2015. Review on recent advances in value addition of jaggery based products. J. Food Process. Technol. 4–7. https://doi.org/10.4172/2157-7110.1000440, 06.

Pandey, A., Semwal, D.P., Bhatt, K.C., Gupta, R., Ahlawat, S.P., 2016. A new report on cultivation of "Sukhlai" (Abelmoschus manihot (L.) Medik. subsp. tetraphyllus (Roxb. ex Hornem.) Borss. Waalk.): a species used as organic clearant in jaggery industry in India. Genet. Resour. Crop Evol. 63, 1447–1455. https://doi.org/10.1007/s10722-016-0451-7.

Pandraju, S., Polamarasetty Venkata Kali, J.R., Mondru, M., 2021. Energy efficient steam boiling system for production of quality jaggery. Sugar Tech 23, 915–922. https://doi.org/10.1007/s12355-020-00915-x.

Patil, B.S., 2021. Health benefits of jaggery tea on the account of COVID-19. Health Sci. J. 10, 1791.

Patil, J.P., Shinde, U., Nevakar, G., Singh, J., 2005. Clarification efficiency of synthetic and herbal clarificants in quality jaggery production. Sugar Tech 7, 77–81.

Pawar, D., Unde, P., Kanawade, V., 2017. Studies on preparation of jaggery granules with nucleation. Int. J. Agric. Sci. Res. 4, 1292–1295.

Rajput, A.K., Avasthi, D.V., Kumar, D., 2014. Variation of estimated insolation from east to west in Uttar Pradesh, India. In: Proceedings of the International Conference on Innovative Applications of Computational Intelligence on Power, Energy and Controls with Their Impact on Humanity. CIPECH 2014, Ghaziabad, pp. 390–394. https://doi.org/10.1109/CIPECH.2014.7019033.

Rane, M.V., Uphade, D.B., 2018. Heat pump for energy-efficient sugarcane juice freeze pre-concentration. Sugar Tech 20, 591–598. https://doi.org/10.1007/s12355-017-0580-0.

Rane, M.V., Uphade, D.B., 2017. Novel long stroke reciprocating compressor for energy efficient jaggery making. In: IOP Conference Series: Materials Science and Engineering. https://doi.org/10.1088/1757-899X/232/1/012004.

Rane, M.V., Uphade, D.B., 2016. Energy efficient jaggery making using freeze pre-concentration of sugarcane juice. Energy Procedia 90, 370–381. https://doi.org/10.1016/j.egypro.2016.11.204.

Rane, M.V., Jabade, S.K., 2005. Freeze concentration of sugarcane juice in a jaggery making process. Appl. Therm. Eng. 25, 2122–2137.

Rao, K.S.S., Sampathrajan, A., Ramjani, S.A., 2003. Efficiency of traditional jaggery making furnace. Madras Agric. J. 90, 184–185.

Rao, P.V.K.J., Das, M., Das, S., 2007. Jaggery – a traditional Indian sweetener. Indian J. Tradit. Knowl. 6, 95–102.

Rao, P.V.K.J., Das, M., Das, S.K., 2008. Thermophysical properties of sugarcane, palmyra palm, and date-palm granular jaggery. Int. J. Food Prop. 11, 876–886. https://doi.org/10.1080/10942910701671281.

Sahu, S.K., Ohara, T., Beig, G., Kurokawa, J., Nagashima, T., 2015. Rising critical emission of air pollutants from renewable biomass based cogeneration from the sugar industry in India. Environ. Res. Lett. 10, 95002. https://doi.org/10.1088/1748-9326/10/9/095002.

Said, P.P., Pradhan, R.C., 2013. Preservation and value addition of jaggery. Int. J. Agric. Eng. 6, 569–574.

Sardeshpande, V.R., Shendage, D.J., Pillai, I.R., 2010. Thermal performance evaluation of a four pan jaggery processing furnace for improvement in energy utilization. Energy 35, 4740–4747. https://doi.org/10.1016/j.energy.2010.09.018.

Selvi, V.M., Mathialagan, M., Mohan, S., 2021. The art and science of jaggery making: a review. Agric. Rev. 1–9 https://doi.org/10.18805/ag.r-2138.

Shanmugan, S., Rajamohan, P., Mutharasu, D., Ibrahim, K., 2014. Performance evaluation of an acrylic mirror booster solar still for neera concentration in jaggery-making industry. Int. J. Sustain. Energy 33, 261–272. https://doi.org/10.1080/14786451.2011.644852.

Shanthy, T.R., Baburaj, K., 2015. Socio-economic impact of multiple furnace over single furnace in jaggery preparation. J. Sugarcane re 5, 65–73.

Shinde, A.B., Sapali, S.N., Sonone, Y.V., 2019. Performance evaluation of a modern jaggery plant with bagasse drying using waste heat recovery from surrounding walls of combustion chamber. In: Recent Developments in Mechanical Engineering(RDME-2019). IOSR Journal of Engineering (IOSR, Pune, pp. 28–32.

Shiralkar, K.Y., Kancharla, S.K., Shah, N.G., Mahajani, S.M., 2014. Energy improvements in jaggery making process. Energy Sustain. Dev. 18, 36–48. https://doi.org/10.1016/j.esd.2013.11.001.

Silva, J., Teixeira, J., Teixeira, S., Preziati, S., Cassiano, J., 2017. CFD modeling of combustion in biomass furnace. In: Energy Procedia. Elsevier B.V., pp. 665–672. https://doi.org/10.1016/j.egypro.2017.07.179

Singh, J., Solomon, S., Kumar, D., 2013. Manufacturing jaggery, a product of sugarcane, as health food. Agrotechnology 10–12. https://doi.org/10.4172/2168-9881.s11-007, 01.

Singh, A, Bangali, B, Singh, R, 2008. Performance evaluation of two pan furnace with forced draft combustion for jaggery making. J. Agric. Eng. 45 (2), 29–32.

Singh, N., Kumar, D., Lal, K., Raisuddin, S., Sahu, A.P., 2010. Adverse health effects due to arsenic exposure : modification by dietary supplementation of jaggery in mice. Toxicol. Appl. Pharmacol. 242, 247–255. https://doi.org/10.1016/j.taap.2009.10.014.

Solís-Fuentes, J.A., Hernández-Ceja, Y., Hernández-Medel, M., del, R., García-Gómez, R. S., Bernal-González, M., Mendoza-Pérez, S., Durán-Domínguez-de-Bazúa, M. del C., 2019. Quality improvement of jaggery, a traditional sweetener, using bagasse activated carbon. Food Biosci 32, 100444. https://doi.org/10.1016/j.fbio.2019.100444.

Srinivas, M., Sravya, B., Raj, S.P., Reddy, K.S., 2020. Crushing method selection for non-centrifugal sugar production by FAHP–ELECTRE I. Int. J. Low Carbon Technol. 15, 328–335. https://doi.org/10.1093/ijlct/ctz081.

Srinvas, M., Prudhvi Raj, S., Marie, L.F., Reddy, K.S., O'Donovan, T.S., 2019. Assessment of optimum energy demand for non-centrifugal sugar production through an alternate process. In: Journal of Physics: Conference Series. IOP Publishing. https://doi.org/10.1088/1742-6596/1276/1/012079.

Tyagi, S.K., 2018. Biomass Pellet Based Combustion Devices. Patent No. 20557/2018-DEL.

Tyagi, S.K., Tyagi, N., Himanshu, Kamboj, S., Agarwal, K.K., Sharma, U., Tyagi, V.V., 2021. Emissions reduction and fuel saving potentials in jaggery industry via cleaner combustion. Int. J. Ambient Energy 1–30. https://doi.org/10.1080/01430750.2021.1914726.

Varshney, V., 2015. Jaggery made using time-tested method is more wholesome [WWW Document]. URL. https://www.downtoearth.org.in/coverage/jaggery-made-using-timetested-method-is-more-wholesome-5501, 4.6.20.

Velásquez, F., Espitia, J., Mendieta, O., Escobar, S., Rodríguez, J., 2019. Non-centrifugal cane sugar processing: a review on recent advances and the influence of process variables on qualities attributes of final products. J. Food Eng. 255, 32–40. https://doi.org/10.1016/j.jfoodeng.2019.03.009.

Venkata Sai, P., Reddy, K.S., 2020. 4-E (Energy-Exergy-Environment-Economic) analyses of integrated solar powered jaggery production plant with different pan configurations. Sol. Energy 197, 126–143. https://doi.org/10.1016/j.solener.2019.12.026.

Vera-Gutiérrez, T., García-Muñoz, M.C., Otálvaro-Alvarez, A.M., Mendieta-Menjura, O., 2019. Effect of processing technology and sugarcane varieties on the quality properties of unrefined non-centrifugal sugar. Heliyon 5. https://doi.org/10.1016/j.heliyon.2019.e02667.

Verma, P., Iyer, S.R., Shah, N., Mahajani, S., 2020. Insights into the crystallization phenomenon in the production of non-centrifugal sugar. J. Food Eng. 290, 110259. https://doi.org/10.1016/j.jfoodeng.2020.110259.

Verma, P., Shah, N., Mahajani, S., 2019a. Effect of sodium hydrosulphite treatment on the quality of non-centrifugal sugar : Jaggery. Food Chem. 299 https://doi.org/10.1016/j.foodchem.2019.125043.

Verma, P., Shah, N.G., Mahajani, S.M., 2019b. Effects of acid treatment in jaggery making. Food Chem. 299 https://doi.org/10.1016/j.foodchem.2019.125094.

Verma, P., Shah, N.G., Mahajani, S.M., 2019c. Why jaggery powder is more stable than solid jaggery blocks. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 110, 299–306. https://doi.org/10.1016/j.lwt.2019.04.093.

Yadav, L., Chaudhary, R., Srivastava, P., Agnihotiri, S., 2018. A Status Report on Khandsari sugar/jaggery(Gur).