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Palmyrah palm (*Borassus flabellifer)* non-centrifugal sugar - Current production practices as a natural sugar and a promising functional food/additive

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A R T I C L E I N F O

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A B S T R A C T

Non-centrifugal sugar (NCS) refers to the unrefined natural sugar that is obtained by solvent (naturally present water) evaporation of tree sap resulting in the subsequent crude crystallization of sugar molecules. Compared to the globally available white cane sugar made of pure sucrose, NCS from the palmyrah palm tree (*Borassus flabellifer*) is an alternative counterpart with the reported bioactive compounds such as vitamins, minerals, phenolics, and antioxidants. To achieve food security for a zero hunger initiative, it is important to have scientific inclusion and technological intervention towards traditionally consumed dietary food. With such focus, the present paper addresses the agronomic production practice of NCS from palmyrah palm sap, the different parameters affecting its quality, and the existing literature available detailing the technological progress to make a standardized production practice. Various nutritional compositions and the functionality of palmyrah palm NCS as an added sugar in numerous food products/formulations are also reported. Finally, perspectives on future research and development concerns ranging from NCS characterization, compositional chemistry and bioactive potential are discussed.

1. Introduction

"Sugar – the symphony of sweetness, mouth feel and flavour" are usually soluble carbohydrates derived from various natural and synthetic sources that may impart calories and energy thereby finding extreme use in food industries. Sugars that are added to foods externally like dairy desserts (such as ice cream, other frozen desserts, and puddings), grain-based desserts (such as brownies, cakes, cookies, doughnuts, pastries, pies, and sweet rolls), sugar-sweetened beverages (such as energy drinks, flavoured waters, fruit drinks, soft drinks, sports drinks, and sweetened coffee and tea), sweets (such as candies, jams, sweet toppings, and syrups) are referred to as added sugars. Sugar is used as an additive in various foods and beverages consumed daily by the world community [1] and also carries out various functional effects in food materials like sensory properties (taste, flavour, texture, appearance, tenderizing agent), physical properties (solubility, freezing point and boiling point enforhancement, overall consistency), microbial properties (preservative agents, fermentative agents) and chemical properties (antioxidant activity, caramelization, Maillard reaction) [2,3]. In this regard, sugarcane and beet sugar have dominated global sugar consumption for ages and have been subjected to widespread use in food formulations since they perform the above-mentioned functions. However, with a healthy food lifestyle becoming a major concern, there is a shift to organic, natural, low-glycemic sources of carbohydrates. Moreover, the high sugar demand of the world community cannot be met by sugar producers on a sustainable basis due to the limited production resources for sugar beet or sugar cane [1]. Provided, the high refinement of cane sugar or common white table sugar is also a huge disadvantage since this results in the loss of valuable dietary bioactive molecules such as flavonoids, glycosides and phenolic acids [4]. Therefore, these concerns raise the opportunity to explore other natural sugar/sweetener sources that are unrefined, very minimally processed, and relatively nutritious option [5].

Non-centrifugal sugar (NCS) is a jargon given by the Food and Agriculture Organization (FAO) which refers to the unrefined, condensed, coarse, bulky, solid dark brown sugar product that is obtained by simply evaporating the tree sap or juice [6]. The World Customs Organization also defines it as '*the product that contains only natural anhedral microcrystals, of irregular shape, not visible to the naked eye, which are surrounded by residues of molasses and other constituents*' [7]. It is produced under different names, such as Gur (India), Desi (Pakistan), Panela (Mexico and South America), Jaggery (India, Burma and African

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countries), Hukuru (Sri Lanka), Htanyet (Myanmar), Panocha (Philippines), Tapa dulce (Costa Rica), Rapadura (Brazil), Chancaca (Peru, Bolivia), Kokuto (Japan) and Namtan Tanode (Thailand) [6,8]. Of these, palm NCS or palm sap sugar or simply palm sugar is very sweet and is used for the preparation of sweetened foods or even consumed directly by the people of Southeast and South Asian countries such as India, Indonesia, Philippines, Thailand, Vietnam and Malaysia [9,10]. Palm NCS is prepared from various monocotyledon palm tree varieties predominantly being palmyrah palm (*Borassus flabellifer*), date palm or toddy palm (*Phoenix dactylifera* and *Phoenix sylvestris*), nipa palm (*Nypa fructicans*), sugar palm (*Arenga pinnata)*, coconut palm (*Cocos nucifera*), fishtail palm (*Caryota urens*), buri palm (*Corypha elata*) and talipot palm (*Corypha unbraculifera*) [10]. Palm sugars from these palm species have been traditionally used as an alternative added sugar mainly because of their noted flavour, taste and sensory attributes in various foods and drinks [10].

Palmyrah palm (*Borassus flabellifer* L.) of the *Arecaceae* family, is a multipurpose plant with great utility and is grown in most South-East Asian countries despite being native to Africa [11]. In these geographic areas, these palmyrah palms are of significant value to local populations. It is also referred to as the 'Tree of Life' with nearly 800 uses including food, beverage, fibre, medicinal and timber applications [12]. *Borassus flabellifer* also contains a bitter compound called flabelliferrins, which are steroidal saponins [13]. The palmyrah

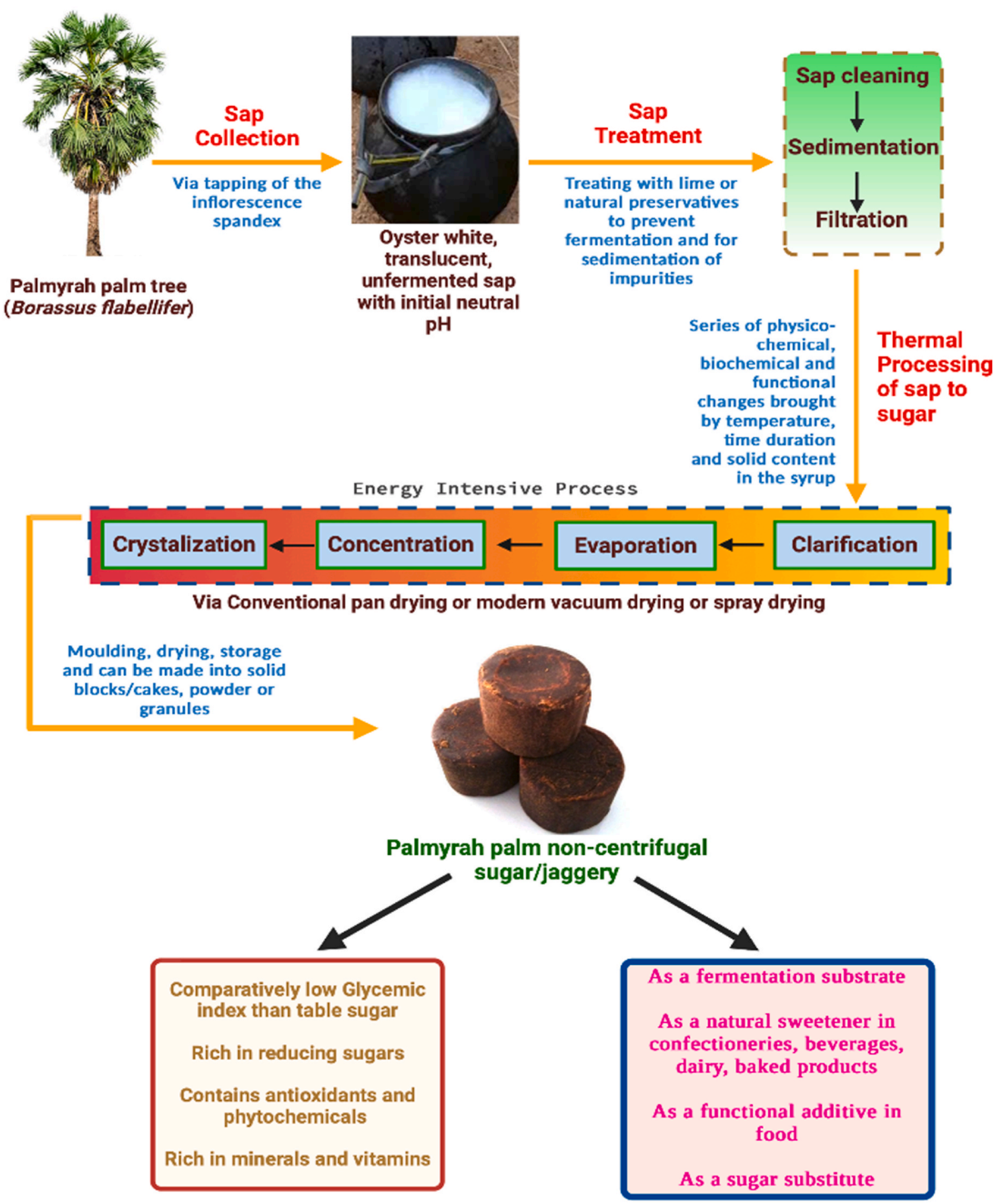

Fig. 1. An overview of production, processing, nutritional benefits, and extended use of palmyrah palm non-centrifugal sugar in food products.

jaggery/sugar/NCS from *Borassus flabellifer* is noted for its earthy, intense taste that is reminiscent of chocolate [14]. The sap collected from these trees, is boiled and upon subsequent crystallization and cooling, the respective crude NCS is produced. Fresh sap is reportedly also a good source of vitamin B as well [15,16]. Often, palm sugars are produced either as solid bulk sugar blocks/cakes, as molten liquid sugar, as granulated sugar particles or as grounded powder. The quality attributes of the prepared palmyrah palm sugar, such as aroma, texture, colour and taste, are largely dependent on monitoring and controlling various physical and chemical changes occurring during the concentration step in its production, particularly when the process approaches the end point (high total soluble solid concentration) [15]. Fig. 1 gives an overview of palmyrah palm NCS production, its processing and its reported benefits as a functional sugar.

Palm sugar, apart from being natural, does not contain any additive or artificial colouring, is minimally processed, unrefined, contains natural sugars and can last for years under proper storage conditions [17,18]. Moreover, it is expected that the global palm sugar industry will be at an estimated US$ 2205.8 million by 2025 [19] and palm sugar as a natural sweetening alternative has gained commercial attention despite its routine regional production and consumption. The potential global use, health benefits and incorporation of this underutilized palm sugar (particularly from *Borassus flabellifer*) into various food products are still poorly understood and are confined to only those local populations that have been consuming it for generations as part of their traditional dietary intake. Although palm sugar from *Arenga pinnata* and *Cocos nucifera* is also substantially consumed, the present review focuses only on the palm sugar derived from *Borassus flabellifer* since it is widely available in the Indian sub-continent and used in many Asian countries to the best knowledge (as it is regarded to be an important value-added food derived from sap because of its nutritional profile and an economic carbohydrate source for many rural and sub-urban populations) [20]. With the vegan sweetener market being projected to grow by 2.49% compound annual growth rate (CAGR) over the forecasted period to reach USD 85.92 billion in 2020 (2021–2026), this review is timely to highlight the use of palmyrah palm NCS as one such natural plant derived sugar [21].

This review paper will address in detail the production and processing of palmyrah palm sugar, its nutritional value, various physicochemical properties and most importantly the prospective use of palmyrah palm sugar in various food substances as an alternative to current sugars and sweeteners. This review highlights those papers that have explicitly mentioned *Borassus flabellifer* or palmyrah palm NCS/jaggery and have also included general palm sugar information wherever relevant. As a result, this review is based on literature collected from scientific search engines and databases using keywords such as *Borassus flabellifer*, palmyrah palm, non-centrifugal sugar, jaggery and natural sweetener. Also, wherever necessary, a comparison has been made between palmyrah palm and cane NCS or pure sucrose in this work to showcase the former as a significantly better choice of added sugar.

2. Production and processing interventions of palmyrah palm NCS

Production of palmyrah palm NCS or jaggery is a continuous, intrinsic and very carefully handled process that requires human effort (in the case of conventional practices) right from the start till the end product is obtained (Fig. 2). Factors such as the genetic and metabolite characteristics of the plant, environmental changes, biotic and abiotic stress, soil characteristics, harvesting period, and the production process determines the availability of the amount of palm sugar [22]. The production process starts with the collection of sap from the palmyrah palm tree. This is followed by a series of steps consisting of gradual thermal changes, physio-chemical changes, clarification and settling. The palm sap/juice is traditionally processed into three types of sugar: liquid sugar (sugar palm syrup), crystalline palm sugar granules and sugar blocks/cakes. This section will detail the production of non-centrifugal and purified sugar from the palmyrah palm (*Borassus flabellifer*) and will also discuss processing intervention advances for the same.

Fig. 2. The practice of making palmyrah palm NCS: 1. Inflorescence sap filtration which is being set up for boiling, 2. Concentrating the sap for jaggery preparation through boiling, 3. Pouring of jaggery syrup concentrates into moulds for making solid NCS, 4. Slicing of the spathe for inflorescence sap extraction, 5. Spoiled jaggery due to fermentation of the sap and 6. Good quality solid jaggery/NCS. Reproduced with permission from [23].

2.1. Sap collection and composition

Initially, the sap/juice (colloquially called *Neera)* is collected from the inflorescence of the palm tree by beating the swollen stalk thus triggering sap flow. This non-destructive, minimally invasive, initial process of collecting fresh, unfermented sap by exudation is called tapping. The tapped part of the tree is the inflorescence spandex, usually the spathe of male and female fruit or the tree itself. Palm trees with slender inflorescence, long internodes, and short petioles are a criterion for higher sap yield [24]. This method allows apical meristem regrowth of the lean tissue of the spadix used for tapping thus ensuring a sustainable practice which further allows for 3–4 times tapping of the palm tree every 5 years [24]. Generally, the fresh sap is sweet, oyster white in colour and translucent, with a nearly neutral pH of 7.0–7.4 [25]. Tapping, in general, for *Borassus flabellifer* is done twice a day for sap collection and different tapping techniques are followed in different countries [26]. Considering that the palmyra palm sap is a rich source of sugars, it gets easily contaminated with fermenting microbes. Hence, the pH of fresh palm sap keeps dropping with time due to an increase in acidity caused by a drastic increase in microbial load [27]. The fermenting organisms are predominantly yeasts, particularly *Saccharomyces cerevisiae* and lactic acid bacteria [28,29]. Recently, it was also found that the palmyrah palm sap in Thailand hosted 86.70% of *Saccharomyces cerevisiae* and various other yeast isolates such as *Hanseniaspora guilliermondii, Lachancea thermotolerans, Pichia kudriavzevii* and *Torulaspora delbrueckii* many of which also have an ethanol-fermenting capacity [30]. The chemical composition of the palmyrah palm sap will vary with the geographical location, season, number of fruits tapped, method of tapping, and collection of the sap [30–32] and will have an impact on the final sugar composition as well. Typically, a palmyrah palm tree can produce around 6–10 L of sap/palm tree/day [24].

Generally, palmyrah palm sap contains 103.6–169.4 g/L total sugars and 8.8–35.6 g/L reducing sugars (comprising sucrose: 92.9–174.4 g/L, glucose: 5.0–18.5 g/L and fructose: 5.0–18.1 g/L) [30]. A typical 100 L of sap will give around 7–8 kg of sugar and 8 kg of molasses although the yield of sugar per tree might differ according to the sex and geographical region [26]. In a study published by Borin and Preston, the authors have reported that in *Borassus flabellifer* there are no significant differences in yield of the sap between days and its Brix value, but the difference in these two parameters are highly significant between farms, months and sex of the palm tree [27]. The sap is also a very good source of vitamin C (as high as 13.25 mg/100 cc for *Borassus flabellifer* which is higher than that of *Cocus nucifera*), vitamin B complex, phytochemicals (α-carotene, β-zeacarotene, and z-carotene, lycopene), volatiles (such as aromatic hydrocarbons, aliphatic ketones, acids, alcohols, heterocyclic compounds and esters) and phenolic compounds (gallic acid, tannic acids) and has TSS in the range of 7–15 °Brix and these values might differ minutely with each farm, sex of the tree, month, and day of harvest [10, 24,26]. The abundant polar side chains of various amino acids in the sap (produced via transaminase reaction) such as glutamine and asparagine react with the carbonyl group of the reducing sugars thus forming many secondary reactions which eventually produce precursors for the characteristic flavour and volatile composition of the sap and the resulting NCS [24]. Moreover, sap from *Borassus flabellifer* has pharmacological properties such as anti-inflammatory, and analgesic effects and showed reduced serum glucose levels in rat models [22].

2.2. Sap treatment

Temperature also plays an important factor in the quantity and quality of sap since sap collection is said to be higher on cool nights [33]. The collected sap if left for a minimum of 10 h at a temperature around 30 °C, will get highly contaminated with natural yeasts, bacterial and fungal spores since sap collection is a slow process from palm trees and hence strictly requires intermediate storage before further processing [34,35]. However, the inclusion of an anti-fermenting agent has been traditionally followed with lime being most commonly used [36]. Bark or leaves (rich in tannins) from various tree species are also used as anti-fermenting agents such as *Schleichera oleosa* bark or leaves, *Shorea cochinchinensis* bark in Cambodia, *Shorea obtusa* in Burma, *Shorea talura* and *Shorea roxburghii* in Thailand, *Shorea robusta*, *Votica hermandiana* bark, *Launaea coromandelica* dried bark, *Anacardium occidentale* leaves, *Vateria acuminta* bark or *Cyminosma pedunculata* [26]. Kiam wood (*Cotylelobium lanceolatum*) addition in palm saps, in particular, has been reported to inhibit the growth of bacteria genera such as *Acetobacter, Flavobacterium, Lactobacillus, Leuconostoc, Micrococcus,* pathogenic bacteria genera such as *Listeria monocytogenes,* toxigenic *Staphylococcus aureus,* enterotoxigenic *Bacillus cereus* and yeast genus *Saccharomyces* as well [31]. Moreover, a recent study by Valder & Nooralabettu, pointed out that even mild heating of the sap at 30 °C for a prolonged period will degrade Vitamin C although no such changes were observed for the lipid content [37]. Moreover, thermal treatments of the sap decreased the yeast populations by more than 100 folds and lactic acid bacterial load was also decreased by 20 folds both at 60C for 5 min at pH 7 and complete microbial decontamination was achieved at 25 min (yeast being more susceptible than bacterium here to thermal treatment). Naknean et al. showed that by adding 30 IU/mL of nisin and pasteurizing the palmyra palm sap at 75 °C for 10 min, the sap had a longer shelf life of 10 weeks, minimized loss of sucrose and polyphenol content, reduced polyphenol oxidase activity and low browning intensity as opposed to the conventional storage life of just 2 weeks [38].

The amount of lime to be used for preserving the palmyrah palm sap, the optimal sap heating temperature and its time duration are in general limited to traditional practices of the locally consuming communities. For example, if the pots containing the sap are under-limed, the resultant NCS becomes sticky and stringent by not becoming crystalline. Whereas, if it is over-limed, the resultant NCS becomes soft and inferior leading to the destruction of sugars and the crystallization process becomes extremely slow. This results in varying quality and a bitter taste to the resulting palmyrah palm NCS. Hence, to address this problem, Velauthamurty et al. conducted lab test experiments with lime collected from traditional kilns [39]. They found that lime of 96% purity can be obtained from seashells at a processing temperature of 850 °C for 30 min which was the best consumable method for producing lime with a minimally adequate amount of energy. Provided, an optimal amount of 2.5 ± 0.4 g/L of lime per sweet sap gave superior quality NCS as per consumer panel studies. The heating temperature and time for producing NCS were also standardized by Madhava et al. [40]. The best NCS of good quality was obtained at optimized processing conditions where 2.1% lime was added at a heating temperature and time of 111 °C and 126 min respectively. At these optimized conditions, low moisture content was observed in the final bulk NCS which drastically improved its shelf life and keeping quality. Also, as a result of these optimized processing conditions, the fat and carbohydrate content remained the same while protein and ash content was higher in the final solid NCS (0.17% fat, 0.98% protein, 2.80% ash, 91.00% carbohydrates at 8.50% moisture content) [40].

Once the sap is allowed to rest, the lime keeps the sap under good quality for around 12 to 18 h after which parts of the lime that have not been dissolved begin to sediment while the rest does not get separated during the straining or filtering process. Following the sedimentation, decanting is done to remove the clear liquid while the sedimented lime particles remain at the bottom of the pots. Even after decanting, a few particles will remain within the liquid which is then filtered through a sand filter or muslin cloth. The clearer the filtered liquid, the more lustrous and attractive the colour of the final NCS will be. Palmyrah palm sap contains high-reducing sugar which promotes the Maillard reaction during the heating process and storage [10]. Sometimes an excess of alkalinity is caused by the dissolved lime that cannot be removed either by decanting or straining. For such cases, certain acidic substances that are soluble in the sap are used. Usually, alum and superphosphate are used by mixing with water and added little by little during the boiling of the sap. Also, the quality of the NCS can be improved by precipitating the lime with CO_2 gas or traditionally with citric acid or unripe tamarind fruit before boiling the sap [40]. The sap must remain a bit alkaline which is consistently checked using a simple litmus paper technique. Hence the filtered and the final sap is maintained at an alkaline pH of about 8–9 [37].

The use of E-class food-grade preservatives such as sodium metabisulfite, calcium hydroxide and sodium benzoate has been shown to effectively control fermentation at ambient temperatures. These can also be used minimally along with other preservation techniques such as pasteurization or microwave treatment to limit processing-enabled degradation of physicochemical properties of the sap while also prolonging the shelf-life of the sap (for example, citric acid and potassium metabisulphite were found to extend the shelf-life for up to 6 months or the use of polymeric membrane filtration which cleared the turbidity of the sap with no nutritional loss) for logistically storing, transporting and for subsequent treatment [24].

2.3. Thermal processing of sap to syrup and then to NCS

In the traditional production of palm sugar syrup, a large volume of filtered palm sap is heated on a wood-fired stove above 100 °C until it becomes concentrated [41]. The onset of thermal exposure causes the translucent whitish palm sap to turn into a brownish solution with a change in absorbance from 0.012 to 1.098 nm (respective sap samples measured at 420 nm at lab-scale using a visible spectrophotometer at different time intervals) within 25 min of thermal processing due to an inverse decrease in the pH values from 7.8 to 4.0 (at and above 80 °C) [37]. Once the sap is produced into a palm sugar concentrate, its total soluble solids which are mainly sugar should be at least 65° Brix or above for food safety purposes [42]. Usually, at the initial phase of heating, the juice or sap starts to rise like milk. Hence to subdue such rising of froth, traditionally crushed castor seeds, chips of copra, 0.5% tannic acid or even sweet oil droplets are added to the pan along with a quick stirring. After 15–20 min of boiling, a white, scum-like substance rises to the top of the boiling juice casing haze formation. This haze is greatly formed due to the protein and polyphenol content present in the sap and also from wood chips or barks used to prevent the fermentation of the sap [38,43]. The protein-phenolic hydrophobic interaction is generated via attraction between the aromatic structure of polyphenols and the nonpolar moieties in proteins [44]. The high molecular mobility of these compounds at high temperatures also promotes haze formation. This scum is removed either by straining the boiling sap or it is skimmed off with the help of a ladle. After 5–10 min, when the temperature of the boiling juice is around 40 °C, the boiling is stopped, and the pan is taken away from the furnace to give time for the dissolved lime to settle down. This step of clarifying the boiling palm sap or juice is called deliming. The deliming process is done to reduce the pH to around 7.5 by using chemical bleaching agents such as phosphoric acid, sulfuric acid, polyvinylpolypyrrolidone, hydro's-sodium hydrosulphite or even triple super phosphate solution. Clarified juice gives NCS its good colour, crystalline texture, hardness, less hygroscopicity and hygiene quality. Provided, clarification is needed for a) if sap pH is more, b) for getting higher crystalline NCS, c) to get more clear syrup and d) for easy mouldability [23]. Naknean et al. reported that the pasteurization and use of chitosan (0.50 g/L) as a clarifying agent gave the clearest and high-quality clarified sap [45]. The use of bentonite resulted in the lowest polyphenol oxidase and invertase activities and gelatin also effectively reduced polyphenol content from the sap as well.

After the deliming step, the now clear brown syrup is poured into the boiling pan and heated gradually to a temperature of 110 °C until all the water evaporates resulting in a sugary syrup. Traditional production uses high temperatures (approximately 110–120 °C) for a longer time. It has been reported that palmyrah palm syrup has around 5.61 mg/g of amino acid content and a predicted glycemic index of 70.05 [45]. The thermal deterioration that takes place during the palm sugar syrup or palm sugar concentrate processing is the main reason for the change in colour, flavour and nutritional value in the final NCS. The most common chemical reactions that influence the quality of syrup are inversion reaction, Maillard reaction and caramelization [10]. Browning of the palm sap during thermal treatment is primarily because of the Maillard reaction initiated by the degradation of proteins into amino groups and the reduction of sucrose into degraded sugar products such as melanoidins [37]. Maillard reaction products like 5-hydroxymethylfurfural and 2, 3-dihydro-3,5-dihydroxy6-methyl-4(H)-pyran-4-one (DDMP) are found in the resultant palmyrah palm sugar where the later has been reported to exhibit antioxidant and anti-carcinogenic activity [46]. During the heating process, amino acids catalyze sucrose to its monosaccharides and are also known to produce C2 – C5 dicarbonyl compounds via retro aldol reaction (which further reacts with amino acids to produce aldehydes and α-amino ketones). Also, bioactive phenolic compound such as 2,3,4-trihydroxy-5- methyl acetophenone has been isolated from the palmyrah palm syrup and they exhibited strong DPPH radical scavenging activity and thus showed promising antioxidant activity [47]. Normally, syrup with a concentration of approximately 70°Brix is stable to store under room temperature for one year [48,49].

Advances in palm sugar syrup processing to produce the subsequent palm sugar by using vacuum evaporators have also been reported [50]. The palm sugar syrup produced by the vacuum evaporator at 70 °C contained a higher level of sucrose, reduced non-enzymatic browning, particularly in storage, less burnt colour and retained desired quality attributes in syrup better than palm sugar syrup produced by heating in a conventional open pan. Once the palm sugar syrup is no more syrupier or rather when it is semi-viscous at a temperature of 120 °C, the pan is taken away from the furnace. The stirring must continue until the viscous-like solution begins to crystallize and stiffen. Care is taken to ensure that there is no rapid cooling involved since prolonged cooling induces large crystal formation. The almost crystalline mass (which is still hot and contains very little liquid) is then poured carefully into moulds for solidifying into various compact solid blocks. This method of boiling the sap and pouring it into moulds to get solid blocks/cakes is very common in countries like India, Burma, Thailand, Malaysia and Indonesia.

3. Quality constraints of palmyrah palm NCS produced via conventional method

The difference in the production process (sap collection, clarification, heat treatment, drying-solidification, crystallization, and addition of additives) and raw materials (agronomic conditions and cultivars) used for NCS production will dictate the quality and the sensory attributes of the final NCS produced [51]. The intensity of heat treatment, the resulting caramelization, molasses and Maillard reaction products add flavour and colour to the NCS by generating melanoidins, caramels, and various small molecular weight organic acids, such as aldehydes, acetal, diacetyl compounds [51]. While the conventional open-pan drying method of producing palmyrah palm NCS is still in practice, it does hold various setbacks. First, this entire method of producing palm sugar via an open pan drying-solidification process is an unorganized practice lacking mechanization and producing a product of unstable quality with low dry matter content (under 80%), often dark, burnt and easily spoiled by microbes mainly due to high hygroscopicity of the NCS [22].

NCS production is similar to other sugar confectionaries with the exception that there must be 5–10% evaporation of moisture during its crystallization and it is essential to control the crystallization process for optimum NCS product quality [52]. Crystallization is heavily influenced by the amount of stirring time and the temperature (it is reported to be around 6 min at 85 °C for cane NCS), the reducing sugar content (the higher the reducing sugar, the smaller the crystal size) and the moisture removal at higher temperature and the subsequent cooling period as well [52]. A sugar-rich complex mixture like NCS containing various sugar fractions (crystalline and amorphous) and sugar compounds is often thermodynamically unstable and requires quality control, especially due to its hygroscopic nature. This is caused when there is incomplete sucrose crystallization during sap evaporation which is encountered predominantly in conventional NCS manufacturing techniques. Respectively, more will be the amorphous phase of glucose and fructose (reducing sugars) resulting in larger associated hygroscopicity and hence higher chances of product deterioration. Therefore, qualitatively studying and optimizing these sugar phase transitions during NCS production will allow for optimal NCS quality maintenance. Verma et al. developed a technique of solvent-assisted separation of individual crystalline and amorphous phase regions of NCS which could be industrially used for monitoring final NCS quality and customization when used as an ingredient for various other food product development such as chocolates and deserts [53].

Second, while NCS is rich in minerals, vitamins, amino acids, organic acids, phenolic compounds and antioxidants, the thermal process of producing it also induces the formation of harmful compounds such as acrylamide, 5-hydroxymethyl- -furfural, methylglyoxal, and advanced glycation end products. These compounds are dependent on the composition of the sap, the resulting molasses and the thermal temperature and time it is treated which is a quality concern [51]. Optimized use of acid such as phosphoric acid during the clarification process of the sap can render the resulting NCS with desirable colour by bleaching the dark pigments [54]. While the concentration of lime used in the clarification step did not affect the mineral and phenolic content, an increase in heating temperature and time reduced its content in the resulting palmyrah palm NCS (for every 10 °C rise in temperature and/or for every 10-min increase in the heating time) which often is a problem with the unstandardized pan-drying method [55]. Third, unlike cane sugar where there are mass agricultural interventions to produce sugarcanes, very few such activities are directed towards growing and sourcing palm sap for palm sugar production. Fourth, most of the palm sugar production activities are taken over by rural communities in selective geographical locations thereby facing supply chain and logistical discrepancies to make palm NCS a standard product for the worldwide market.

4. Recent processing methods and their resulting palmyrah palm NCS characteristics

While the conventional method uses pan/wok-drying to solidify/crystallize the palm sap syrup to palm sugar, modern drying practices such as vacuum drying, spray drying, ultrafiltration and membrane drying have also been explored to convert the palm sap/syrup into granulated sugar. Sarkar et al. have schematically illustrated the process for spray drying and membrane filtration processing methods for palm sap to sugar conversion [56]. Moreover, these processing technologies can offer standardization of production procedure and can also aid in understanding the origin of various bioactive compounds and chemical changes occurring during the manufacturing and storage period as opposed to the conventional method which has rather a high variability in its production process [57]. In a study published by Thi Lee et al. both conventional thermal processing and ultrafiltration processing of palmyrah palm syrup (although the former yielded higher content of aroma profile possible due to higher temperature-time operation, heavy Maillard reaction and caramelization) yielded a variety of 38 volatile molecules which were identified and classified into six groups in the order of alcohols > acids > ketones > sulfurs > pyrazines > phenols and aldehyde (Table 1) [58]. These volatile profiles could be more or less hypothesized to be identified even in the resulting NCS from the corresponding syrup as well. For example, sulfur compounds like dimethyl sulfoxide and dimethyl sulfone found in the palmyrah palm syrup have been identified even in the resulting sugar granules produced via the vacuum drying method (next section).

Table 1
Presence of dynamic volatile molecular profile in palmyrah palm syrup produced via both conventional thermal processing as well as ultrafiltration methods (although the former yielded higher content of aroma profile possible due to higher temperature-time operation, heavy Maillard reaction, caramelization etc.). Adapted from [58].

Volatile Compound Groups	Identified Volatile Compounds	Odour Description
Total alcohols	R-(R′,R')-2,3-butanediol	Sweet, grassy, fruity
	S-(R′,R')-2,3-butanediol	Sweet, flowery, rancid
	2-Furanmethanol	Roasted, nutty, fruity
	5-Methyl-2-furanmethanol	Sweet, fruity, minty
	5-Methyl-2-pyrazinylmethanol	Acidic, sweat-like, sweet
Total ketones	4,5-Dihydro-2-methyl-3 (2H)-furanone	Toasted, buttery
	3-Hydroxy-2-butanone	Sweet, nutty, dairy-like
	1-Hydroxy-2-propanone	Sweet, grassy, coffee-like
	Butyrolactone	Cooked, sweet
	2 (5H)-Furanone	Pungent, cheesy
	3-Methyl-1,2-cyclopentanedione	Sweet, maple-like
	2-Acetyl pyrrole	Herbaceous, metallic
	Pantolactone	Sweet, caramel
	2,5-Dimethyl-4-hydroxy-3 (2H)-furanone	Sweet, cotton candy-like
	2-Pyrrolidinone	Sweet, cotton candy-like
	2,3-Dihydro-3,5-dihydroxy-6-methyl-4 H-pyran-4-one	Sweet, maple-like
	2,5-Pyrrolidinedione	Sweet, cotton candy-like
Total pyrazines	2-Methyl-pyrazine	Sweet, grassy, acidic
	2,5-Dimethyl-pyrazine	Nutty, earthy, roasted
	2,6-Dimethyl-pyrazine	Nutty, sweet
	2,3-Dimethyl-pyrazine	Nutty, roasted coffee-like
	2,3,5-Trimethyl-pyrazine	Nutty, earthy, roasted
	2-Ethyl-3,6-dimethyl-pyrazine	Nutty, earthy, coffee-like
Total acids	Propanoic acid	Rancid, acidic
	2-Methyl-propanoic acid	–
	Butanoic acid	Cheesy, yogurt-like
	2-Propenoic acid	Baked, vinegar-like
	3-Methyl-butanoic acid	Cheesy, foul smell
	Pentanoic acid	Rancid, buttery
	2-Hydroxy-propanoic acid	Grassy, sweet-like
	Benzoic acid	Sweet, caramel
	Dodecanoic acid	Dairy-like, caramel
Total sulfurs	Dimethyl sulfoxide	Rancid, pungent, metallic
	Dimethyl sulfone	Sweet, waxy, sulfuric
Total phenols and aldehyde	2-Methoxy-phenol	Sweet, medicinal
	2,6-Dimethoxy-phenol	Sweet, maple-like
	Vanillin	Sweet, cotton candy-like

Recently, a detailed study of vacuum drying of palmyrah palm sugar at various high temperature-time combinations and its associated physicochemical and nutritional changes was analysed [22]. Since the caramelization reaction, which occurs above 120 °C is absent in this processing method, browning is primarily caused due to the Maillard reaction and the produced sugar was light brown when compared to traditionally produced dark brown sugar blocks. As expected, the mineral and vitamin load of the palmyrah palm sugar in this processing method had a very good composition since all the components as seen in the initial inflorescence sap were detected in the resulting NCS [22]. Potassium was the highest (688.45–705.27 mg/100 g), followed by sodium (23.10–24.50 mg/100 g) and iron (1.88–2.05 mg/kg vs. 2.3 mg/kg) all of which were higher than brown sugar from sugarcane. Moreover, the palmyrah palm sugar produced in this method contained 10 vitamins namely vitamins A, B_1, B_2, B_3, B_5, B_6, C, D_2, E, and folic acid with vitamin E content being the highest, with 52.15–55.12 mg/100 g and vitamin B complexes collectively ranging from 0.04 to 2.15 mg/100 g. The presence of 5-hydroxymethylfurfural, an almost ubiquitous cyclic aldehyde known to be produced in thermally processed foods due to sugar degradation via Maillard reaction, was significantly higher at 100 °C (more than the levels mentioned by Codex standards) than at respective lower temperatures since the rate of Maillard reaction is fastened exponentially at higher temperatures [59]. Sulfur-containing Maillard odorants such as dimethyl sulfoxide (0.10–0.15 mg/100 g) and dimethyl sulfone (0.01–0.02 mg/100 g) were the most dominant aroma compounds and provided a cooked meat-like flavour. The total phenolic content of the granulated sugar was highest at 80 °C (7.55–8.94 mg/100 g) and decreased subsequently as temperature increased since phenols were destroyed during the heating process. Overall, weighing out the pros and cons, vacuum drying processing at 90 °C for 75 min had viable industrial production prospects for palmyrah palm sugar with good bioactive phytochemical content and a shortened production time as opposed to the conventional method.

5. Physico-chemical and quality parameters of palmyrah palm sugar

Palmyrah palm sugar is widely available in solid blocks, liquid syrup and commercially even in granular forms. The demand for palmyrah palm sugar granules is growing rapidly due to ease of use, handling, packaging and storage [60]. Also, unlike solid sugar blocks which are hygroscopic and deteriorate easily with reduced shelf life, sugar granules or powder particles (Table 2) are compact and retain all the characteristics of raw jaggery in terms of taste, aroma profile, and sweetness. Thermal properties of foods or food products, such as specific heat, thermal conductivity, and thermal diffusivity are essential to understanding their thermal behaviour and controlling heat transfer processes during their production, processing and handling [61–63]. Rao et al. studied the effect of moisture content on bulk density, thermal conductivity, thermal diffusivity and specific heat of granular sugar samples prepared from palmyrah palm juice to establish a correlation between relative moisture content with the above-mentioned properties [64]. The bulk density of palmyrah palm sugar granules showed a linear correlation with their corresponding moisture content. Thermal conductivity increased with an increase in both moisture content as well as bulk density. As reported, the thermal conductivity of palmyrah palm sugar granules was in the range of 0.36–0.39 W m^{-1} K^{-1} when the moisture content was ≥10% DB. This range of thermal conductivity is very close to the reported values of sugar solutions, syrups, honey, molasses and caramel syrup [65]. Thermal diffusivity at 30 °C showed a non-significant decrease in its value as moisture content increased for the sugar granules. This might be attributed to the fact that these granules have increasingly higher bulk density with an increase in moisture content. Specific heat at 30 °C for the sugar granules showed a drastic increase in moisture content between 5.8 and 6.2 % DB. Further increase in moisture content resulted in the specific heat approaching near saturation around 10–13% DB. An increase in specific heat might be attributed to increasing water levels as moisture content increases [65].

The hygroscopic nature of the palmyrah palm jaggery will essentially cause it to undergo caking and sticky issues over time which will eventually alter its physicochemical, organoleptic and functional properties. Any free-flowing powder material having low molecular weight sugars will transform first into lumps, followed by an agglomerated solid state, and finally into a sticky material (stickiness occurs usually 10–20 °C above glass transition temperature) due to poor stability above its glass transition temperature (Tg) as a result of plasticization by water (because if water activity or humidity) or temperature changes [66,67]. Rao et al. determined the detailed relationship between moisture content, Tg and sticky point temperature of amorphous natured (since this jaggery is concentrated by removing water to form an agglomerated solid mass) palmyrah palm jaggery granules through modelling of its sorption isotherms [68]. The critical moisture content of palmyrah palm jaggery varied typically over a range of 10–30 g/kg and beyond these values, the jaggery is likely to deteriorate faster. It was found that beyond water activity (a) of $a \leq 0.5$, the equilibrium moisture content of the jaggery increased as temperature increased due to a particular 'cross-over behaviour' often noted in high sugar-containing food materials. This is because sugars start to undergo dissolution at high temperatures and high humidity environments thereby causing the opening up of sorption sites within the sugar molecules thus allowing it to hold more water [69]. When compared to sugarcane and date palm jaggery, palmyrah palm jaggery had the highest Tg of around 347.3 K (74.5 °C). The Tg decreased with an increase in moisture content mainly due to water plasticization of low molecular weight compounds in a sugar-rich carbohydrate mixture like palmyrah palm jaggery itself. However, this effect reaches a saturation-like limit with one of the reasons being counteraction against the lowering of Tg by high molecular weight compounds like proteins against low molecular weight sugars. When Tg goes below the ambient temperature, the stability and quality characteristics will become an issue and critical values of moisture and water activity play a huge role since these two factors mainly depress the Tg to ambient temperature [67]. The critical moisture content for palmyrah palm jaggery granules at 25 °C and 35 °C (these temperature values were taken considering sugar usage in tropical and sub-tropical regions) was 3.1 and 4.3% respectively in a corresponding Tg versus a_w plot. The sticky point temperature (Tsc) of the jaggery granules decreased with an

Table 2
Palmyrah palm sugar granules properties.

Properties of palmyrah palm sugar powder during disintegration processing from NCS solid blocks	Range/Values	Reference
Height	31.2–44.2 mm	63
Diameter	83.6–101.3 mm	
True volume	0.00012–0.00019 m^3	
True density	1021.89–2242.021 kgm^{-3}	
Bulk density	657.25–720.08 kgm^{-3}	
Before disintegration	628.93–882.82 kgm^{-3}	
After disintegration		
Porosity	46.44–51.12 %	
Before disintegration	34.35–52.87 %	
After disintegration		
Moisture Content	3.42 ± 0.66% w.b.	
Coefficient of friction	0.476	
On stainless steel surface	0.773	
On mild steel surface	0.424	
On galvanized steel surface		
Colour (CIE lab system)	1.78–53.93	43
L* (lightness) a* (redness)	9.87–34.75	
b* (yellowness)	3.09–78.94	
Transmittance (at 650 nm)	1.34–50.45 %	
pH	4.50–5.37	
Total acidity	0.24–0.86 %w/v as lactic acid	
Total soluble solids	59.01–73.05 °Brix	
Total sugars	23.77–71.89 %w/w	
Reducing sugars	3.54–23.94 %w/w	
Total microbial count	1.20×10^3– 4.80×10^6	
Yeast and mold count	CFU/ml	
Osmophillic yeast	1.30×10^2– 5.30×10^4	
	CFU/ml	
	2.00×10^2–1.46×10^5 CFU/ml	

increase in moisture content and when the moisture content was around 4.0%, the difference between Tsc and Tg reduced significantly. The Tsc followed a linear pattern as Equation (1) for palmyrah palm jaggery specifically and a generalized correlation between Tsc and Tg can be made as per Equation (2) with both the equations being within the moisture (M) range of $0 \leq M \leq 4.3$ % DB.

$$Tsc = 341.7\ K - 10.9 * M \tag{1}$$

$$Tsc = 1.077 * Tg - 13.263 \tag{2}$$

Hence moisture level affects the above-mentioned factors where all of these will prove essential during the quality analysis, storage and shelf-life characteristics of the palmyrah palm NCS. From a stable shelf life point of few, powdered sugar granules have increased shelf life even at higher temperatures and humidity as compared to solid bulk sugar since they have increased crystalline phase resulting in higher moisture loss and hence less water activity for microbial contamination (SEM images of the crystalline and amorphous phase of the NCS can be found in the author's work) [70].

6. Nutritional composition and functional properties of palmyrah palm NCS

Back in 1970, Rao et al. had published one of the earliest works where they examined the nutritional value of palmyrah palm sugar (produced via conventional open-pan drying method) [71]. While the exact nutritional content will vary because of varying agronomic and processing conditions, their typical values were evaluated for their proximate, mineral, vitamins and amino acids compositions as depicted in Table 3. As noted from the table, carbohydrates constitute the major portion of palmyrah palm sugar and hold the promise to be an alternative to cane sugar. Joshi & Sohonie, in their study, indicated that non-reducing sugars comprised the major portion of the total carbohydrate in all the varieties of jaggery [72]. They also reported that the non-reducing sugar in palmyrah palm jaggery is higher than sugarcane jaggery refined cane sugar. The major sugar component of palmyrah palm sugar is sucrose, similar to cane sugar, and also has a significantly higher amount of glucose and fructose [18]. The higher amount of sucrose and glucose in palmyrah palm jaggery also makes it a good energy source for convalescents [73]. Palmyrah palm sugar contains very low amounts of protein since most of it is degraded during the Maillard reaction occurring during the thermal treatment of the sap. Yet, it was comparatively higher than sugarcane jaggery and refined cane sugar [74]. The number of amino acids mentioned in the table is attributed to both the protein and non-protein fractions in the palm sugar. The table manifests that palmyrah palm sugar has six out of nine essential amino acids. A study of amino acid patterns in different jaggery shows that the amino acid profile of palmyrah palm jaggery is better than cane jaggery. A study by Ho et al. reported that 15 amino acids were present in palmyrah palm sugar with asparagine, glutamine, and arginine as the major amino acids [75]. Various authors have reported the presence of vitamins B_1, B_2, B_3, B_6, B_{12} and C in palmyrah palm sugar [76–78]. The fresh sap of palmyrah palm is a good source of vitamin B complex [78] and hence the vitamin content in the subsequent NCS. Palm jaggery promises to be an excellent source of minerals as can be seen from the table. The high levels of potassium and low levels of sodium in palmyrah palm jaggery indicates the possibility of using palm jaggery for hypertension and oedema due to heart and liver disease. Joshi & Sohonie suggested that it could be used for treating diseases characterized by marked loss of potassium and as a diuretic [72]. Palmyrah palm sugar is a good source of iron, and it seems to be bioavailable and is absorbed quickly into the small intestine [79] but as such no conclusive *in-vitro* studies have proven the iron bioavailability exclusively.

Table 3
Nutrition profile of palmyrah palm NCS (produced using conventional open pan drying method). Adapted from [71].

Proximate, crude mineral, vitamin and amino acid composition of palmyrah palm sugar	
Moisture	8.3 g/100 g
Protein	1.04 g/100 g
Fat	0.19 g/100 g
Minerals	3.15 g/100 g
Carbohydrates	87.32 g/100 g
Total Sugar	82.6 g/100 g
Reducing Sugar	1.7 g/100 g
Calories	364.4 g/100 g
Vitamin composition of palmyrah palm sugar	
Thiamine	10.7–29.9 μg/100 g
Riboflavin	353–494 μg/100 g
Nicotinic acid	3.30–5.12 mg/100 g
Vitamin C	7.3–33.0 mg/100 g
Mineral composition of palmyrah palm sugar	
Calcium	140–233 mg/100 g
Phosphorus	16–27 mg/100 g
Iron	6–10 mg/100 g
Sodium	8–20 mg/100 g
Potassium	102–140 mg/100 g
Copper	50–120 mg/100 g
Cobalt	2–20 mg/100 g
Nickel	4–24 mg/100 g
Magnesium	5–42 mg/100 g
Amino acid composition of palmyrah palm sugar	
Lysine	1.45 mg/100 g
Phenylalanine	1.7 mg/100 g
Leucine	8.7 mg/100 g
Threonine	11.2 mg/100 g
Isoleucine	7.2 mg/100 g
Tyrosine	28.7 mg/100 g
Tryptophan	1.7 mg/100 g
Cystine	23.2 mg/100 g

The glycemic index (GI) is a measurement that is associated with carbohydrates in food and how they affect blood glucose levels. Based on the GI values, foods are classified into three categories namely low GI value (55 and less), moderate GI value (56–69) and high GI value (70 and more). Low GI foods are slowly digested, absorbed, and metabolized and hence cause a slower and lower rise of glucose and insulin levels in the blood. Generally, palm sugar has a low GI value of 35–42 compared to refined cane white sugar which has a GI value of 58 [1][80]. Despite having sucrose as a major component, like cane sugar, palmyrah palm sugar has a lower starch digestion rate and GI values as reported [17]. In addition, they also showed that palm sugar-sweetened bread exhibited a lower glycemic index value than cane sugar-sweetened bread. A mixture of palm sugars and cornstarch resulted in a slow digestion rate and consequently, lower glycemic index values than those of refined cane sugars [18]. Trinidad et al. and Vayalil, reported that palm sugars contain a significant amount of dietary fibre, especially inulin and it could play an important role in lowering the GI values of sugars compared to refined sugarcane which contains almost 100% of sucrose [81–83]. Research by Mahilrajan et al. also shows that palmyrah-based edible products have low GI [84][85,86]. All these studies provide us with evidence that this palm sugar can be a healthy alternative sweetener in the context of GI values. The presence of phytochemicals along with reducing sugar (because of their noted lower glycaemic potency than pure sucrose) might be the reason for the low GI of palmyrah palm NCS [87].

7. Palmyrah palm sugar as a functional additive

In this section, the functionality of added palmyrah palm sugar in different food products and in the fermentation process is reported such as organic matter enhancement, low-cost fermentative sugar substrate, physicochemical property improvement, presence of polyphenol and dietary fibres and lowering of glycemic index etc. Whilst those studies that mention the use of *Borassus flabellifer* derived sugar exclusively has been selectively reported here, other palm sugar studies are also reported here since they would regardless present the same outcomes due to jaggery's hygroscopic nature, Maillard reaction features and sugar content. The following studies are examples of various functionality that palmyrah palm NCS offers as a sweetener/additive in food formulations (Table 4 and Fig. 3).

7.1. Improvement in the functionality of food

While the mention of just palm sugar has been used by the authors from literature in this section, these other developments are still included in this paper since the physicochemical characteristics (especially moisture) of various palm sugar including palmyrah palm NCS are mostly the same and will eventually yield same results in food formulation.

Recent interest in substituting pure sucrose with palm sugar has been on the rise in developed countries though such products are already available in South–Asian markets. Nevertheless, the utilization of sucrose which can be up to 50% of the chocolate ingredients evokes health concerns related to high sugar levels and calories [88]. The utilization of palm sugar will not only provide a new choice of alternative chocolate sweetener but will also create distinct chocolate characteristics [88]. Saputro et al. have worked extensively with chocolate manufacturing by using palmyrah sugar as a sugar substitute and studying the resulting properties of such chocolates manufactured on a small scale using Stephan universal machine UMC 5 in two distinct stages [46,82,88,89]. The moisture content of palm NCS (and the resulting hygroscopic nature of the chocolate) caused sticky patches on the chocolate surface, a higher degree of particle agglomeration, less flow behaviour, an increase in hardness [80,89], lowering of the melting temperature and the enthalpy of the sugar phase in the chocolate [89,91], denser chocolate (due to lower palm sugar particle density which is very fine (18–25 μm)) and a lighter colour (higher L^* value reading in a colourimeter, indicating a lighter colour) [80].

The utilization of palm sugar as a sweetener in chocolate had a huge impact not only on the sweetness but also on the aroma profile as they were noted to contain aldehydes, furans, terpenes, ketones, pyrazines, alcohols, acids, and pyrrole-based compounds (Table 4) [46,103]. Some volatiles such as 2-furoic acid, 1-hydroxy-2-propanone, 3-hydroxy-2-butanone [90], 2,3-dihydro-5-dihydroxy-6-methyl-4H-pyran-4-one (DHM), 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one (DDMP) [41] were only present in chocolate containing palm sugar. Most of these aroma-contributing volatiles are a result of the Maillard reaction taking place both during the processing of palm sugar and during chocolate manufacturing. Chitram's Bean to Bar chocolates, an artisanal chocolate manufacturer in India, has successfully commercialized award-winning 70% dark chocolates made with locally sourced palmyrah palm sugar that is noted for its distinct earthy aroma and flavour [104].

The agar-agar pudding developed with palm sugar was highly preferred by the consumers as well as the panellists due to its rich aroma and light colour [9]. An important observation was that the iron present in the pudding because of the addition of palm sugar was expected to be easily bioavailable. This is one critical example bringing to light that palm sugar can be used as a fortification agent in iron-deficient foods. In another study, yoghurt, a source of probiotic bacteria containing was substituted with palmyrah palm sugar and found that the physicochemical properties were very much similar to that of cane sugar-substituted yoghurt [93]. Additionally, the palmyrah palm substituted yoghurt had an overall acceptance in consumer acceptance studies than cane sugar.

Phenolics are one of the main groups of bioactive phytochemicals present in sour cherry fruit that display a broad spectrum of health-promoting benefits. Sour cherry puree prepared using palm sugar showed the preservation of a wide group of phenolics such as anthocyanins, flavan-3-ols, flavonols and hydroxycinnamic acids (Table 4) even after storing them for 6 months at 4 °C and 30 °C [105,94]. Though products processed with sugar showed lower concentrations of

Table 4
Functionality of added palmyrah palm NCS to various categories of food products.

Food	Added Functionality by Palmyrah palm NCS	Reference
Chocolate	• High moisture content and particle agglomeration due to hygroscopic nature and the rich glucose and fructose content of palmyrah palm sugar • Less flow behaviour and an increase in hardness which affects chocolate snapping quality • Reducing sugars and minerals contributed to lowering the melting temperature and the enthalpy of the sugar phase in the chocolate • Chocolates were highly dense and smooth surfaced resulting in lighter colour (higher L* value) due to higher scattering of light. • Heat-resistant chocolates can be developed through partial replacement of fat with palm sugar • High concentrations of aroma compounds such as pentanal, hexanal, octanal, 2-pyrrolidinone, 2,3-dimethylpirazine, 2,3,5-trimetylpirazine, and 2,3,5,6-tetramethylpyrazine, and phenyl ethyl acetate (honey and floral notes), 2-furoic acid, 1-hydroxy-2-propanone, 3-hydroxy-2-butanone, 2,3-dihydro-5-dihydroxy-6-methyl-4H-pyran-4-one (DHM), 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one (DDMP) (caramel and roasted notes)	[41,46,51,80,88–91]
Kombucha	• Decrease in pH due to the formation of useful organic compounds. • Successful culture and yield of SCOBY due to good presence of sucrose and other reducing sugar • Slight increase in the alpha-glucosidase inhibitory activity	[92]
Deserts	• Fortification of deserts with palmyrah NCS showed increase iron bioavailability. • Good sensory quality and consumer acceptance	[9,93]
Wheat-products	• Lower starch digestion rate and glycemic index as compared to sugarcane sugar. • Increased gelatinization temperature of the starch granules since sugar competes with starch for water resulting in reduced water activity. • Presence of dietary fiber inulin.	[17,81,82]
Sour cherry puree	• Darker colour, enriched aroma and higher antioxidant activity. • Polyphenol content in palm sugar-added products was significantly higher than the pure sucrose-added as they preserve these compounds at different storing conditions. These compounds include anthocyanins such as cyanidin-3-O-sophoroside, cyanidin-3-O-glucosylo-rutinoside, cyanidin-3-O-glucoside, cyanidin-3-O-rutinoside, peonidin-3-O-rutinoside; flavan-3-ols such as (+)-catechin and (−) –epicatechin; hydroxycinnamic acids such as neochlorogenic acid, 3-p-coumarylquinc acid, chlorogenic acid, 3,5-dicaffeoylquinic acid; flavonols such as quercetin-3-glucoside-di-rhamnoside, quercetin-3-O-rutinoside, quercetin-3-O-galactoside, isorhamnetin-3-rutinoside-7-rhamnoside, kaempferol-3-O-rutinoside, isorhamnetin-3-O-rutinoside • Lower degree of polymerization of flavan-3-ols resulting in less astringency.	[94,95]
Candy crystals	• Temperature dependent proportional change in viscosity and density of crystals due to increase in total soluble solids of sugar	[96]
Breakfast Dumpling	• Traditional dumpling consumed in South India made using Palmyrah palm jaggery. • Proximate analysis revealed biofortified product rich in potassium (1373 mg/kg) is	[97]

(continued on next page)

Table 4 (*continued*)

Food	Added Functionality by Palmyrah palm NCS	Reference
	present in higher concentration followed by magnesium (237.8 mg/kg), phosphorous (29.34 mg/kg), manganese (4.079 mg/kg), zinc (3.909 mg/kg), iron (2.386 mg/kg) which was comparatively higher than other breakfast • Presence of rich flavonoids (148.25 mg/100 g) and fat-soluble vitamins such as vitamin A (retinol acetate), vitamin D3 (cholecalciferol), vitamin E (α- tocopherol), and vitamin K (phytonadione)	

polyphenolic compounds than the products processed without sugar, the polyphenol content in palm sugar-added products was significantly higher than the pure sucrose-added [95]. It may be a result of inter-molecular interactions, such as the preferential binding of larger oligomers to cell wall polysaccharides [95]. Provided, anthocyanins were noted to be more stable in those SCP that contained natural sweeteners than without sweeteners or additives during storage at 4 °C.

7.2. Understanding the glycemic effect of palm sugar in food products

One of the major aspects of using palm sugar as a sweetener has been positively linked to its low glycemic index (GI) [17]. Hence, to understand the glycemic effects of palm sugar, Srikaeo & Thongta studied the effects of palm sugar on the *in-vitro* digestibility of starch-containing wheat flour in comparison with other common sweeteners such as sorbitol and sugarcane sugar [17]. The calorie of palmyrah palm sugar was approximately 4.0 kcal/g. From the study, it was seen that sorbitol, though completely expected, gave the lowest GI value of around 45 kcal/g, while sugarcane sugar gave the highest GI value which was about 75 kcal/g. Palmyrah palm sugar on the other hand gave a GI value of about 61 kcal/g. Although, the major sugar component in palm sugars is still sucrose, the starch digestion rate and GI values were found to be lower than those of sugarcane [17]. Palm sugars were reported to contain a significant amount of dietary fibre, especially inulin [81,82]. These fibres can essentially be broken down into useful short-chain fatty acids in the gut by the gut microbiota through fermentation. Palm sugar also has glucose and fructose fractions constituting approximately 3–9 % each respectively apart from sucrose (which makes up nearly 70–80%).

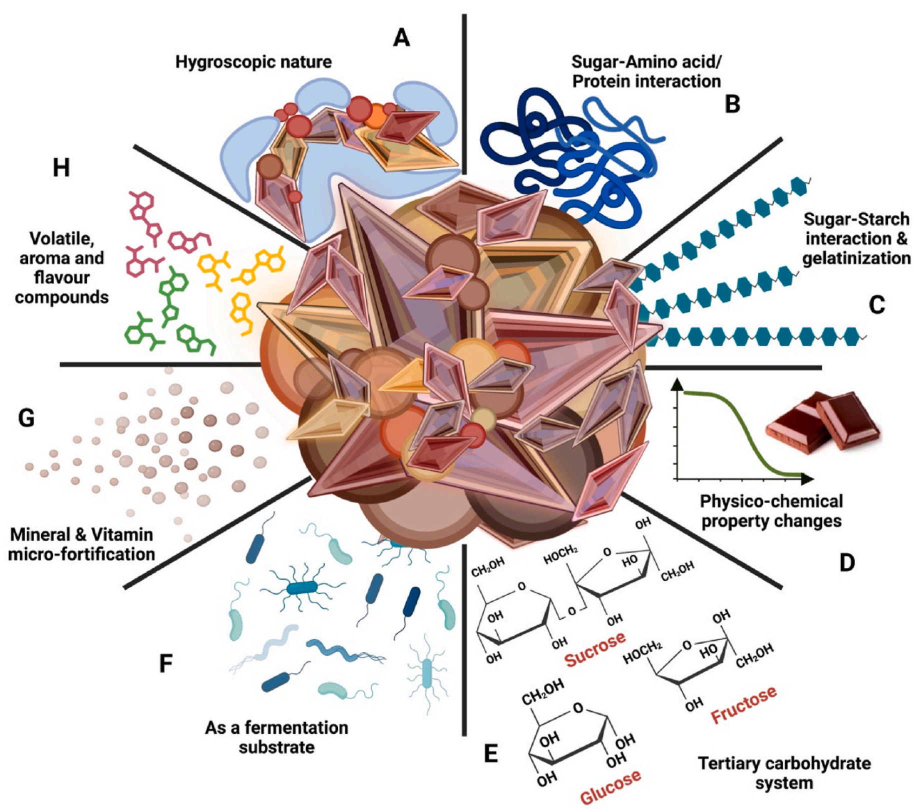

Fig. 3. Illustration showing the complex bulk nature of palmyrah palm NCS (irregular crystalline and amorphous region with residual molasses) and the various functionalities of the NCS as an added sugar. A) The hygroscopic nature of NCS due to the presence of reducing sugars results in the formation of sugar networks through bound-water molecules. The hygroscopic nature of NCS is dependent on the crystal size, water activity and is a function of temperature. By increasing the nucleation rate during NCS production, more crystalline particles will be formed (powdered NCS) resulting in less water activity (release of bound water from the crystalline surface) and hence more product stability [98]. B) Sugar molecules are known to protect the native structure of proteins, increase their denaturation temperature and pH-dependant changes in their properties like viscoelasticity, foaming capacity, solubility, gelation etc. which adds functionality to the food formula as well [99–101]. Likewise, sugar and amino acids participate in chemical pathways in the Maillard reaction producing numerous other compounds. C) In an NCS-starch water system, the sugar molecule competes with starch for water by lowering the water activity which subsequently decreases the chemical potential of water and raises the energy expenditure of other reactions requiring water. Moreover, sugar binds to the amorphous region of the starch molecule. Thus, collectively both these scenarios increases the gelatinization temperature for starch [102]. D) Physico-chemical properties of food formula added with NCS are altered such as surface colour, density, microstructure, sorption isotherms, total soluble solids, melting temperature, rheology, texture and glass/phase transition temperature. E) NCS is a thermodynamically complex tertiary carbohydrate system with co-melting behaviour of these sugars which might affect the physical property of the food product. F) NCS is a fermentable substrate due to sugar and organic molecule-rich presence (carbon source) and can have potential therapeutic value. G) Palmyrah palm NCS is a rich source of minerals, vitamins and antioxidants which can be used as a potential micronutrient fortification ingredient in food formulations. H) Palmyrah palm NCS has a dynamic volatile and aroma compounds profile (produced predominantly due to Maillard reaction and caramelization) thus imparting sensory characteristics to food products.

These may vary depending on the botanical sources and environmental conditions [106]. All these factors are estimated to play an important role in lowering the glycemic index when compared to refined sugarcane sugar which is made up of purely 100% sucrose.

Further, in the above study by Srikaeo & Thongta, differential scanning calorimetry results showed that the addition of palmyrah sugar, in general, increased the gelatinization temperature of the starch granules [18]. This is because sugar competes with starch for water and by doing so, it reduces the water activity and the interaction with starch respectively. Therefore, flour mixed with palm sugar has a high cooking time because starch granules gelatinize at high temperatures. Bread made from palm sugar had relatively lower water activity ($a_w = 0.89$), more firmness and a relatively lower GI value of 63.92 kcal/g when compared to cane sugar-based bread which had higher water activity ($a_w = 0.94$), less firmness and a significantly higher GI value of 81.34 kcal/g.

7.3. As a fermentation substrate

Palmyrah palm is a good fermentation substrate and is used as a sugar source for fermented beverages as well as for industrially useful metabolite production. Watawana et al. observed that kombucha (fermented tea obtained from infusing tea leaves with various strains of the symbiotic combination of bacteria and yeast (SCOBY)) prepared with palmyrah jaggery showed a significant decrease in pH due to the formation of various useful organic acids during fermentation indicating the presence of a good amount of sucrose and glucose and the culture used, grew at an ample amount of nearly 77.34% indicating successful livelihood within the tea made from palmyrah palm jaggery [92]. Also, it was noted that there was a slight increase in the alpha-glucosidase inhibitory activity of the kombucha tea prepared from palmyrah palm jaggery.

Industrially relevant biopolymers can be produced using palmyrah NCS as a sugar source for host microbes. For example, bacterial cellulose was produced using palmyrah NCS via fermentation using *Gluconacetobacter liquefaciens* MTCC 3135 [107]. The resulting study showed a maximum bacterial cellulose production of 17.79 ± 2.4 g/L under optimized conditions and the purity of the cellulose was similar to a commonly used high-sugar substrate thus making palmyrah palm NCS a potential low-cost feedstock. Likewise, optically pure D (−)lactic acid (an important monomer for producing poly lactic acid biopolymer which is now a widely used synthetic plastic material) was produced under optimized conditions using palmyrah palm jaggery as a carbon source and it was reported that the process had a yield of 189.0 ± 8.53 g/L optically pure D (−)lactic acid as fermented by *Sporolactobacillus inulinus* NBRC 13595 [108]. The reported process had one of the highest yields for pure D (−)lactic acid upon using palmyrah palm jaggery as a sugar substrate with a 2.5-fold reduction in production cost as compared with the conventional medium.

8. Prospects and discussion

To achieve food security for a zero-hunger initiative shortly, it is important to have scientific inclusion and technological intervention towards traditionally consumed dietary food. While such food products have been presumably consumed for ages, providing scientific evidence to support the health benefits and claims is the need of the hour to create and promote such food for a wider consumer market in a standardized manner. Moreover, with many organizations recommending limited intake of food products with added sugar for healthy well-being, the demand for alternative sweeteners that are comparatively a more nutritious option than table sugar (refined white sugar) has been on the rise. Palmyrah palm NCS is one such dietary food whose production, and consumption have been geographically confined with very few detailed studies being undertaken to investigate its underlying chemistry regarding its optimized processing, quality characteristics, bioactive molecular presence, and its post-consumption benefits. While there are good aspects to the traditional production method such as the use of naturally derived clarifying agents, the use of other chemicals would still require monitoring to keep them below the allowed regulatory limits. Therefore, this section discusses various aspects for further investigation which will in the future aid in highlighting the beneficial potentials of Palmyrah palm NCS as an added sweetener.

While palmyrah palm NCS is traditionally produced via an energy-intensive open-pan drying method (which is still the current production practice), various other modern drying methods could be studied to develop quality standardized and nutrition retention ways for NCS production. Although the vacuum drying method has been extensively studied by Huynh Thi Le et al. for palmyrah palm NCS production, NCS production in general, is still undertaken by cottage industries which could benefit from scaleup improvements within the current production method itself. Recently, Thulsasiraman et al. had published a detailed review of a strategic outlook for sugarcane NCS production, processing, quality enhancement and policies for the modernization of the NCS industry [109]. The authors stress the fact that, despite rapid infrastructure progress of developing countries, the NCS industry has been facing very slow technological interventions and the continuation of age-old practices that hinder the transition of these small-scale industries towards large-scale, automated, manufacturing feasibility. The report notes that the existence of '*imprudent clarification methods, unscientific and unhygienic operational methods, improper storage and packing methods*' are the major constraints associated with NCS production which is certainly the case with any palm NCS production as well. Starting from clarification of palmyrah palm sap, processing interventions such as the use of activated carbon along with other reported compounds such as bentonite, aluminium polychloride, and Magnafloc can be used to remove impurities, pigments, turbidity and scum; using inert gases such as nitric oxide and CO_2 to retard the activity of polyphenol oxidase since it converts compounds like catechol and monophenol into ortho-quinone which will further polymerizes to produce melanin that causes dark brown pigment formation in the sap; treating the sap using lanthanum phosphate coated ultrafiltration membrane and ozone treatment has also been found to effectively decrease the colour of the sap, remove turbidity, initiate higher crystal growth etc. The energy efficiency of the NCS production practice could also be enhanced using better open pan-drying systems such as fuel-saving, modified single pan or reduced emission of harmful pollutants such as PM2.5, CO and CO_2 in multiple pan systems [110,111]. Modern drying techniques such as spray-drying, vacuum boiling, and mechanical recompression technology of palmyrah palm sap into powdered NCS can also be utilized to produce light-coloured, optimized sugar granules. The choice of drying method is one of the important factors in determining the resulting moisture content and case-hardening effect (i.e., often drying at higher temperatures results in the drying of only the outer surface leaving the inner core wet with localized higher water activity which will cause increased microbial growth) which will eventually impact the shelf-life of the solid NCS blocks which is produced via the conventional method [112]. Because rural practices make use of solar drying, the maximum loss of moisture even at temperatures around 35–40 °C at 30% relative humidity was seen as sufficient for a stable shelf-life [112]. Drying of a solid NCS block is governed by the reducing sugar content and its crystalline nature, the temperature of drying and the external humidity. Moreover, NCS is a complex sugar system and its nature and quantity of crystalline phase from the reducing sugar fractions (i.e., more than 6% reducing sugars and lower crystalline phase results in higher moisture content) influence its hygroscopic nature and hence the need to develop better packaging and storage systems [112]. Utilizing hydroxy propyl methyl-cellulose (HPMC) and carboxy methyl cellulose (CMC) based edible coating [113] and active packaging, modified atmospheric packaging and storage in reduced humidity conditions will enable good shelf life for the jaggery. Thus, the processing and production of palmyrah palm NCS must take into consideration the above factors to attain a standardized quality sugar product.

The potential of using palmyrah palm NCS as a functional ingredient in food product formulations is already on the rise with various manufacturers retailing their products under the label of 'functional food', 'fortified food' or 'nutraceutical'. This is primarily attributed to the mineral, vitamins, and phytochemicals like phenols, flavonoids and some amount of dietary fibre present in the palmyrah palm NCS. Whilst we have concisely reported those published work that mentions the functionality of food product because of the addition of palmyrah palm sugar as an added sweetener, there exists a lot of ambiguity in the academic experiments since many papers fail to mention the palm source of their NCS (which could also be due to lack of information present on the palm species from which the NCS is derived even in markets and retails) and hence specific functional/phytochemical aspects cannot be specially attributed to a particular geographic palm species. Regardless, this calls for potential research to be conducted in the area of food formulation, and biochemical and dietary analysis of using palmyrah palm NCS as an added sweetener and as a functional ingredient. NCS is a thermodynamically complex system with the exitance of sucrose, glucose and fructose, where each of these sugar fractions exhibit its physical properties in a synergic or singular manner such as crystallinity, solubility, melting, moisture absorption, glass transition and flow characteristics. Therefore, the addition of NCS in a food formulation will eventually have an impact from the above properties of these sugar fractions and hence an eventual effect on the rheology, tribology, and overall consumption palate of the food product. Understanding the co-melting behaviour of a tertiary sugar product like NCS is important for food manufacturers to control the functional properties of various foods such as bakery, confectionery, desserts and preservative items during their processing when using NCS as a sweetener or ingredient. Whilst sucrose has a higher melting temperature (184.1 ± 1.6 °C) than fructose (120.9 ± 1.7 °C) and glucose (155.8 ± 0.4 °C), it was noted that in a sucrose-fructose-glucose mixture, sucrose co-melts along with fructose and glucose at lower melting temperatures as evidenced by its decreased enthalpy [114]. This is because of the dissolution of sucrose in the fructose/glucose liquid melt as confirmed by microscopic imaging. Also, because fructose has a lower melting temperature than glucose, fructose will gain more Gibbs energy (when the temperature is higher than the melting point, the Gibbs energy of liquid sugar will increase more rapidly than the solid sugar) than glucose and hence sucrose melts easily in the liquid fructose melt than glucose [114]. Therefore, this phenomenon will affect food formulations that are looking to substitute pure sucrose, fructose or glucose with palmyrah palm NCS thus altering the physical and functional property of food.

Numerous papers report the health benefits of palmyrah palm NCS intake in a regular diet. Whilst such claims are once again attributed to its mineral, vitamins, amino acids, and phenolic compounds, the post-consumption fate, presence, and bioavailability of the same is highly unresearched leaving a gap in scientific facts and public consensus. The potential of using palmyrah palm NCS as a micronutrient fortification agent in food holds good prospects due to the presence of its mineral particularly potassium, calcium and iron along with other vitamins. However, the bioavailability of these minerals post-consumption is a question that needs experimental validation to attest to various health benefit claims. Often, non-heme iron (iron from plant sources) is poorly absorbed under physiological conditions but because palmyrah palm NCS also contains vitamin C, the potential for iron to be bioavailable in good amounts is a possibility since under low pH of the stomach, vitamin C (ascorbic acid) forms a chelate complex with ferric (Fe^{3+}) iron and becomes soluble in the alkaline environment of the duodenum [115]. However, this hypothesis of mineral bioavailability in palmyrah palm NCS can be said for certain only after conducting in-vitro studies. Likewise, the presence of various phytochemicals such as phenols flavonoids and other compounds in palmyrah palm NCS requires further investigation both before and after NCS production to understand the effect of such processing on the availability and loss of such compounds. For example, *Borassus flabellifer* fruit is known to contain phenolic compounds like benzoic acid (p-Hydroxybenzoic), cinnamic acid (p-Coumaric, ferulic) [116] and compounds like 2,3,4-trihydroxy-5--methyl acetophenone, nicotinamide, and uracil are isolated from the syrup [47]. However, no paper has exclusively reported a complete analysis of various dietary phenolic compounds in the final NCS. Such information will help in understanding the diverse geographic, cultivar and growth condition-specific phytochemical composition in the NCS. Such analysis will also reveal dietary phenols and fibre composition which are also known to be prebiotic in gut metabolism. Inulin, a well known dietary fibre is reported to be present in palmyrah palm NCS but new studies need to effectively quantify them before and after processing and their bioavailability as well. Modern metabolomics and proteomics approaches can enable information about dietary phenol and fibre composition and their metabolic fate post-gut fermentation as well [117]. Because palm species are noted to have polyphenols and often it is destroyed during intense thermal processing, perhaps in the future encapsulation strategies can be developed to preserve these compounds within the sap or even post-processing using modern drying technologies thus making palmyrah palm NCS an actual nutraceutical food addressing various health benefits and claims [118]. Finally, with government norms, incentives, origin traceability measures and promotions, this current agronomic cottage industry can be modernized by preserving the traditional practices with sustainable technological interventions so that *Borassus flabellifer* cultivation can be improved and the subsequent NCS can be vastly made available for global consumption as a truly nutritional natural sweetener.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Yes, have acquired consent to publish.

Availability of data and materials

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The author has contributed solely to this work.

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.

Data availability

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References

[1] W.G. Abdullah, U. Rianse, R.M. Iswandi, S.A.A. Taridala, W. Widayati, I. S. Rianse, L.R. Zulfikar Baka, W.K. Abdi Baka, Muhidin, Potency of natural sweetener: Brown sugar, Adv. Environ. Biol. 8 (21) (2015) 374–385.
[2] H.D. Goff, J. Cooper, Beyond Sweetness: the Functional Roles of Sugar in Foods and the Challenges in Replacing/Reducing it, Canadian Sugar Research Institute, 2016. Available from: https://www.sugar.ca/sites/default/uploads/files/Facts-Carbs-Beyond-Sweetness_LR.pdf.
[3] R.A. Clemens, J.M. Jones, M. Kern, S.Y. Lee, E.J. Mayhew, J.L. Slavin, S. Zivanovic, Functionality of sugars in foods and health, Compr. Rev. Food Sci. Food Saf. 15 (2016) 433–470.
[4] A. Singh, U. Lal, H. Mukhtar, P. Singh, G. Shah, R. Dhawan, Phytochemical profile of sugarcane and its potential health aspects, Phcog. Rev. 9 (17) (2015) 45.
[5] K. Srikaeo, R. Thongta, Effects of sugarcane, palm sugar, coconut sugar and sorbitol on starch digestibility and physicochemical properties of wheat-based foods, Int. Food Res. J. 23 (3) (2015) 923–929.
[6] W.R. Jaffé, Health effects of non-centrifugal sugar (NCS): a review, Sugar Tech 14 (2) (2012) 87–94.
[7] World customs organization, Retrieved from: https://www.wcoomd.org/-/media/wco/public/global/pdf/topics/nomenclature/instruments-and-tools/hs-nomenclature-2017/2017/0417_2017e.pdf?la=en.
[8] A.K. Thakur, Potential of jaggery (Jaggery) manufacturing in Punjab state, in: Proceedings of the National Seminar on Status, Problems and Prospects of Jaggery and Khandsari Industry in India, Indian Institute of Sugarcane Research, Lucknow, 1999, pp. 70–76.
[9] K. Hori, S. Jaroenkornburi, R.B.R.A. Purboyo, S. Kim, G. Ishibashi, S. Kai, M. Kang, Knowledge of iron nutrition by university students in Japan, Korea, Thailand and Indonesia, J. Consum. Stud. Home Econ. 19 (4) (1995) 349–358.
[10] A.D. Saputro, D. Van de Walle, K. Dewettinck, Palm sap sugar: a review, Sugar Tech (2019).
[11] A.K. Chaurasiya, I. Chakraborty, J. Saha, Value addition of Palmyra palm and studies on the storage life, J. Food Sci. Technol. 51 (2014) 768–773.
[12] S. Arulraj, B.J. Augustine, Underutilized palms, in: K.V. Peter (Ed.), Underutilized and Underexploited Horticultural Crops, vol. 3, New India Publishing Agency, New Delhi, 2008, pp. 415–429.
[13] S. Sandhya, K. Sudhakar, D. Banji, K.R. Vinod, R. Aradhana, Pharmacognostic characterization of Borassus flabellifer leaf, J. Advanced Pharmac Res. 1 (2) (2010) 88–93.
[14] A. Srivastava, S.K. Bishnoi, P.K. Sarkar, Value addition in palmyra palm (Borassus flabellifer L.): a potential strategy for livelihood security and poverty alleviation, Rashtriya Krishi 12 (1) (2017) 110–112.
[15] P.V.K.J. Rao, M. Das, S.K. Das, Changes in physical and thermo- physical properties of sugarcane, palmyra-palm and date-palm juices at different concentration of sugar, J. Food Eng. 90 (4) (2009) 559–566.
[16] A.K. Ghosh, A.K. Srivastava, V.P. Agnihotri, Production Technology of Lump Sugar-Jaggery/Jaggery, Daya Publishing House, Delhi, 1998, pp. 178–209.
[17] K. Srikaeo, R. Thongta, Effects of sugarcane, palm sugar, coconut sugar and sorbitol on starch digestibility and physicochemical properties of wheat based foods, Int. Food Res. J. 22 (3) (2015) 923.
[18] K. Srikaeo, J. Sangkhiaw, W. Likittrakulwong, Productions and functional properties of palm sugars, Walailak J. Sci. Technol. 16 (11) (2018) 897–907.
[19] M.L. Sanyang, S.M. Sapuan, M. Jawaid, M.R. Ishak, J. Sahari, Recent developments in sugar palm (Arenga pinnata) based biocomposites and their potential industrial applications: a review, Renew. Sust. Energy Rev. 54 (2016) 533–549.
[20] T.A. Davis, D.V. Johnson, Current utilization and further development of the palmyra palm (Borassus flabellifer L., Arecaceae) in Tamil Nadu state, India, Econ. Bot. 41 (1987) 247–266.
[21] S. Anwar, Q.A. Syed, F. Munawar, M. Arshad, W. Ahmad, M.A. Rehman, M. K. Arshad, Inclusive Overview of Sweeteners Trends: Nutritional Safety and Commercialization, ACS Food Science & Technology, 2023.
[22] D. Huynh Thi Le, W.-C. Lu, P.-H. Li, Sustainable processes and chemical characterization of natural food additives: palmyra palm (Borassus flabellifer linn.) granulated sugar, Sustainability 12 (7) (2020) 2650.
[23] P.C. Vengaiah, D. Ravindrababu, G.N. Murthy, K.R. Prasad, Jaggery from Palmyrah palm (Borassus flabellifer L.)- Present status and scope, Indian Journal of Traditional Knowledge 12 (4) (2013) 714–717.
[24] C. Sarma, G. Mummaleti, V. Sivanandham, S. Kalakandan, A. Rawson, A. Anandharaj, Anthology of palm sap: the global status, nutritional composition, health benefits & value added products, Trends Food Sci. Technol. 119 (2022) 530–549.
[25] O. Lasekan, A. Buettner, M. Christlbaure, Investigation of important odorant of palm wine (Elaeis guineensis), Food Chem. 105 (2007) 15–23.
[26] C. Dalibard, Overall view on the tradition of tapping palm trees and prospects for animal production, Livest. Res. Rural Dev. 11 (1) (1999) 5. Available from: http://www.lrrd.org/lrrd11/1/dali111.htm.
[27] K. Borin, T.R. Preston, Conserving Biodiversity and the Environment and Improving the Wellbeing of Poor Farmers in Cambodia by Promoting Pig-Feeding Systems Using the Juice of the Sugar Palm Tree (Borassus Flabellifer), vol. 7, Livestock Research for Rural Development, 1995, p. 15. Available from: http://www.lrrd.org/lrrd7/2/5.htm.
[28] S. Jitbunjerdkul, Effect of antimicrobial agents on the quality of palm sugar products, Songklanakarin J. Sci. Technol. 11 (1989) 161–165.
[29] S. Uzochukwu, E. Balogh, O.G. Tucknot, M.J. Lewis, P.O. Ngoddy, Role of palm wine yeasts and bacteria in palm wine aroma, J. Food Sci. Technol. 36 (1999) 301–304.
[30] F.T. Obahiagbon, P. Oviasogie, Changes in the physico-chemical characteristics of processed and stored Raphia hookeri palm sap (shelf life studies), Am. J. Food Technol. 2 (2007) 323–326.
[31] S. Limtong, S. Am-In, R. Kaewwichian, C. Kaewkrajay, S. Jindamorakot, Exploration of yeast communities in fresh coconut, palmyra, and nipa palm saps and ethanol-fermenting ability of isolated yeasts, Antonie Leeuwenhoek (2020).
[32] P. Naknean, M. Meenune, G. Roudaut, Characterization of palm sap harvested in Songkhla province, Southern Thailand Int Food Res J 17 (2010) 977–986.
[33] K. Borin, A Study on the Use of the Sugar Palm Tree (Borassus Flabellifer) for Different Purposes in Cambodia. M Sc Thesis, Swedish University of Agricultural Sciences, Uppsala, 1996, p. 67.
[34] J.P. Romera, Le Borassus et le sucre de palme au Cambodge, Agron. Trop. 8 (1968) 801–843.
[35] U. Pethiyagoda, Coconut Inflorescence Sap, Perak Planters' Association Journal, Malaysia, 1978, pp. 86–91.
[36] A. Kovoor, The Palmyrah Palm: Potential and Perspectives. FAO Plant Production and Protection Paper No 52, FAO, Rome, 1983, p. 77.
[37] R. Valder, K.P. Nooralabettu, Physico-chemical changes in palmyra palm (Borassus flabellifer) sap at different temperature, Int. J. Sci. Eng. Res. 9 (1) (2018) 761–766.
[38] P. Naknean, Improvement in shelf life and safety of pasteurized palm sap (Borassus flabellifer linn.) by the addition of nisin, J. Food Saf. 33 (4) (2013) 515–525.
[39] K. Velauthamurty, S. Mary, G. Sashikesh, S. Srivijeindran, Enhance the quality of palmyrah (Borrasus flabellifer) jaggery, J. Nat. Prod. Plant Resour. 5 (2) (2015) 37–42.
[40] M. Madhava, D.R. Babu, P.C. Vengaiah, B.H. Babu, Optimization of process parameters for production of palmyrah palm jaggery, Journal of Agricultural Engineering 52 (1) (2015) 14–19.
[41] C.W. Ho, M.W. Aida, Y.M. Maskat, H. Osman, Optimization of headspace solid phase microextraction (HS-SPME) for gas chromatography-mass spectrometry (GC-MS) analysis of aroma compound in palm sugar (Arenga pinnata), J. Food Compos. Anal. 19 (2006) 822–830.
[42] Thai Industrial Standards Institute Ministry, Palmyra Palm and Palmyra Palm Products, Bangkok, Thailand, 2003.
[43] M. Phaichamnan, W. Posri, M. Meenune, Quality profile of palm sugar concentrate produced in Songkhla Province, Thailand, Int. Food Res. J. 17 (2010) 425–432.
[44] R.A. Katrine, M.L. Pinelo, F.A. Vikbjerg, B.M. Let, S.A. Meyer, Protease-assisted clarification of blackcurrant juice: synergy with other clarifying agents and effects on the phenol content, J. Agric. Food Chem. 54 (2006) 6554–6563.
[45] P. Naknean, N. Juntorn, T. Yimyuan, Influence of clarifying agents on the quality of pasteurised palmyra palm sap (Borassus flabelliferLinn), Int. J. Food Sci. Technol. 49 (4) (2013) 1175–1183.
[46] A.D. Saputro, D. Van de Walle, M. Hinneh, J. Van Durme, K. Dewettinck, Aroma profile and appearance of dark chocolate formulated with palm sugar–sucrose blends, European Food Research and Technology 244 (7) (2018) 1281–1292.
[47] M.V. Reshma, J. Jacob, V.L. Syamnath, V.P. Habeeba, B.S. Dileep Kumar, R. S. Lankalapalli, First report on isolation of 2,3,4-trihydroxy-5-methylacetophenone from palmyra palm (Borassus flabellifer Linn.) syrup, its antioxidant and antimicrobial properties, Food Chem. 228 (2017) 491–496.
[48] N. Potter, J. Hotchkiss, Food dehydration and concentration, in: N. Potter (Ed.), Food Science, Chapman and Hall, New York, 1995, pp. 201–243.
[49] G. Luis, C. Rubio, A. Gutiérrez, C. Hernandez, D. González-Weller, C. Revert, A. Hardisson, Palm tree syrup: nutritional composition of a natural edulcorant, Nutr. Hosp. 27 (2012) 548–552.
[50] P. Naknean, M. Meenune, G. Roudaut, Changes in physical and chemical properties during the production of palm sugar syrup by open pan and vacuum evaporator, J. Asian of Food & Agro-Industry. 2 (2009) 448–456.
[51] J.Y. Chen, G.C. Yen, N.T. Tsai, J.A. Lin, Risk and benefit of natural and commercial dark Brown sugars as evidenced by phenolic and maillard reaction product contents, J. Agric. Food Chem. 69 (2) (2021) 767–775.
[52] P. Verma, S.R. Iyer, N. Shah, S. Mahajani, Insights into the crystallization phenomenon in the production of non-centrifugal sugar, J. Food Eng. (2020), 110259.
[53] P. Verma, N.G. Shah, S.M. Mahajani, A novel technique to characterize and quantify crystalline and amorphous matter in complex sugar mixtures, Food Anal. Methods 13 (2020) 2087–2101.
[54] P. Verma, N.G. Shah, S.M. Mahajani, Effects of acid treatment in jaggery making, Food Chem. (2019), 125094.

[55] A. Upadhyaya, P.P. Bhalerao, P. Bhushette, A. Dabade, S.K. Sonawane, Optimization study of palm jaggery and palm candy production and process, Applied Food Research 3 (1) (2023), 100269.
[56] T. Sarkar, M. Mukherjee, S. Roy, R. Chakraborty, Palm sap sugar is an unconventional source of sugar exploration for bioactive compounds and its role in functional food development, Heliyon 9 (4) (2023), e14788.
[57] L. Moreno, O. Medina, A.L. Rojas, Mucilage and cellulosic derivatives as clarifiers for the improvement of the non-centrifugal sugar production process, Food Chem. 367 (2021).
[58] D.H. Thi Le, C.-S. Chiu, Y.-J. Chan, C.-C.R. Wang, Z.-C. Liang, C.-W. Hsieh, W.-C. Lu, A.T. Mulio, Y.-J. Wang, P.-H. Li, Bioactive and physicochemical characteristics of natural food: palmyra palm (Borassus flabellifer linn.) syrup, Biology 10 (10) (2021) 1028.
[59] P. Naknean, M. Meenune, Characteristics and antioxidant activity of palm sugar syrup produced in Songkhla Province, southern Thailand, Asian Journal of Food and Agro-Industry 4 (2011) 204–212.
[60] M.T. Nighitha, I.P. Sudagar, Engineering properties of palmyrah palm jaggery (Borassus flabellifer L.), Trends in Biosciences Journal 10 (43) (2017) 8974–8976.
[61] P. Rice, J.D. Selman, R.K. Abdul-Rezzak, Effect of temperature on thermal properties of 'Record' potatoes, Int. J. Food Sci. Technol. 23 (1998) 281–286.
[62] N. Unklesbay, K. Unklesbay, F. Hsieh, K. Sandik, Thermophysical properties of extruded beef/corn flour blends, J. Food Sci. 57 (6) (1992) 1282–1284.
[63] N.N. Mohsenin, Thermal Properties of Food and Agricultural Materials, Gordon and Breach, Science Publishers Inc, 1980.
[64] P.V.K.J. Rao, M. Das, S.K. Das, Thermophysical properties of sugarcane, palmyra palm, and date-palm granular jaggery, Int. J. Food Prop. 11 (4) (2008) 876–886.
[65] R.P. Singh, D.R. Heldman, Thermal conductivity of selected food products, in: Introduction to Food Engineering, third ed., Elsevier, New Delhi, 2004, p. 599.
[66] J.M. Aguilera, J.M. Del Valle, M. Karel, Caking phenomena in amorphous food powders, Trends Food Sci. Technol. 6 (1995) 149–155.
[67] Y. Roos, Phase Transition in Foods, vol. 366, Academic Press Inc, San Diego, 1995.
[68] P.V.K.J. Rao, M. Das, S.K. Das, Effect of moisture content on glass transition and sticky point temperatures of sugarcane, palmyra-palm and date-palm jaggery granules, Int. J. Food Sci. Technol. 45 (1) (2009) 94–104.
[69] E. Ayranci, G. Ayranci, Z. Dogantan, Moisture sorption isotherms of dried apricot, figs, and raisin at 20 C and 30 C, J. Food Sci. 55 (1990) 1591–1593, 1625.
[70] P. Verma, N.G. Shah, S.M. Mahajani, Why jaggery powder is more stable than solid jaggery blocks, LWT 110 (2019) 299–306.
[71] G.R. Rao, M. Panemangalore, R. Rajagopalan, Nutritional properties of neera and palm jaggery, Indian J. Nutr. Diet 7 (1) (1970) 44–52.
[72] M.R. Joshi, K. Sohonie, Nature of carbohydrates in palm jaggery, J. Sci. Ind. Res. (India) 15 (c) (1956) 281. Available from: http://lib3.dss.go.th/fulltext/scan_ebook/j_of_sci_in_1956_v15_n12.pdf.
[73] P.C. Vengaiah, G.N. Murthy, M. Sattiraju, H.P. Maheswarappa, Value added products from palmyrah palm (Borassus Flabellifer L), Journal of Nutrition and Health Sciences 4 (1) (2017).
[74] G. Naik, Palm Jaggery. The All-India Village Industries Association, second ed., 1945. Available from: https://archive.org/details/PalmSugar/page/n5/mode/2up.
[75] C.W. Ho, W.M. Aida, M.Y. Maskat, H. Osman, Effect of thermal processing of palm sap on the physico-chemical composition of traditional palm sugar, Pakistan J. Biol. Sci. 11 (7) (2008) 989–995.
[76] M.R. Joshi, K. Sohonie, Vitamin B_{12} & the alkali-stable vitamin B_{12} - like factors in palm jaggery, J. Sci. Ind. Res. (India) 16 (c) (1957) 68. Retrieved from: http://lib3.dss.go.th/fulltext/scan_ebook/j_of_sci_in_1957_v16_n3.pdf.
[77] L. Arcieri, Organic Sweetener, United States Patent Application Publication, 2014. No: US 2014/0335252 A1.
[78] Philippine Coconut Authority, Composition of Nutritional Value of Coco Sap. Techno Guide Sheet No. 16, Davao Research Center, Department of Agriculture, 2016.
[79] K. Hori, R.B.R.A. Purboyo, Iron content of palm sugar and its chemical form in Indonesia, J. Consum. Stud. Home Econ. 15 (1991) 287–293.
[80] A.D. Saputro, D. Van de Walle, R.P. Aidoo, M.A. Mensah, C. Delbaere, N. De Clercq, K. Dewettinck, Quality attributes of dark chocolates formulated with palm sap-based sugar as nutritious and natural alternative sweetener, European Food Research and Technology 243 (2) (2017) 177–191.
[81] T.P. Trinidad, A.C. Mallillin, R.S. Sagum, R.R. Encabo, Glycemic index of commonly consumed carbohydrate foods in the Philippines, J. Funct.Foods 2 (2010) 271–274.
[82] P.K. Vayalil, Date fruits (Phoenix dactylifera Linn): an emerging medicinal food, Crit. Rev. Food Sci. Nutr. 52 (2012) 249–271.
[83] N.Z.R. Anwar, A. Jamaluddin, N. Shahidan, Z. Zakaria, Nutritional composition and glycaemic index of milk chocolate using different sweeteners, Journal of Agrobiotechnology 9 (1S) (2018) 62–68.
[84] S. Mahilrajan, B. Sandrasegarampillai, V. Arasaratnam, T. Kumanan, R. Kailayalingam, Glycemic index and insulin index of palmyrah based edible products commonly consumed in jaffna, IOSR Journal of Biotechnology and Biochemistry 3 (2017) 37–42.
[85] I.C. Arts, P.C. Hollman, Polyphenols and disease risk in epidemiologic studies, Am. J. Clin. Nutr. 81 (2005) 317–325.
[86] A. Scalbert, I.T. Johnson, M. Saltmarsh, Polyphenols: antioxidants and beyond, Am. J. Clin. Nutr. 81 (2005) 215–217.
[87] C.H. Edwards, M. Rossi, C.P. Corpe, P.J. Butterworth, P.R. Ellis, The role of sugars and sweeteners in food, diet and health: alternatives for the future, Trends Food Sci. Technol. 56 (2016) 158–166.
[88] A.D. Saputro, D. Van de Walle, S. Kadivar, M.A. Mensah, J. Van Durme, K. Dewettinck, Feasibility of a small-scale production system approach for palm sugar sweetened dark chocolate, European Food Research and Technology 243 (6) (2017) 955–967.
[89] A.D. Saputro, D. Van de Walle, S. Kadivar, M.D. Bin Sintang, P. Van der Meeren, K. Dewettinck, Investigating the rheological, microstructural and textural properties of chocolates sweetened with palm sap-based sugar by partial replacement, European Food Research and Technology 243 (10) (2017) 1729–1738.
[90] A. Apriyantono, E. Wiratma, H. Husain, L.N. Lie, M. Judoamidjojo, N. L. Puspitasari-Nienaber, S. Budiyanto, H. Sumaryanto, Analysis of volatiles of kecap manis (a typical Indonesian soy sauce), in: J.A. Taylor, D.S. Mottram (Eds.), Flavour Science, Recent Developments, The Royal Society of Chemistry, Cambridge, 1996, pp. 62–65.
[91] R. Nafingah, J. Kurniasari, A. Cahyani, E. Harmayani, A.D. Saputro, Investigating the impact of palm sap sugar proportion and fat content on heat stability of milk chocolate. The 3rd international symposium on agricultural and biosystem engineering, IOP Conf. Ser. Earth Environ. Sci. 355 (2019).
[92] M.I. Watawana, N. Jayawardena, S.J. Ranasinghe, V.Y. Waisundara, Evaluation of the effect of different sweetening agents on the polyphenol contents and antioxidant and starch hydrolase inhibitory properties of kombucha, J. Food Process. Preserv. 41 (1) (2016).
[93] L. Vijay Vijay, N. Karthikeyan, G. Kumaresan, C. Pandiyan, Development of palm sugar substituted yoghurt, Int. J. Agric. Environ. Biotechnol. 15 (2022) 379–383.
[94] P. Nowicka, A. Wojdyło, Bioactive compounds and sensory attributes of sour cherry puree sweetened with natural sweeteners, Int. J. Food Sci. Technol. 50 (3) (2014) 585–591.
[95] P. Nowicka, A. Wojdyło, Stability of phenolic compounds, antioxidant activity and colour through natural sweetener addition during storage of sour cherry puree, Food Chem. 196 (2016) 925–934.
[96] L. Chauhan, K.S. Prakash, P.P. Srivastav, K. Bashir, Physicochemical and thermal properties of candy crystals prepared from palmyra-palm jaggery, J. Food Process. Eng. 40 (1) (2017), e12337.
[97] S.G. Dharini, S. Mithul, D. Gokul, S. Mathew, M. Mithun, S. Chakkaravarthi, Nutritional characteristics and phytochemical screening of traditional panai (Borassus flabellifer) olai kozhukattai, J. Food Distrib. Res. 1 (1) (2021) 1–6.
[98] P. Verma, N.G. Shah, S.M. Mahajani, Why jaggery powder is more stable than solid jaggery blocks, LWT 110 (2019) 299–306.
[99] S. Ajito, H. Iwase, S.I. Takata, M. Hirai, Sugar-mediated stabilization of protein against chemical or thermal denaturation, J. Phys. Chem. B 122 (37) (2018) 8685–8697.
[100] L.E. Belyakova, A.S. Antipova, M.G. Semenova, E. Dickinson, L.M. Merino, E. N. Tsapkina, Effect of sucrose on molecular and interaction parameters of sodium caseinate in aqueous solution: relationship to protein gelation, Colloids Surf. B Biointerfaces 31 (1–4) (2003) 31–46.
[101] X. Yang, E.A. Foegeding, Effects of sucrose on egg white protein and whey protein isolate foams: factors determining properties of wet and dry foams (cakes), Food Hydrocolloids 24 (2–3) (2010) 227–238.
[102] A. Beleia, R.A. Miller, R.C. Hoseney, Starch gelatinization in sugar solutions, Starch Staerke 48 (7-8) (1996) 259–262.
[103] A.C. Aprotosoaie, S.V. Luca, A. Miron, Flavor chemistry of cocoa and cocoa products—an overview, Compr. Rev. Food Sci. Food Saf. 15 (2016) 73–91.
[104] S. Vaidyanathan, Lassi, moringa, pepper: a Coimbatore man is winning awards by infusing Indian flavours in chocolates, Scroll. Available from, https://scroll.in/magazine/909412/lassi-moringa-pepper-a-coimbatore-man-is-winning-awards-by-infusing-indian-flavours-in-chocolates, 2019.
[105] I. Damar, A. Eksi, Antioxidant capacity and anthocyanin profile of sour cherry (Prunus cerasus L.) juice, Food Chem. 135 (2012) 2910–2914.
[106] H. Purnomo, Sugar components of coconut sugar in Indonesia, ASEAN Food J. 7 (1992) 200–201.
[107] S. Senthilnathan, S.S.A. Rahman, S. Pasupathi, P. Venkatachalam, S. Karuppiah, Stoichiometric analysis and production of bacterial cellulose by gluconacetobacter liquefaciens using Borassus flabellifer L. Jaggery, Appl. Biochem. Biotechnol. 194 (8) (2022) 3645–3667.
[108] S.R. Reddy Tadi, A. Evr, A.M. Limaye, S. Sivaprakasam, Enhanced production of optically pure D (–) lactic acid from nutritionally rich Borassus flabellifer sugar and whey protein hydrolysate based–fermentation medium, Biotechnol. Appl. Biochem. 64 (2) (2017) 279–289.
[109] Venkatesh Thulsasiraman, A.M. Nandhu, V. Silpa, Balakrishnan Dharmalingam, S. Padma, V. Reshma, S. Sajeev, Ravi Pandiselvam, Anjineyulu Kothakota, Current Production Strategies and Sustainable Approaches towards the Resurgence of Non-centrifugal Cane Sugar Production – a Review, Sustainable Food Technology, 2023.
[110] M.S. Venkatesan, C. Lakshmanan, N. Raman, Jaggery making process and preservation: a review, Agric. Rev. (2022).
[111] S.K. Tyagi, S. Kamboj, N. Himanshu Tyagi, R. Narayanan, V.V. Tyagi, Technological advancements in jaggery-making processes and emission reduction potential via clean combustion for sustainable jaggery production: an overview, J. Environ. Manag. 301 (2022), 113792.
[112] P. Verma, N. Shah, S. Mahajani, Drying characteristics of non-centrifugal sugar, Dry. Technol. 38 (16) (2020) 2162–2171.
[113] A. Kumar, K. Chand, N.C. Shahi, A. Kumar, A.K. Verma, Optimization of coating materials on jaggery for augmentation of storage quality, Indian J. Agric. Sci. 87 (10) (2017) 1391–1397.
[114] Y. Wang, T. Truong, H. Li, B. Bhandari, Co-melting behaviour of sucrose, glucose & fructose, Food Chem. 275 (2019) 292–298.

[115] T. Ems, K. St Lucia, M.R. Huecker, Biochemistry, iron absorption, in: StatPearls. Treasure Island (FL, StatPearls Publishing, 2022. Available from: www.ncbi.nlm.nih.gov/books/NBK448204/.
[116] T.S. Agostini-Costa, Bioactive compounds and health benefits of some palm species traditionally used in Africa and the Americas – a review, J. Ethnopharmacol. 224 (2018) 202–229.
[117] S.M. Aravind, S. Wichienchot, R. Tsao, S. Ramakrishnan, S.J.F.R. I. Chakkaravarthi, Role of dietary polyphenols on gut microbiota, their metabolites and health benefits, Food Res. Int. 142 (2021), 110189.
[118] Z. Fang, B. Bhandari, Encapsulation of polyphenols–a review, Trends Food Sci. Technol. 21 (10) (2010) 510–523.