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Recent Trends in Jaggery Making Processes: A Review

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ABSTRACT

Jaggery is an unrefined sugar produced by evaporating water from sugarcane juice, making it one of India's oldest cottage industries. Approximately 25-30% of India's total sugarcane production is used for jaggery and khandsari, with an output of 9.2 million tonnes in 2024. The process generates bagasse, a fibrous residue from crushed sugarcane, commonly used as fuel for open-pan boiling. However, this traditional method has low heat utilization efficiency, often requiring additional combustible materials, leading to higher pollution and CO_2 emissions. This paper reviews the existing processes used in jaggery production, identifying best practices and future techno-economically viable improvements. One promising alternative is the freeze pre-concentration process, which selectively removes water from juice before concentration. This method, followed by steam-jacketed pan-based concentration, reduces bagasse consumption and enhances jaggery quality by minimizing prolonged high-temperature exposure. Additionally, incorporating a vapor recompression system can enable evaporation under vacuum, where compressed steam efficiently heats the jacketed pan. By evaluating various jaggery production methods, this review provides valuable insights for jaggery producers, researchers, equipment manufacturers, policymakers and stakeholders in both government and private sectors. Advancements in processing techniques can lead to energy savings, improved product quality and greater benefits for farmers.

Key words: Freeze concentration, Heat pump, Jaggery making processes, Techno-economics, Vapour recompression.

The jaggery is prepared by water removal from sugarcane juice. Conventionally, the water is removed by evaporation in an open pan using the heat of combustion from sun-dried bagasse. There are very few research papers available on the jaggery-making process, as regional as well as local names know jaggery. Jaffe, 2012 has listed region-wise and country-wise names of jaggery. It is most commonly known as jaggery, panela, rapadura, non-centrifuge sugar, raw sugar and brown sugar. In the olden days, jaggery was a traditional sweetener served with water as a welcome drink to the guests in the rural segment of India. It also contains iron, calcium, phosphorus, copper and vitamin C. It increases the nutritive value of jaggery, as the molasses is not removed; phenolic, minerals and antioxidants are retained in the product. Thus, the consumption of jaggery gives additional health benefits than sugar. The jaggery contains micronutrients, which have antitoxic and anti-carcinogenic properties (Nath *et al*., 2015). It distinguishes the use of jaggery from white sugar. The jaggery has local as well as global market. India has exported 0.76 million MT of jaggery in 2022-23 (APEDA, 2024). There are three major issues observed in the current jaggery making process. The first major issue is a requirement for additional fuel along with bagasse. The second major issue is the lack of skilled as well as unskilled labour. The third major issue is harsh and hazardous working conditions for labours working with non-engineered equipment. The thermal efficiency of various jaggery making processes has been reported by many researchers. The furnace heat utilization efficiency is very low, which is ~15% for single, ~30% for two and 50 to 60% for four pans. Hence, additional fuel is required, such as wood, agricultural residues and even old tyres (Rao *et al.,* 2023). Researchers have also made attempts to improve heat utilization for jaggery making. It mainly depends on the number of pans, sizes of pan, furnace, air vents, chimney, flue gas flow path and patterns. These attempts involve use multi-pan instead of single pan, use of bottom baffles to existing pans (Aglave, 2015), fuel and airflow control (Shiralkar *et al.*, 2014), control fuel feeding with energy and exergy analysis (Sardeshpande *et al.*, 2010), use of CFD analysis for heat transfer and flow path of flue gases in four pan (Madrid *et al.*, 2017), drying of wet bagasse using heat of furnace wall (Shinde and Sapali, 2020),energy losses (Sharon *et al.*, 2013), energy improvement (Kumar and Kumar, 2023). It is important to adopt energy-efficient jaggery-making methods for the benefit of jaggery makers and sugarcane producers. The jaggery makers may use the optimum quantity of clarificants if they are aware of their role and significance in the juice clarification process.

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Conventional jaggery making process is reported for standard operations including different time stages. Details about clarificants are reported, including their purpose and health effects. Classification of jaggery making processes is presented based on the method of water removal. Modified jaggery making processes involve multiple-effect evaporation, freeze concentration and vapour recompression processes. In the freeze concentration process, water is selectively removed in the form of ice, while it is removed at low pressure in a closed vessel in vapour recompression processes. Both processes have their own benefits and drawbacks. These are listed in respective sections. The importance of processes used for jaggery making are reviewed.

Conventional jaggery making

The harvested sugarcane from the field is stored near the crushing area in a conventional jaggery making process. The juice is extracted by a horizontal roller crusher operated using an electric motor or diesel engine. Fig 1 shows the layout of a typical single-pan conventional jaggery making unit in an isometric view.

The conventional jaggery making process with a typical quantity is shown in Fig 2. Typical extraction efficiency ranges from 60 to 70%. Residue of juice extraction, bagasse, contains about 45 to 55% moisture. It is sun-dried up to 15 to 25% by spreading in open space. Juice is filtered to remove suspended fine bagasse particles and pumped to a settling cum storage tank. As the earlier batch finishes, filtered juice is preheated to 70 to 85°C in a pan and the first scum is removed. Clarificants like milk of lime, phosphoric acid, hydros powder and mucilage of lady's finger are added to improve clarification and quality of jaggery. Frothing and bubbling of juice are reduced by continuous stirring using manual scrapping at the bottom of the pan or a rotating horizontal rod mechanism. Second

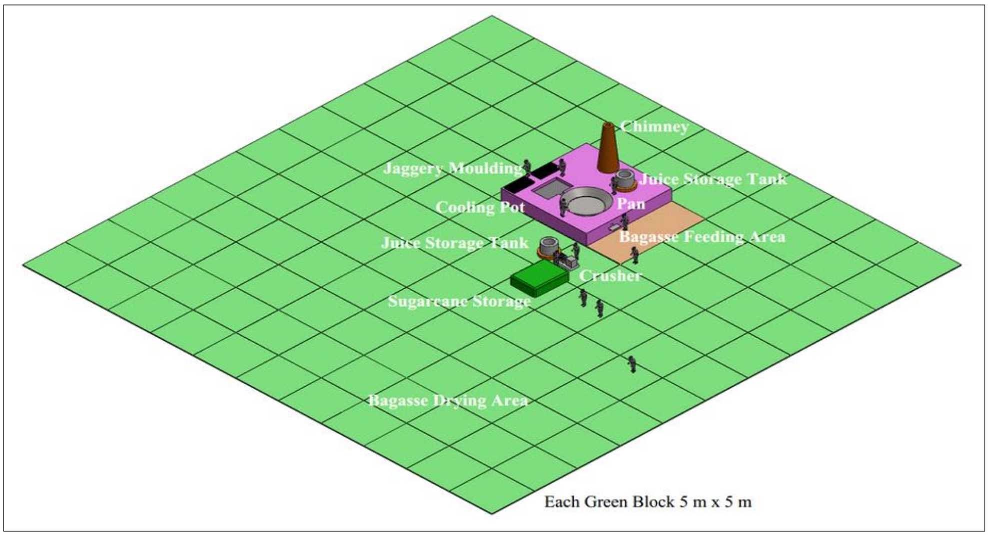

Fig 1: Layout of single pan conventional jaggery making unit.

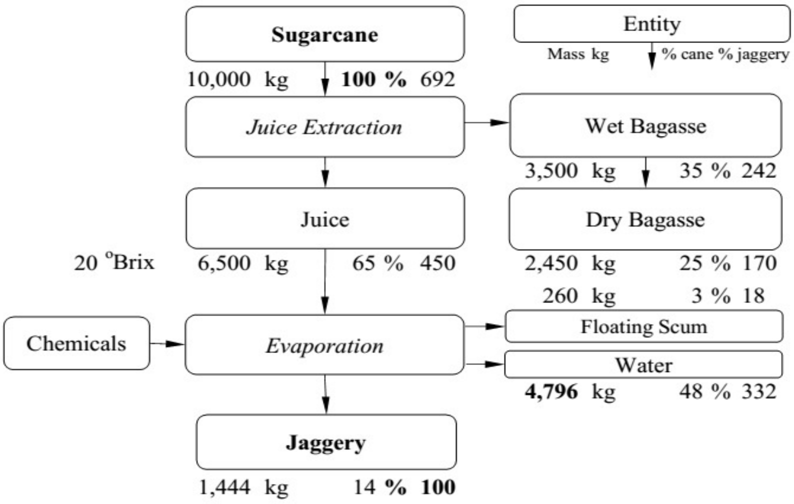

Fig 2: Conventional jaggery making process (with typical value).

scum is removed as concentration progresses. Total scum quantity ranges from 1.5 to 4% of juice. Continuous stirring helps to prevent frothing, spillage of juice from the pan and caramelization of sugar by reducing hot spot formation, such as turbulence in juice, instead of pool heating. The viscosity of syrup is tested by a skilled person. Syrup from the pan is poured into a cooling and crystallizing pot. This cooled syrup is poured in moulds covers with wet cotton cloth or gunny bags. It facilitates easy removal of solid jaggery from moulds. This conventional jaggery making process may slightly vary from region to region. Fig 3 shows stages of jaggery making process with respect to time and temperature (Jabade, 2005). This time required for one batch also depends on initial concentration of raw juice. It varies typically from 16 to 20°Brix. The quality of jaggery depends on variety of sugarcane (Pawar *et al.*, 2022), its cultivation, farming, practices applied in usage of water and fertiliser, boiling practices like use of clarificants, furnace firing practices, pan and furnace dimensions, *etc.* Venkatesan *et al.*, 2024 provided a review of the single and multi-pan processes.

The striking point for solid jaggery is 118°C, while it is 105°C for liquid jaggery. A sweet sorghum is also a source of liquid syrup/jaggery, which prepared using similar process like a jaggery making process.It has a concentration of 74-76°Brix. It is reported the solution temperature variation with time. In conventional jaggery-making practice, the experience of the jaggery-man plays an important role in the operation of stages, temperatures are not measured. Measurement of temperature along with concentration variation allows the automation of process.

The number of open pan/s used for concentrating juice depends on severity of bagasse use. The furnace heat utilization efficiency of single pan process is about 15% (Sharon *et al*., 2013). It increases to about 30% (Anwar, 2010) and 55% (Shiralkar *et al*., 2014) for three and four pan process respectively. It shows that furnace heat utilization efficiency increases with number of pans. An initial

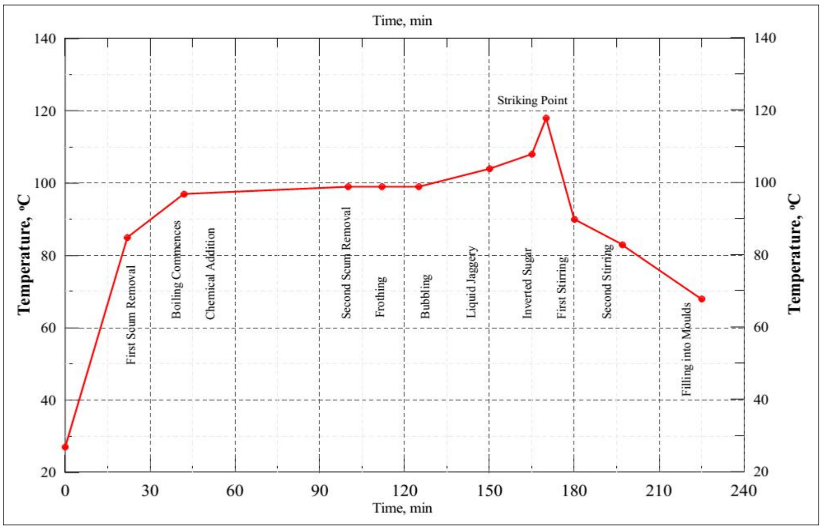

Fig 3: Stages of jaggery making process with respect to time and temperature (Jabade, 2005).

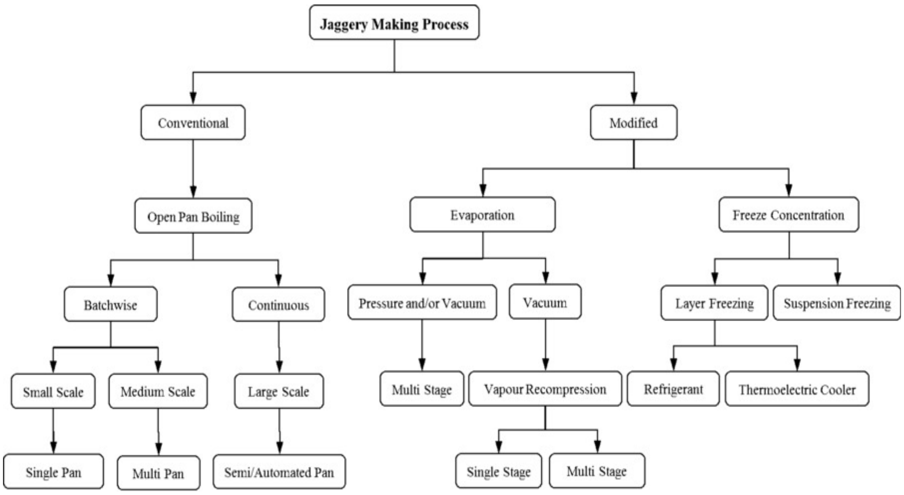

Fig 4: Classification of jaggery making process.

investment also increases with increase in number of pans and operators. In four pan process with modifications in bagasse feeding rate reduced bagasse consumption from 2.39 kg/kg jaggery to 1.75 kg/kg of jaggery (Sardeshpande *et al*., 2010). The quality of jaggery is still being questioned, as chemical clarificants are used to enhance the colour of the juice. Organic sugarcane cultivation and crushing of the same sugarcane for organic jaggery making using only vegetative clarificants shows huge potential in the Indian market as well as for export. Sugar processing uses sulphur dioxide and lime. India has exported 1.4% of total jaggery and confectionary exported by all countries in 2024. This huge opportunity can be met by continuous and automated operation of small jaggery units. It will offer additional employment and help to improve the status of debt-ridden sugarcane farmers.

Classification of jaggery making processes

Classification of jaggery making processes is shown in Fig 4. It is classified based on the available literature.

The jaggery making process is mainly classified into two categories, conventional and modified processes, as shown in Fig 4. The conventional process of jaggery making is an open pan boiling of raw juice with a batch-wise or continuous process. Most of jaggery making units were small capacity units. They were upgraded to medium scale by increasing the number of pans in series and they are operated in a batch-wise process. An automation of unit allows the continuous and large capacity operation. Generally, the capacity of jaggery making units ranges from 10 to 500 TCD cane crushing.

The modified jaggery making process is classified as a closed pan evaporation of raw juice and a freeze concentration process. The closed pan evaporation process is further classified based on pressure developed inside the vessel due to heating sources in a confined space. If low pressure external steam is used, then this multiple closed pan evaporation process may operate at vacuum in some vessels and positive pressure in remaining vessels and if evaporated vapour from the juice are compressed and used as heating source, it is known as a vapour recompression process. The vapour recompression process can be operated in a single stage or in a multi-stage. The freeze concentration process is classified as a layer freezing process and a suspension freezing process. The layer-freezing process is a batch-wise process achieved using either a fluid refrigerant-based refrigeration system or a solid-state thermoelectric cooler-based refrigeration system.

Clarificants

The chemical and vegetative clarificants are listed in Table 1 from various references. It gives the detailed information about quantity to be used in jaggery making process with the major effect in the process. the jaggery making involves these chemical and/or vegetative clarificants for clarification process. An organic jaggery making may involve only the vegetative clarificants.

Effect of initial concentration on water removal processes

The quantity of water removal slightly varies with variation in raw juice concentration. It is not matter of concern, if single process for water removal is employed. It is required to consider, when two or more process of water removal are used (Uphade, 2018). An outlet concentration of first process and choice of second process could change by variation of raw juice concentration. Fig 5 shows the effect of initial concentration on water removal processes. As the initial concentration reduces, it increases the duty of water removal process and vice-a-versa. It is further explained in section on freeze concentration system as the limiting concentration for the process.

Modified jaggery making process

The modified jaggery making processes involves multiple effect evaporation, freeze concentration process and vapour recompression process. These processes are explained

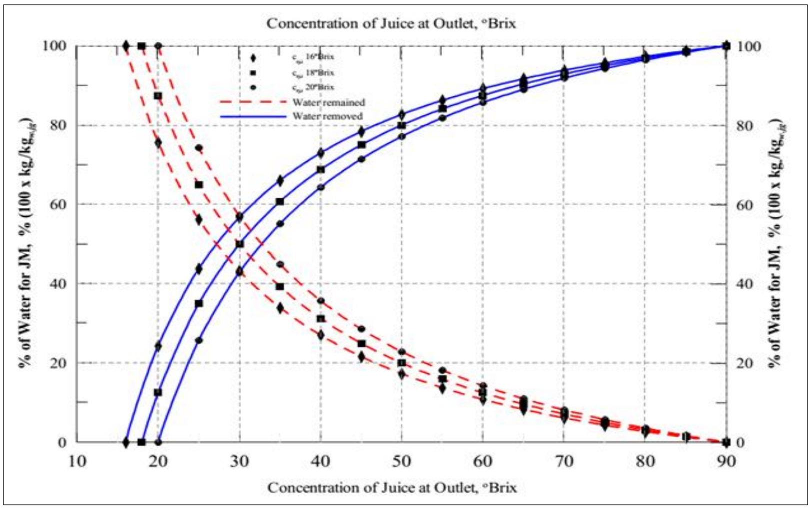

Fig 5: Effect of initial concentration on water removal processes.

Table 1: Chemical and vegetative clarificants used in conventional jaggery making.

Chemical Clarificants	Formula	Quantity Used	Purpose/Effect	References
Lime/Calcium Carbonate	$CaCO_3$	30 to 50 g/ 100 kg juice	Maintains pH and facilitates removal of floating residue.	Sardeshpande *et al.*, 2010
			Scum formation and enhancement of clarification	Mohan and Agrawal, 2020
Milk of lime/ Calcium hydroxide	$Ca(OH)_2$	1 kg lime (80-90% purity) + 4 L H_2O => ~ 60-70 ml milk of lime/ 100 kg juice	Acts as complex agent and improves the consistency of jaggery by increased crystallization of sucrose, but at the same time it darkens colour if added in excess	Sharon *et al.*, 2013
		0.2 kg/m^3 juice	-	Shiralkar *et al.*, 2014
		-	Acts as complexing agent and form scum, it is removed during boiling	Arya *et al.*, 2013
		-	Makes juice clear and light in colour	Bhardwaj and Singh, 2013
Phosphoric acid	H_3PO_4	30 to 50 g/ 100 kg juice	Maintains pH and facilitates removal of floating residue	Sardeshpande *et al.*, 2010
		150 ml/m^3 kg juice	-	Shiralkar *et al.*, 2014
		-	Bleaching agent, electrolyte or pH-adjusting agent	Sharon *et al.*, 2013
Superphosphate	$Ca(H_2PO4)_2$	-	Bleaching agent, electrolyte or pH adjusting agent	Sharon *et al.*, 2013
		Phosphates used in sugar making	Helps to prevent destruction of reducing sugars	Kulkarni, 1996
Citric acid	$C_6H_8O_7$	0.04% (400 mg/kg liquid jaggery)	Avoids crystallization and make liquid jaggery attractive in colour	Nath *et al.*, 2015
Sodium hydrosulphite/ Hydros powder	Na_2SO_4	-	Bleaching agent-decolourization effect	Sharon *et al.*, 2013
		- 10-12.5 g/ 100 L juice	Makes juice clear and light in colour	Bhardwaj and Singh, 2013 Shrivastava and Singh, 2021

Table 1: Continue....

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Sodium bi/carbonate	$NaHCO_3$/ Na_2CO_3	- 2.19 g/kg juice	Makes juice clear and light in colour	Bhardwaj and Singh, 2013 Singh *et al.*, 2021
Potassium metabisulphite	$K_2S_2O_5$	0.1% (1 g/kg liquid jaggery)	Improves shelf life of liquid jaggery without deterioration in quality	Nath *et al.*, 2015
Benzoic acid	$C_7H_6O_2$	0.5% (5 g/kg liquid jaggery)	Improves shelf life of liquid jaggery without deterioration in quality	Nath *et al.*, 2015
Chemiflocs	-	-	Bleaching agent, electrolyte or pH adjusting agent	Sharon *et al.*, 2013
Nitric oxide	NO	-	Better colour and sucrose content, helps increase shelf life of jaggery	Hussain *et al.*, 2012 Selvi *et al.,* 2021
Vegetative clarificants		**Quantity used**	**Purpose/Effect**	**Reference**
Bhendi /Okra/ lady's finger/ Hibiscus esculentus		30 to 50 g/ 100 kg juice	Natural clarificant	Sardeshpande *et al.*, 2010
		-	Makes juice clear and light in colour	Bhardwaj and Singh, 2013
Deola		45 g/100 kg juice 35-38 g/ 100 L juice	Makes light coloured jaggery by eliminating impurities in suspension, colloidal and colouring compounds by accumulation	Nath *et al.*, 2015 Shrivastava and Singh, 2021
Castor/Mustard/ Groundnut oil		10 to 15 ml/pan	Prevents frothing to certain extent and facilitates easy flow of jaggery	Bhardwaj and Singh, 2013
Cooking oil		200 ml/m^3 kg juice	-	Shiralkar *et al.*, 2014
Chikani, Kateshevari		-	-	Sharon *et al.*, 2013

in brief. It covers multiple effect evaporation process, freeze concentration process and vapour recompression process. Membrane distillation process (Nene *et al.,* 2002) also clarifies the juice, but it not included here.

Multiple effect evaporation

Norbert Rillieux in 1830 has conceived an idea of multiple effect evaporation. It requires low pressure steam as heating medium in first effect and further effects are operated using the low pressure vapour generated in earlier effects. Raw juice enters into the first effect and after single pass through calendria, it is sucked to next effect. It is shown in Fig 6. Low pressure steam at 112°C enters into heating side of first effect. The vapours are generated at 103°C and they are used as heating source for second effect. Further effects operated at 94, 78, 55°C. The vapours from last effect are condensed in the jet type mixing condenser. Condensed vapours in earlier effects can be used as distilled water. Water evaporation from each effect is close to 1 kg for 1 kg steam application in first effect. In quadruple effect evaporation, total 3.922 kg water is evaporated using 1 kg steam.

Open pan boiling process is modified to boiling of juice inside the closed vessel. Water is evaporated at vacuum or slightly more pressure than atmosphere. In multiple effect evaporation, MEE, mostly first vessel is operated at about 1.2 bar pressure and remaining vessels are operated at vacuum upto 635 mm of Hg. Typical water evaporation rate is as shown in Table 2.

SMER for 1 kWh electric heating of cold water from 30°C to 100°C at 100% electric heating efficiency is 1.41 kg/kWh.

It indicates that Multiple Effect Evaporation, MEE, process evaporates additional 64% of water, 2.513 kg of water than open pan water evaporation at 1 atm pressure by electric heating. MEE process becomes beneficial only if the low pressure steam is freely available. Sugar factories engaged in white and raw sugar making, having plenty of low pressure exhaust steam from power turbines and mill turbines. Thus, MEE is commonly used for pre-concentration of raw juice to 55 to 60°Brix. Conventional jaggery units removes the floating scum in regular interval. It has to be removed at different stages of jaggery making, Fig 3. Hence, process of multiple effect evaporation practiced in white sugar making cannot be easily adopted for jaggery making process.

Advantages of MEE process

a. Low temperature in condenser, reduces the caramelization and inversion of sugar, it helps to improve the quality of jaggery.
b. Saves bagasse during pre-concentration process.
c. Ease of automation of process facilitates any capacity unit.
d. Compact installation.

Disadvantages of MEE process

a. Requires low pressure steam, hence it is not suitable for small or medium capacity jaggery units.
b. Requires trained personnel for operation.
c. High initial cost and high inventory.

Freeze concentration system

The water is removed in the form of ice from sugarcane juice by selective freezing (Rane and Uphade, 2016). This process of water removal is shown by freezing curve in sucrose-water phase equilibrium diagram, Fig 7. The freeze concentration process for jaggery making is explained in next sections and it covers methodology, heat pumps, limiting concentrations and inclusion in ice.

The sugarcane juice at room temperature and 20°Brix is subcooled from point ‘a’ to ‘b’. Solidification of water in layer form commences, at point ‘b’, at -1.5°C, simultaneously concentration of remaining juice increases, during process

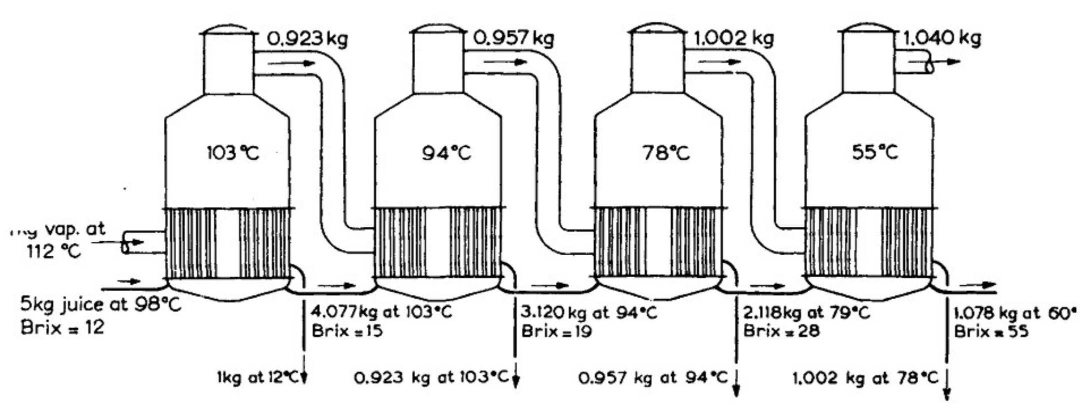

Fig 6: Multiple effect evaporation (Hugot, 1986).

Table 2: Water evaporation rate in quadruple effect evaporation (Hugot 1986).

Stage	$t_{cst/vap}$ ℃	t_{jc} ℃	p_{jc} abs bar	$dt_{st/vaptjc}$ °C	Rate of evaporation kg/kg steam	
					Without circulation	With circulation
First	112	103	1.2	9	0.923	0.923
Second	103	94	0.82	11	0.958	0.972
Third	94	78	0.47	16	1.002	1.047
Fourth	78	55	0.16	23	1.040	1.162
Total					3.923	4.104

'b' to 'c'. Due to dissolved sucrose in water, water gets freeze out at -1.5°C instead of 0°C if the water is pure. This drop in freezing temperature of water in juice is called as freezing point depression. Concentration of outlet juice depends on quantity of water frozen out and it is limited by eutectic temperature, which is -13.9°C at 63°Brix. Beyond this point, the whole juice gets solidified and aim of concentration of juice cannot be achieved.

It shows that from 1 kg solution at 20°Brix, out of 800 g of water, 500 g water is removed in the form of ice, which is 63% of total water in the initial solution. Rane and Jabade, 2005 proposed freeze concentration of sugarcane juice using a heat pump and have shown that concentration of juice from 20 to 40°Brix saves about 77% bagasse with improvement in quality. Specific power requirement is 17.2 kWh_e/m^3 water removal. Freezing of water inside the tube is reported by Miyawaki *et al.*, 2005 for coffee extract, tomato juice and sucrose solution. Rane and Padiya, 2010 showed two stage heat pump with external condenser for freeze concentration of seawater desalination requires 9 to 11 kWh_e/m^3 water at COP_c 8 to 12.

Heat pump based systems

The schematic of Freeze Pre-concentration System, FPCS, for sugarcane juice pre-concentration from 20°Brix to 40°Brix is shown in Fig 8 a and b. Fig 8a is the refrigerant based freeze pre-concentration system.

This system consists of heat exchangers namely Liquid-Liquid Heat Exchanger, LL_HE, two Latent Heat Exchangers, LHE and Concentrated Juice Heat Exchanger, CJ_HE. LL_HE precools the sugarcane juice using streams of concentrated juice coming from CJ_HE and cold water coming from LHE during each half cycle. One LHE is used freezing of water from juice flow and another for melting of ice. They are operated alternately as evaporator and condenser. CJ_HE recovers the superheat

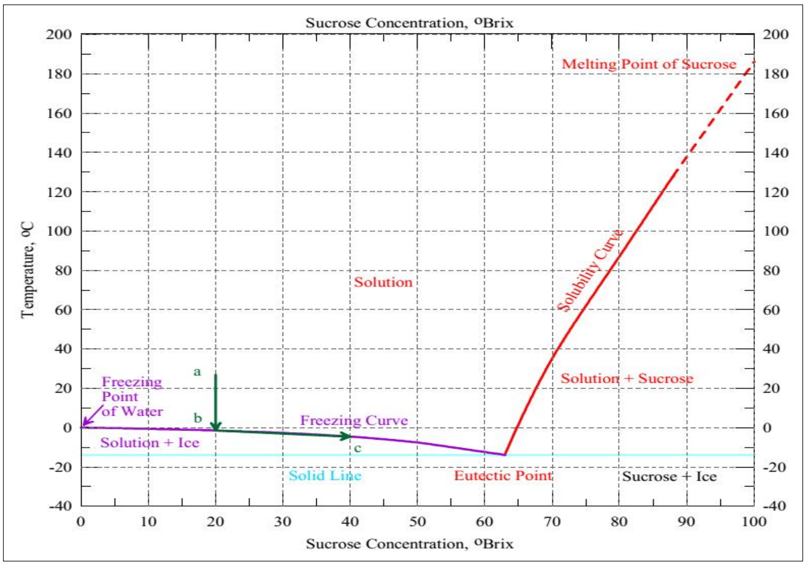

Fig 7: Sucrose-water phase equilibrium diagram (Mathlouthi and Reiser, 1995).

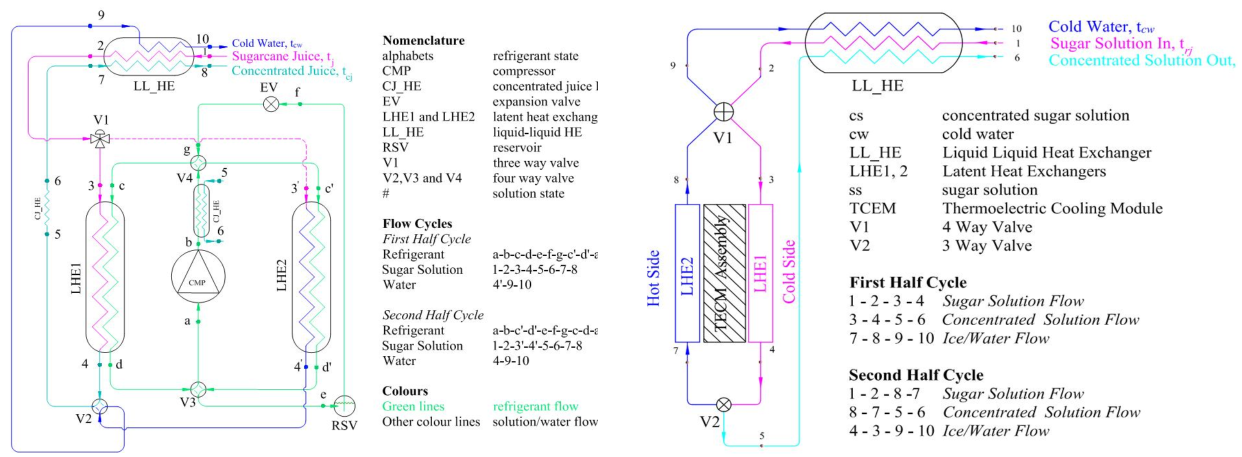

Fig 8a: Refrigerant based fPCS.

Fig 8b: Thermoelectric based FPCS.

Fig 8: Heat pump based FPCS (Uphade, 2018).

of refrigerant for heating of concentrated juice coming from evaporator. The process of cooling and heating in LHE is shown in Table 3.

This system consists of 1 three-way valve, V1, for directing juice flow to LHE, working as an evaporator and 3 four-way valves, V2, V3 and V4. Valve, V2, for directing concentrated juice flow coming from evaporator to LL_HE and two valves, V3 and V4 for directing refrigerant flow in heat pump circuit.

Working principle

The refrigerant based FPCS system is explained here. Fresh sugarcane juice at room temperature about 27°C enters in the evaporator, LHE1, through LL_HE where it gets pre-cooled to -1.5°C before entering into the evaporator, LHE1. At freezing temperature of juice, which is -1.5°C, ice layer starts to build up inside the tube. It will start to build up pressure drop, as a result pressure drop across the evaporator will increase. This reduces the evaporator temperature, as ice thickness has low thermal conductance. Expected thickness of formed ice in the system is 1 to 3 mm. Simultaneously, in condenser, LHE2, ice gets heated in two steps, comprising sensible heating from -4.6°C to 0°C, followed by latent heating, at 0°C. At certain low evaporator pressure, all three way and four-way valves are operated for the second a half cycle of the system. During second half cycle, LHE1 acts as condenser and LHE2 will acts as evaporator.

Refrigerant circuit removes heat from the evaporator and rejects it into condenser. Sugarcane juice circuit gives heat in evaporator and ice receives back in condenser. Compressed refrigerant enters into the CJ_HE and dissipates superheat for heating concentrated juice coming out from evaporator, LHE1 and then used to precool incoming juice. Refrigerant vapour are further cooled by melting ice in condenser, LHE2. Liquid refrigerant from LHE2 is directed to four-way valve, V3 and expanded into the evaporator, LHE1, through expansion valve. It receives heat from precooled juice. Saturated vapours of refrigerant are sucked by the compressor and the half cycle repeats after switching of valve back to the first half cycle.

Thermoelectric-based FPCS is shown in Fig 8b. It works with electrons as a refrigerant and there is no fluid

Table 3: Process of cooling or heating in LHE during each half cycle.

LHE	Work / In/Out	First half cycle process	Second half cycle process
LHE1	Work as	Evaporator/Cold Side	Condenser/Hot Side
	Inlet	Subcooling of raw juice, freezing of water, concentration of juice, subcooling of ice	Sensible and latent heating of ice Melting of ice
	Outlet	Concentrated juice	Water
LHE2	Work as	Condenser/Hot Side	Evaporator/Cold Side
	Inlet	Sensible and latent heating of ice Melting of ice	Subcooling of raw juice, freezing of water, concentration of juice, subcooling of ice
	Outlet	Water	Concentrated juice

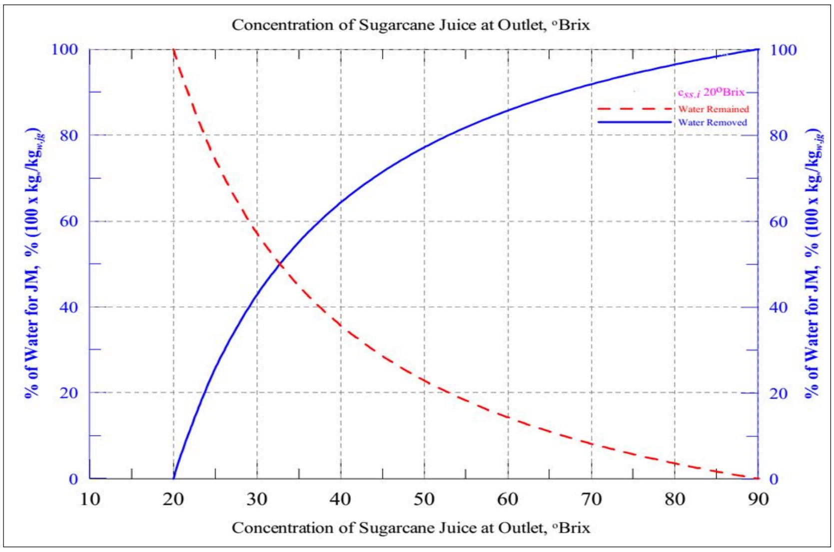

Fig 9: Water removed/remained from/in juice vs outlet concentration (Uphade, 2018).

refrigerant. It is also called a solid-state heat pump. There are no environmental issues of ODP and GWP. Coefficient of performance is high for low-temperature lift as compared with fluid-based FPCS. This system is comparatively simple, as it uses less number of valves. It is easy to switch the cycle operation by reversing the polarity of the DC supply and operating valves V1 and V2. It offers noise and vibration-free operation. However, the initial cost is higher for the same cooling capacity FPCS system.

Limiting concentration for freeze concentration system

Freeze concentration from 20°brix to 33°brix removes about 50% of the total water available in juice. Fig 9 shows the variation in water quantity removed during a change in concentration starting with 20°Brix. The dotted line indicates the water quantity remaining in the juice. The shaded portion shows the area of freeze pre-concentration from 20°Brix to 40°Brix. During this concentration change, 62.5% water is removed in the form of ice and the remaining 37.5% water is to be removed by steam-jacketed boiling. Increase in outlet concentration from 40°Brix to 50°Brix, 13% more water get removed. This rate of water removal may not be justified by increase in sugar loss. Three cases are presented in the next section.

Limiting factors for outlet concentration include ice and eutectic point, 63°Brix. Inclusion increases as the inlet juice concentration increases. It also depends upon the velocity of juice and ice growth rate. Hence, freezing close to the eutectic point is not considered due to high sugar loss in water.

Rodrigues and Fernandes (2012) have listed the comparison of film or layer freezing reported by different authors. They concluded that the orientation of ice crystal growth to reduce inclusion also plays an important role along with parameters like Ice growth Rate, IGR, solution velocity and solute type. The initial cost for a commercial fruit juice concentrator with FCS is 3 to 4 times higher than MEE. Marie *et al.,* 2020 have predicted the potential energy consumption of 3.8 kJ energy for 1 kg of jaggery using solar thermal and freeze concentration. Low-pressure steam is unavailable for small-capacity jaggery-making units. Multiple-effect evaporation increases the initial and maintenance costs of conventional units. Further investigations on the reduction of sugar inclusion in ice for the flow of juice inside the tube are needed to estimate inclusion. Removal of proteins and polyphenols in a later stage of concentration at 40°Brix is required to investigate along with its effect on ice crystal growth to implement FPCS.

Inclusion in Ice

Inclusion in ice is found experimentally by Chen *et al*. (1998) for falling film flow of solution over a vertical plate, Eq (1) is shown below as average distribution coefficient,

$$\text{ADC} = -0.142 + 2.05\ .\ c_{ss} + 0.139\ \frac{V_{ice}}{V_{ss}^{\ 0.5}} \qquad \text{.... (1)}$$

It is tested in the range of 1.3 to 30°Brix of sucrose solution flow over 450 mm length x 50 mm wide and 1 mm thick vertical stainless steel plate. The sucrose solution velocity is 0.3 to 1.1 m/s and the ice growth rate is up to 1.6 micron/s. Coolant, glycol solution, temperature is -3.5 to -13°C.

Chen *et al*., 2014 suggested a more generic correlation for inclusion. This correlation was tested in the falling film flow of solution over a flat plate, eq (2) is shown below,

$$\text{ADC} = -0.1 + 0.32\ .\ t_{fpd} + 0.04\ .\ t_{fpd}^{\ 2} + 0.12\frac{V_{ice}}{V_{ss}^{\ 0.5}} \qquad \text{.... (2)}$$

Solution concentration is in the range of 10 to 40°Brix for sucrose solutions, whole milk, skim milk, orange juice, glycol solution, fructose solutions, NaCl solutions and potato starch suspensions. Fig 10 shows the variation in ADC by Chen *et al*. (1998) and Chen *et al*. (2014).

Error in Chen *et al*., 2014 correlation is in the range of -5 to 5% compared to Chen *et al*. (1998) for 20°Brix solution inlet concentration for a range of 0.3 to 1.1 m/s solution

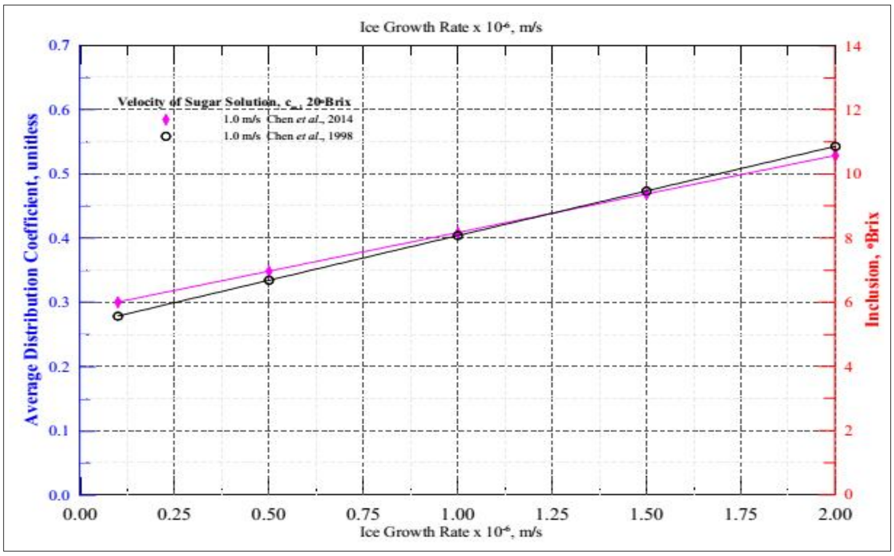

Fig 10: Comparison of ADC.

velocity, 0.1 to 1.6 micron/s ice growth rate. The effect of solution velocity and ice growth rate on average solution loss is shown in Table 4 for 20 to 40°Brix. Absolute sugar loss in separated ice/water is the ratio of sugar in separated ice to the total available sugar in raw juice. It depends on the raw juice concentration and final concentration. The loss of sugar in ice is undesirable and efforts should be made to reduce it. An economic viability of FCS needs to justify absolute sugar loss in separated water. These heat pumps may be operated using solar power during the day.

Advantages of FPCS

a. Saving of bagasse during initial 63% water removal, it gives additional earnings to farmers
b. Quality of jaggery gets improved without chemical use.
c. Reduction in pan size required for boiling of concentrated juice.
d. Operation of the system is also possible using solar photovoltaic cells.
e. Reduces the number of workers required to handle the boiling process.
f. Drinkable cold water was obtained.

Disadvantages of FPCS

a. Sucrose gets lost in cold water and produces up to 9.4°Brix. It may still be advantageous as this water can be used as sweet drinkable water with traces of sugar.
b. Retrofitting of the system to a conventional unit needs to change the mindset of farmers.

Table 4: Effect of solution velocity and ice growth rate on absolute sugar loss for c_{ss} 20 to 40°Brix.

$v_{ss.i}$ m/s	IGR µm/s	$c_{wt.av.ice}$ °Brix	$s_{wt.av.s.ls.ice}$ %	$s_{act.ls.ice}$ %
1.0	1.0	18.3	4.7	38.7
1.0	0.5	16.0	4.1	34.5
1.5	0.5	15.6	3.9	33.7

Vapour recompression system, VRS

Water vapour from raw juice is recompressed using a turbo-compressor or thermo-compressor and used for heating the same juice in a vertical cylinder pre-concentrator (Hugot, 1986). It gets condensed. This process is limited to pre-concentration of juice due to low heat and pool boiling mass transfer coefficient. Fig 11 shows the mechanical vapour recompression system (Rane and Uphade, 2021). Rane *et al*., 2022 have demonstrated the viability of a table-top jaggery maker using a novel near-isothermal steam compressor. It is an energy-efficient process based on the Vapour Recompression process. Mechanical vapour recompression is a well-known industrial process of water distillation, for many years for desalination. An industrial plant of 3000 m^3/day of distilled water production is installed in a single capacity unit; it consumes 6.9 kWh/ton of water (Lokiec and Ophir, 2007). It indicates that a well-designed concentration system for sugarcane juice can give better SMER.

Advantages of VRS

a. Controlled temperature in condenser reduces the caramelisation and inversion of sugar, it improves the quality of jaggery.
b. No requirement of bagasse firing.
c. Saves bagasse can be composted on the farm to improve the productivity of sugarcane
d. Ease of automation of process facilitates any capacity unit.
e. Compact installation.

Disadvantages of VRS

a. High initial investment and maintenance costs.
b. Mechanical compressor requires power.
c. Skilled operator required.
d. More robust vessel is required as compared with conventional pan, as system works below atmospheric pressure.

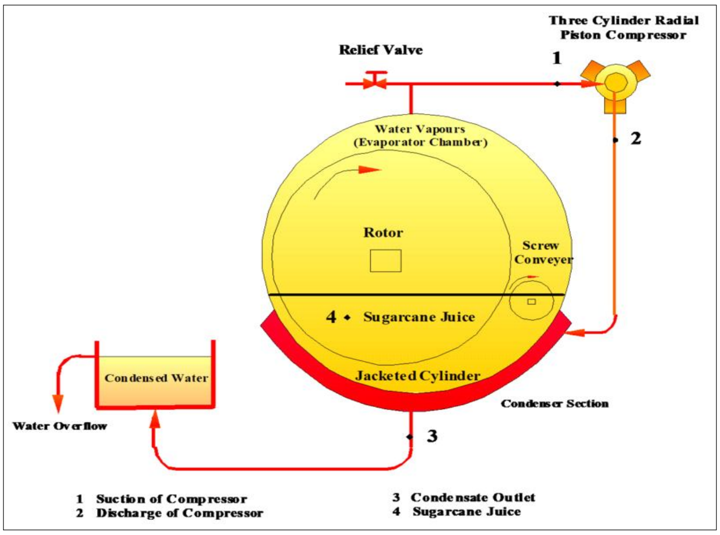

Fig 11: Vapour recompression system.

Table 5: Techno-economic analysis.

Author(s)	Purpose	Remarks
Das, 2001	Diagnostic study SME jaggery cluster Madhepura	Clustering of jaggery units can provide the additional revenue of Rs. 1.94/kg of jaggery to the sugarcane growers. Provided detailed strategies and plans for the execution of the jaggery cluster.
Dwivedi, 2010b	An empirical study on jaggery industry	Provided guidelines for policymakers to streamline strategies that promote stabilization of the sugarcane economy and make the nation a credible supplier of jaggery in the international market, benefiting jaggery makers, sugarcane growers and related stakeholders. Medium and large manufacturing units are more profitable, while small ones profit less.
Sachinkumar and Anilkumar, 2012	SWOT analysis of jaggery making process through a survey of about 258 jaggery units in the state of Karnataka.	Significant strength is the large employment potential and large demand for jaggery. Major issues are poor furnace performance, availability of skilled labours, chemical uses, highly unhygienic conditions, and scientifically inefficient processes to produce quality jaggery, proper payment to sugarcane growers, unorganized rural sectors need institutional support for quality jaggery production, handling, storage, management and higher returns at low cost. Local research centers may play a significant role in sustainable development.
Suryavanshi and Patel, 2012	Techno-economic analysis of jaggery production in Maharashtra.	Increasing thermal efficiency saves bagasse. Saved bagasse may be utilized for briquette making as additional income. This leads to earning more profit.
Shivnaikar *et al.,* 2012	Financial appraisal of organic and inorganic jaggery preparation in Bagalkot district- An economic analysis.	Recovery for the organic jaggery preparation unit was estimated at 11%, and for the inorganic jaggery preparation unit, it was 10.48%. The benefit-cost ratio was estimated at 1.26 in the case of organic jaggery making unit, while it was 1.22 in inorganic jaggery making unit.
Shanthy and Baburaj, 2015	Socio-Economic Impact of Multiple Furnace Over Single Furnace in Jaggery Preparation.	The jaggery productivity of triple pan furnaces was twice that of local furnaces. The impact of multiple pan furnaces was greater in economy, time-saving, labour use, production, productivity, and efficiency of jaggery unit operation than the local types. The single-pan and double-pan furnaces were consuming more time, and they were uneconomical in terms of productivity and net income
Kumar and Kumar, 2021a	Thermo-economic analysis of modified jaggery making plant.	An automatic fuel feeding system has been implemented to optimize the rate of bagasse supply in the furnace as the uniform heat supply. Jaggery production rate was 0.61 kg/min. The unit cost for jaggery production and the payback period of the plant were found to be 0.45 $/kg and 1.24 years.
Kumar and Kumar, 2021b	Performance evaluation of modified jaggery making plant: A comparative study	Modified pan has a payback period of 0.71 years compared to a traditional pan of 3.73 years; It resulted in an extra profit of $5,951.3 per annum.

Techno-economic surveys

Techno-economic surveys are listed in Table 5. There are very few researchers who have focused on the economic analysis of jaggery making processes. This economic analysis may vary from time to time as the cost of goods changes and it may or may not be valid in the present situation. However, the research in this field gives a proper insight into the feasibility and sustainability of the jaggery-making unit. Hence, time-to-time updates on economic analysis are equally important for sugarcane producers, jaggery makers, researchers, equipment manufacturers, financial authorities, policymakers involved in government and private organizations like fertiliser manufacturers and technical associations, etc. There is different profit-to-investment ratios for small, medium and large capacity jaggery making units. The medium and large capacity units are typically sustainable and the payback period is shorter based on this ratio (Dwivedi, 2010a). The thermal efficiency improvement leads to saving bagasse. The saved bagasse may be used for paper and pulp making (Kumar and Kumar, 2023). The saved bagasse may also be used for briquette making (Suryavanshi and Patel, 2012) and mushroom growing. It gives additional profit to the jaggery maker. The revenue of production may be increased by making jaggery as a value-added product like organic jaggery, jaggery-based chocolate (Sree *et al.*, 2025), whey in jaggery, *etc.*

Future directions for jaggery making industry

Jaggery is a highly nutritious sweetener and a superior alternative to refined white sugar. With growing health consciousness and increasing awareness of the adverse effects of excessive white sugar consumption, jaggery presents a promising opportunity for both domestic and international markets. Additionally, its export potential is immense. To enhance the sustainability and efficiency of the jaggery-making industry, researchers, agricultural institutions and policymakers should focus on the following key areas:

- Enhancing thermal and energy efficiency to reduce fuel use and costs.
- Using modified processes with automation to reduce skilled labor needs and enhance hygiene with safety.
- Raising consumer awareness on jaggery vs. refined sugar.
- Standardizing equipment for improved shelf life and quality.
- Strengthening financial support for growers and producers.
- Leveraging carbon credits for sustainable revenue.

CONCLUSION

This review provides valuable insights into both conventional and modified jaggery-making processes. Traditionally, jaggery is produced by evaporating water from sugarcane juice through open-pan boiling. It fulfills approximately 38% of India's sweetener demand and is nutritionally superior to refined sugar due to its rich composition of iron, calcium, phosphorus, copper and vitamin C. The additional health benefits of jaggery further distinguish it from white sugar. However, the literature indicates that the heat utilization efficiency of conventional furnaces is significantly low.

An innovative approach, such as freeze pre-concentration, selectively freezes water in sugarcane juice, increasing its concentration from 20 to 40°Brix before further evaporation in a steam-jacketed pan. This method reduces bagasse consumption by eliminating 63% of the water before exposure to high temperatures, thus improving jaggery quality. Vapour recompression and multiple-effect evaporation further enhance efficiency by evaporating water under reduced pressure, saving the entire bagasse while maintaining uniform heating. This controlled heating process significantly improves the quality of jaggery. While these modified techniques improve efficiency and product quality, their economic viability on commercial and industrial scales remains to be fully validated. Techno-economic analysis suggests that value-added jaggery products hold greater potential for financial feasibility and can generate additional revenue streams for producers.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Animals were not involved in this research work.

Conflict of interest

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