



REVIEW ARTICLE

Sugarcane, Sugar Beet, and Sweet Sorghum Processing: Similarities and Differences to Underpin Sustainable Practices

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Abstract

Sugar crop industries are increasingly implementing sustainable practices to supply natural sugar and other products that follow a circular approach spanning the entire sugar product life cycle which requires action from suppliers to consumers. These include sustainable cultivation practices, processes, products, and packaging to optimize economic gain while markedly reducing environmental and social losses. Sustainable practices by growers, processors, and refiners must be tailored to each sugar crop due to differences in composition which strongly impact harvesting and processing, although there are some similarities. Sugarcane (*Saccharum officinarum*), sugar beet (*Beta vulgaris*), and sweet sorghum (*Sorghum bicolor*) are all rich sources of sucrose. As a general rule, sugar beet (tuberous root) contains (based on total soluble sugars) 98.9% sucrose, 0.12% fructose, and 0.12% glucose, sugarcane (grass stalk) contains 94% sucrose, 3% glucose, and 3% fructose, while sweet sorghum (grass stalk with seed head) contains 80% sucrose, 10% glucose, and 10% fructose. The considerably lower invert sugars and higher amounts of nitrogen-containing compounds in beet than cane allow them to be deliberately degraded at higher alkaline pH processes during beet-sugar manufacturing to prevent Maillard color reactions. The high relative contents of glucose, fructose, starch, and aconitic acid in sweet sorghum currently make the manufacture of white sugar from this sugar crop techno-economically unfeasible. This partially explains why sweet sorghum for syrup production remains a smaller, cottage-type industry, whereas the sugarcane and sugar beet industries are worldwide commodity industries. One of the most profound differences between beet and cane-sugar processes is that during white sugar manufacture the colorants are more easily removed during the beet process, which is also a major reason why industrial chromatography is used to recover more sugar from beet molasses but not sugarcane molasses. Sugarcane and particularly sweet sorghum are rich sources of phenolic antioxidant colorants which need to be further exploited. Other differences and similarities in the processing of the crops are discussed in this review paper as well as the integrated production of refined sugar from both cane and beets at the same plant.

Keywords Sugarcane · Sugar beet · Sweet sorghum · Sustainability · Feedstock composition · Processing differences and similarities

Introduction

Currently, approximately 111 countries produce table sugar (sucrose) from either sugarcane or sugar beets, and 8 countries produce sugar from both commodity crops (Anon 2024) (Fig. 1). In 2023, sugar crops represented 22% of the global production of primary agricultural crops, only second to cereals at 32% (FAO 2023). Global production of sugar in 2024/2025 is expected to reach 186.5 million tonnes (raw value), the highest on record, with global consumption rising continuously in line with population growth (Ohidussaman 2024). Sugarcane (*Saccharum* spp.) is the world's largest crop by production yield (1.9 billion tonnes; FAO 2023)

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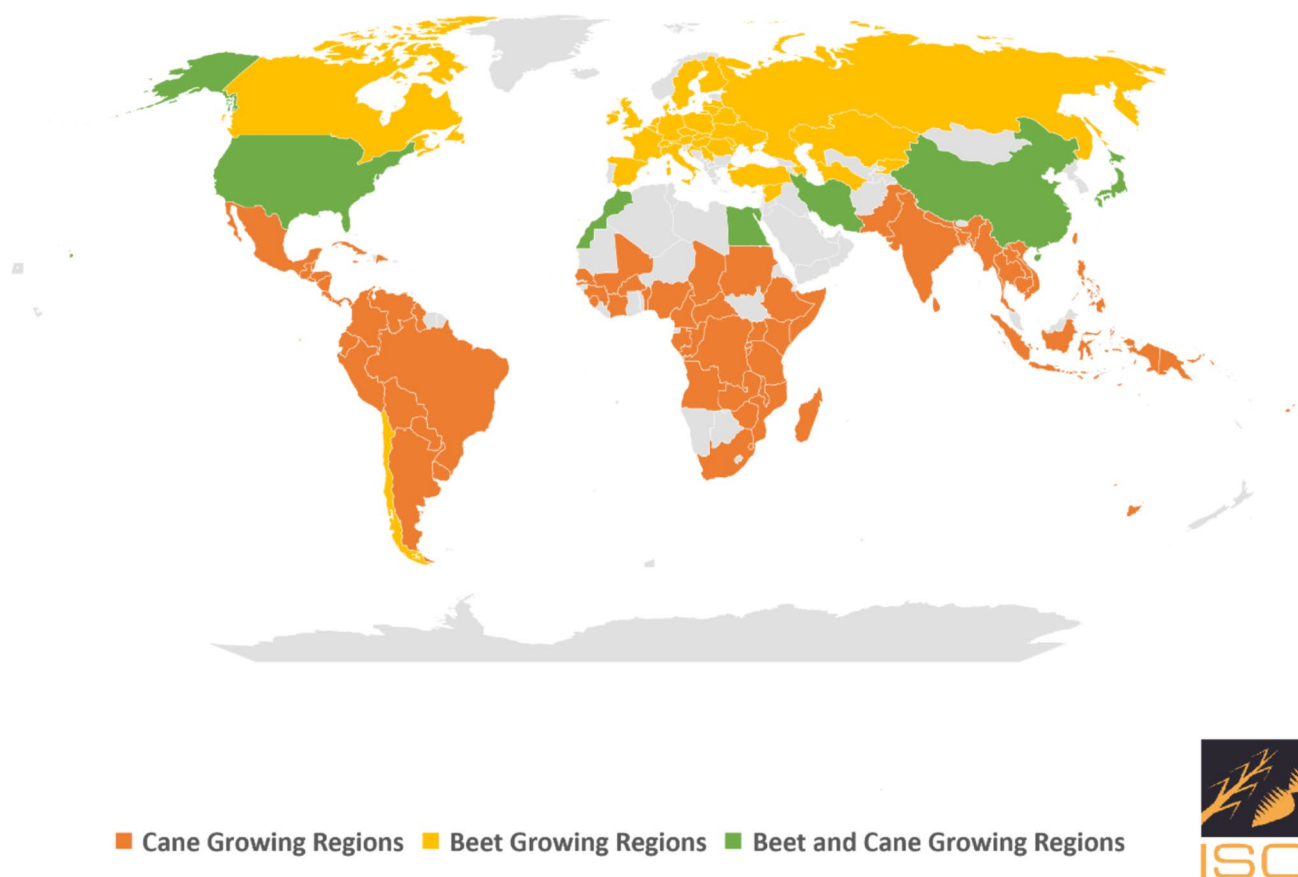


Fig. 1 Current sugarcane and sugar beet growing regions around the world. From the International Sugar Organization (ISO). (Note: Although Alaska is part of the USA, it does not grow any sugar commodity crops)

and, on average, accounts for nearly 80% of global sugar production (Anon 2024). In the 2023/24 season, the top ten sugar-producing countries were Brazil, India, Europe, China, USA, Thailand, Russia, Mexico, Pakistan, and Australia, with Brazil and India the top two producers with 19.6 and 17.0% of world production, respectively (Ohiduzzaman 2024). The major sugar consumption markets around the world are India, Europe, China, USA, Brazil, Indonesia, Russia, Pakistan, Mexico, and Egypt (Anon 2024).

Sustainability of Major Sugar (Commodity) Crops

Like many other industries, the global sugar industry is facing sustainability issues related to the environment, society, and economy (Eggleston 2010). As a result, sugar industries in many countries around the world are increasingly implementing sustainable practices to supply natural sugar and other products, following a circular approach which spans the entire sugar product life cycle and requiring action from suppliers to consumers (Eggleston et al. 2021a, b) (Fig. 2). These include sustainable cultivation practices including high yield crops (FAO 2023), processes, products, and

packaging to optimize economic gain while markedly reducing environmental and social losses. One of the main aims in the sustainability of sugar crops is the recycling of water during processing, as well as the recycling of processing aids, e.g., calcium oxide. Sustainable practices must be tailored to each sugar crop due to differences in composition which strongly impacts harvesting and processing, although there are some similarities.

Agricultural Aspects of Sugarcane, Sugar Beet, and Sweet Sorghum

Like for all crops, the agricultural aspects, i.e., cultivation, harvesting method, transport, and storage of the harvested sugar crop, all have a considerable effect on the feedstock quality. In turn, the quality of the feedstock processed at the industrial plant has a large impact not only on processing efficiency but also on the quantity and quality of the end product.

Sugar beets (*Beta vulgaris* L.) are tuberous roots that are currently cultivated, harvested, and processed in numerous temperate and sub-tropical countries for sugar production

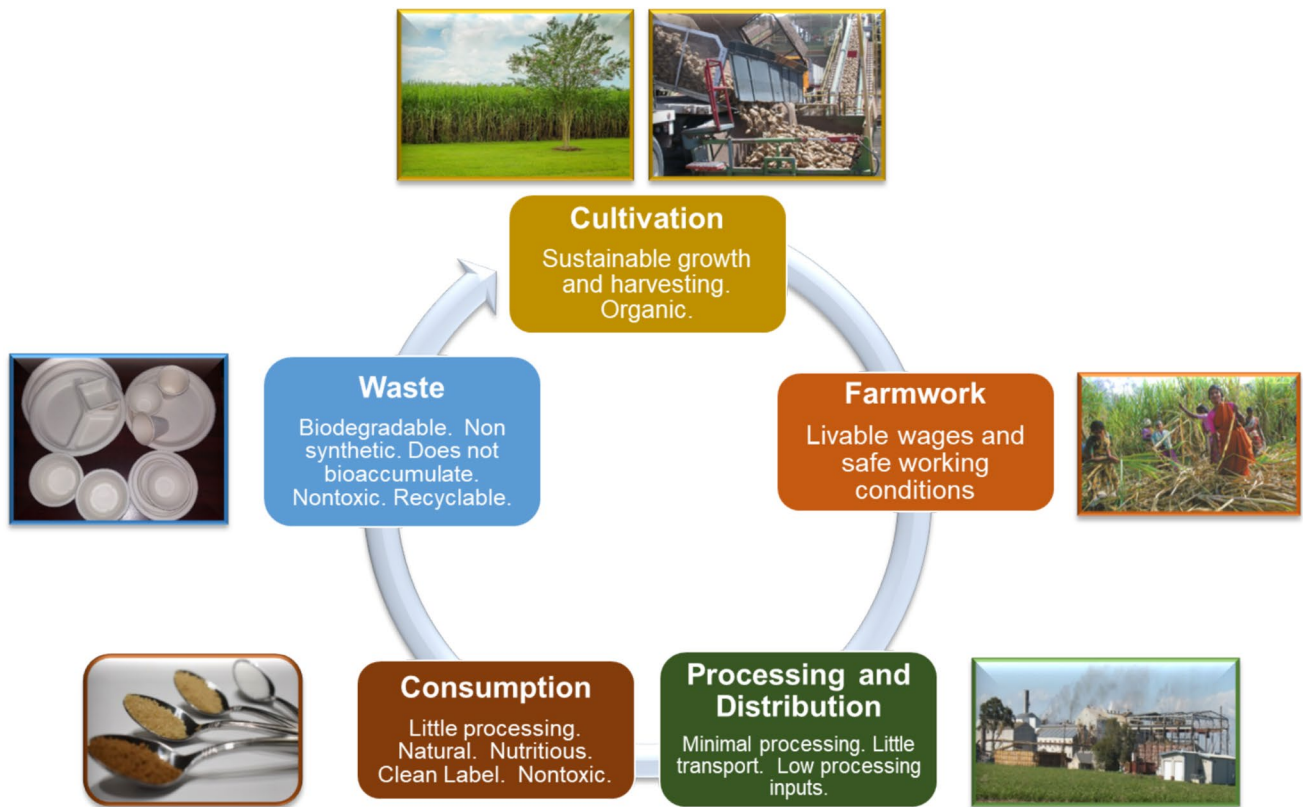


Fig. 2 Circular view of both sugarcane and sugar beet sustainability, which includes the entire life cycle of natural sugar production. From Farm to Retailer or from Farm to Fork, this 360-degree approach will

ensure resources are kept in use for as long as possible. Modified from Eggleston et al. (2021a, b)

(Eggleston et al. 2010) (Fig. 1). Additionally, apart from its significance in the global sugar industry, sugar beet also has application in animal feed and bioenergy production. Sugar beet is a biennial plant which during the first year produces a sugar-rich, enlarged root. Sugar beet is primarily a spring-planted crop in northern temperate zones, between 30° and 60° latitude (Fig. 3), although it is also grown in Chile, Venezuela, and Uruguay (Draycott 2006). “Tropical” sugar beets can also be cultivated in subtropical areas where irrigation is available, e.g., in Egypt.

Sugarcane (*Saccharum officinarum* L.) is a tall member of the grass (*Poaceae*) family which can be grown in tropical and sub-tropical regions of the world (Figs. 1 and 3). It grows relatively rapidly being a C4 crop with a high photosynthetic efficiency and is high yielding (Table 1), which allows it to play a pivotal role in the global sugar industry as a primary source of sucrose (table sugar). In addition to sugar, in various countries sugarcane is used to produce molasses (as a by-product), ethanol, and bioenergy. Sugarcane is vegetatively propagated and managed almost universally as a perennial crop; the plant crop being followed by multiple ratoon crops. As such, the harvesting, transport, processing, and refining of sugarcane represent

a mature global industry. Sugarcane is limited, however, to where it can be grown successfully because of its relatively long crop cycle and low tolerance to cold temperatures (Eggleston et al. 2010). As shown in Table 1, it requires more water for cultivation than sugar beets and is more sensitive to droughts than sweet sorghum. Nevertheless, over many centuries, sugarcane has demonstrated a remarkable ability to grow under a wide range of soil and climatic conditions, exhibiting relatively stable yields in locations where other crops have failed.

Like sugarcane, sweet sorghum is also a tall grass (*Poaceae*) with a sugar-rich stalk but, unlike sugarcane, also has a grain head. Due to various techno-economic reasons, sweet sorghum is not used for white sugar production but instead is mostly used for the manufacture of syrup. In the 1880s, sweet sorghum was a meaningful crop in the USA, producing around 113.4 million L of syrup (Winberry 1980). Commercial production fell significantly since then because of the availability of less-expensive refined sugar and corn syrups as well as the arrival of the sorghum aphid pest (Knoll et al. 2023). As a consequence, sweet sorghum has remained a small, cottage-type industry in the USA (average farm size of 1.2–2.4 ha; USDA-NASS 2017) and many other

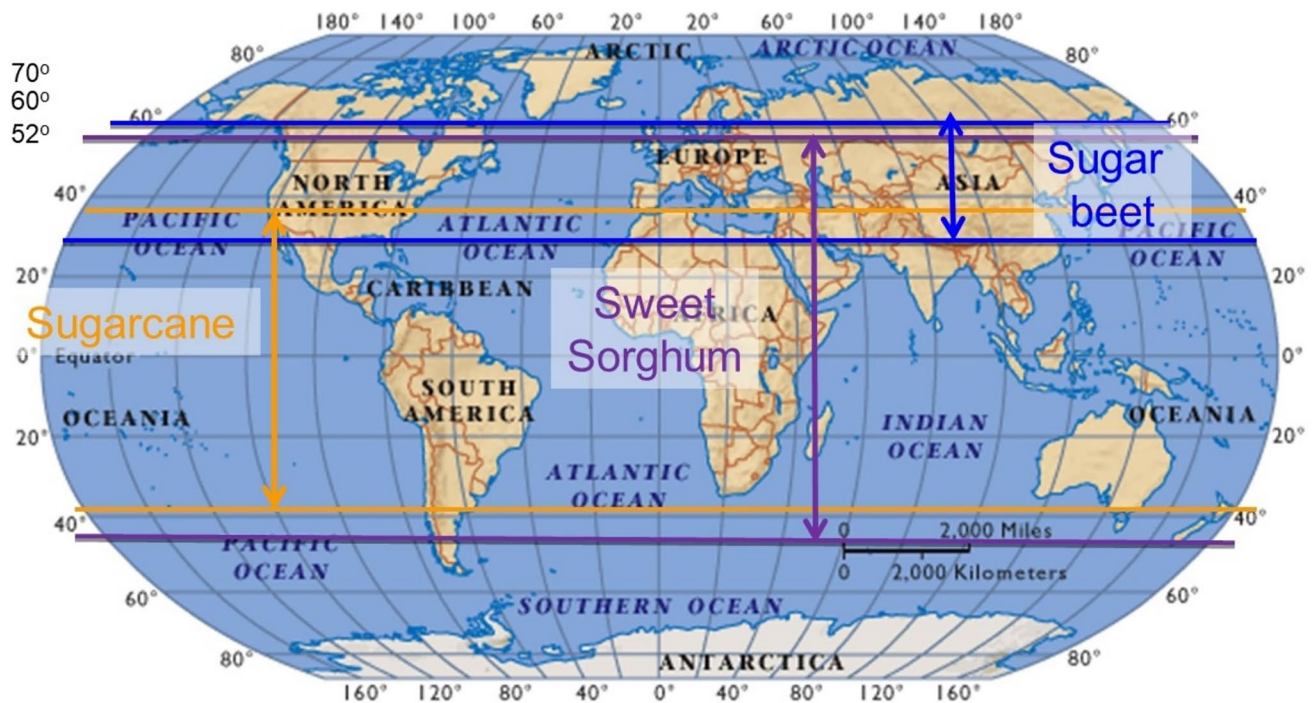


Fig. 3 Illustration of where sugarcane, sugar beet, and sweet sorghum crops can be cultivated globally. Modified from Debor (2009)

Table 1 Agricultural cultivation differences among sugar crops

Parameter	Sugarcane (<i>Saccharum officinarum</i> L.)	Sugar beet (<i>Beta vulgaris</i> L.)	Sweet sorghum (<i>Sorghum bicolor</i> L.)	References
Plant classification	C4 warm season grass	C3 temperate season tuberous root	C4 warm and temperate season grass	Eggleston et al. (2010)
Plant life cycle	Perennial	Biannual	Annual	Eggleston et al. (2010)
Crop duration (months)	12–18	5–6	3–6	Appiah-Nkansa et al. (2019); Mokariya and Malam (2020)
Crop planting season	One season	One season	All seasons	Mokariya and Malam (2020)
Propagation	Vegetative	Seed	Seed	
Water management (m ³ /ha)	36,000	18,500	8000	Appiah-Nkansa et al. (2019)
Fertilizer requirements	High management 250–500N: 125P:125 K*	Moderate management 120N:60P:60 K	Low nitrogen management 90N:40P:50 K	Appiah-Nkansa et al. (2019); Kim and Day (2011)
Crop yield (tonnes/ha) ^a	60–90	50–100	45–60	Cutz and Santana (2014), Appiah-Nkansa et al. (2019), Avram-Waganof and Morgenroth (2019)
Sugar yield (tonnes/ha)	7–13.5	8–18	3–7	Cutz and Santana (2014), Appiah-Nkansa et al. (2019), Avram-Waganof and Morgenroth (2019)

*N:P:K values are the ratios of nitrogen: phosphorus: potassium in fertilizers

^a The geographical areas for the crop yield data were not stated in the references

countries, whereas the sugarcane and sugar beet industries are worldwide commodity industries. On the other hand, in India during the 2019/2020 season sweet sorghum was

cultivated and harvested in 4.65 M ha and is expected to play “a significant role in addressing the growing need

for renewable energy to displace fossil fuel-based energy resources” (Mokariya and Malam 2020).

Sweet sorghum is one of the four major types of sorghum (*Sorghum bicolor* L.) grass crops: forage, grain, biomass, and sweet (Stefaniak et al. 2012). Due to its much lower need for agricultural inputs as well as its versatility and adaptability, sweet sorghum can be cultivated and processed over a much larger geographical area than sugarcane and sugar beets (Fig. 2). These advantages over other sugar crops indicate the future promising potential of sweet sorghum, especially as a biofuel/bioproduct feedstock. Sweet sorghum is an annual C-4 crop and has one of the highest intercepted radiation use efficiencies (RUEs) of any plant species, allowing it to grow rapidly under optimal conditions producing multiple crops per year (Table 1). Sweet sorghum is cultivated from seed and, as listed in Table 1, has considerably less water and fertilizer requirements than both sugarcane and sugar beets. With current changes in climate and greater incidences of droughts around the world, sweet sorghum could become a much more useful agricultural crop. Additionally, Woods (2000) reported that sweet sorghum’s real potential lies in its ability to grow under sub-optimal conditions, e.g., non-arable and marginal lands, where the combinations of high RUE and high water and nutrient use efficiencies allow it to continue to produce a sugar and fiber-rich stalk where other crops would struggle. It needs to be noted that the lower crop and sugar yields for sweet sorghum compared to sugarcane and sugar beet in Table 1, are more a reflection of the much less research and development efforts put into sweet sorghum, including breeding for new cultivars, and consequently there exists a huge potential for

improvement. Some researchers (Cutz and Santana 2014; Kim and Day 2011) have advocated the processing of sweet sorghum at the front or back end of the sugarcane season to make more economical use out of the in-place sugarcane factory infrastructure.

Feedstock Compositions

The approximate composition of the juice extracted from each of the three sugar crops is listed in Table 2. As a general rule, sugar beet contains (based on total sugar solids) 98.9% sucrose, 0.12% fructose, and 0.12% glucose, sugarcane contains 94% sucrose, 3% glucose, and 3% fructose, and sweet sorghum contains 80% sucrose, 10% glucose, and 10% fructose (Table 2). Variations to these values exist because of differences in cultivar, seasonal, environmental, and regional conditions. Since sugarcane contains considerably more impurities than sugar beets, it precludes the manufacture of white sugar without further decolorization steps in a refinery (Table 2). The considerably lower amount of invert sugars and higher amount of nitrogen-containing compounds in beet than cane allow them to be deliberately degraded at higher alkaline pH processes in beet-sugar manufacture to prevent Maillard color reactions (Clarke et al. 1997). The high relative content of glucose, fructose, starch, and aconitic acid in sweet sorghum currently makes the manufacture of white sugar from this sugar crop technoeconomically unfeasible (Table 2). This partially explains why sweet sorghum for syrup production remains a small-scale industry. Additionally, the high content of invert (glucose and fructose) sugars in sweet sorghum precludes the

Table 2 Approximate juice compositions from sugar crop feedstocks

Parameter	Sugarcane	Sugar beet	Sweet sorghum	References
Juice Brix (%)	10–20	17–22	9.3–20	Clarke (1993); Kim and Day (2011);
Juice Purity (%) [*]	~80–85	~88–93	~75	Avram-Waganoff and Morgenroth (2019)
Sucrose (% on total sugars)	94	98.9	80	Bohn et al. (1998)
Glucose (% on total sugars)	3	0.12	10	Bohn et al. (1998)
Fructose (% on total sugars)	3	0.12	10	Bohn et al. (1998)
Polarimetry to measure apparent sucrose content	✓	✓	X	Imbachi-Ordonez et al. (2023)
Nitrogenous compounds (% on solids)	0.3–0.6	1.0–1.2	0.2–0.9	Clarke (1993); Bohn et al. (1998)
Prevalent processing pH	Slightly acidic	Alkaline	Slightly acidic	Clarke et al. (1997)
Total starch (% on soluble solids)	Up to 0.6	None	Up to 1.8	Eggleston et al. (2017)
Aconitic acid	Moderate	None	High	
Natural phenolic colorants	High	Low	Very high	Eggleston et al. (2021a, b)
Processing-derived colorants	Moderate ^a	High	Moderate ^a	
White sugar production	✓	✓	X	

^{*}Purity is sucrose/Brix × 100. Purity values are approximations and can vary markedly from country to country, within country, and from factory to factory

^aProcessing-derived colorants in sugarcane and sweet sorghum are highly dependent on processing conditions in individual factories and are mainly melanoidins, caramels, and melanins. During sugarcane processing, a small amount of processing-derived colorants are formed from the alkaline degradation of invert sugars during juice liming (Davis 2001)

use of polarimetry as a simple measure of apparent sucrose, a technique which is still used worldwide in both the sugar beet and sugarcane industries, particularly for crop payments to growers (Imbachi-Ordonez et al. 2023). This is because polarimetry, although rapid and precise, is an indirect measurement of sucrose since other optically active components, i.e., invert sugars, can contribute to and skew the “pol” value. The greater the concentration of invert sugars the less accurate is the apparent pol value.

One of the most profound differences between beet and cane-sugar processes is that in white sugar manufacture, the colorants are more easily removed during the beet process, and this is discussed in more detail in the next section.

Sugar Crop Processing: Similarities and Differences

The industrial processes for extracting and manufacturing sugar from sugarcane (Fig. 4) and sugar beet (Fig. 5) have both similarities and differences that are important to understand how to specifically tailor sustainability efforts for each crop. In Table 3 are listed typical production parameters for sugarcane and sugar beet processing which further highlight the main technological differences between these two large-scale sugar industries.

Six major differences between the processing of sugarcane and sugar beets are:

1. There is considerably less glucose and fructose in sugar beet than sugarcane which allows the processing pHs to be mostly alkaline in beet factories (Table 2)
2. The amount and types of color produced during beet processing compared to sugarcane processing, which allows the direct processing of beets into white sugar (Table 2)
3. Sugarcane factories are essentially self-sufficient in fuel because they can burn bagasse (fibrous by-product), whereas the beet factory does not produce a consumable by-product for fuel
4. Most (but not all) cane-sugar factories still employ tandem roller mills for juice extraction that require large amounts of power and extensive maintenance, whereas the beet industry universally employs continuous diffusers
5. Juice purification tends to be more simple in sugarcane than sugar beet processing with less lime (CaO) consumption (Table 3)
6. Globally, steam consumption is considerably higher in the processing of sugarcane compared to sugar beets (Table 3).

Traditionally, raw sugar is manufactured at the sugarcane factory and white, refined (cane) sugar at the refinery. Sometimes the refinery is far removed from the factory but close

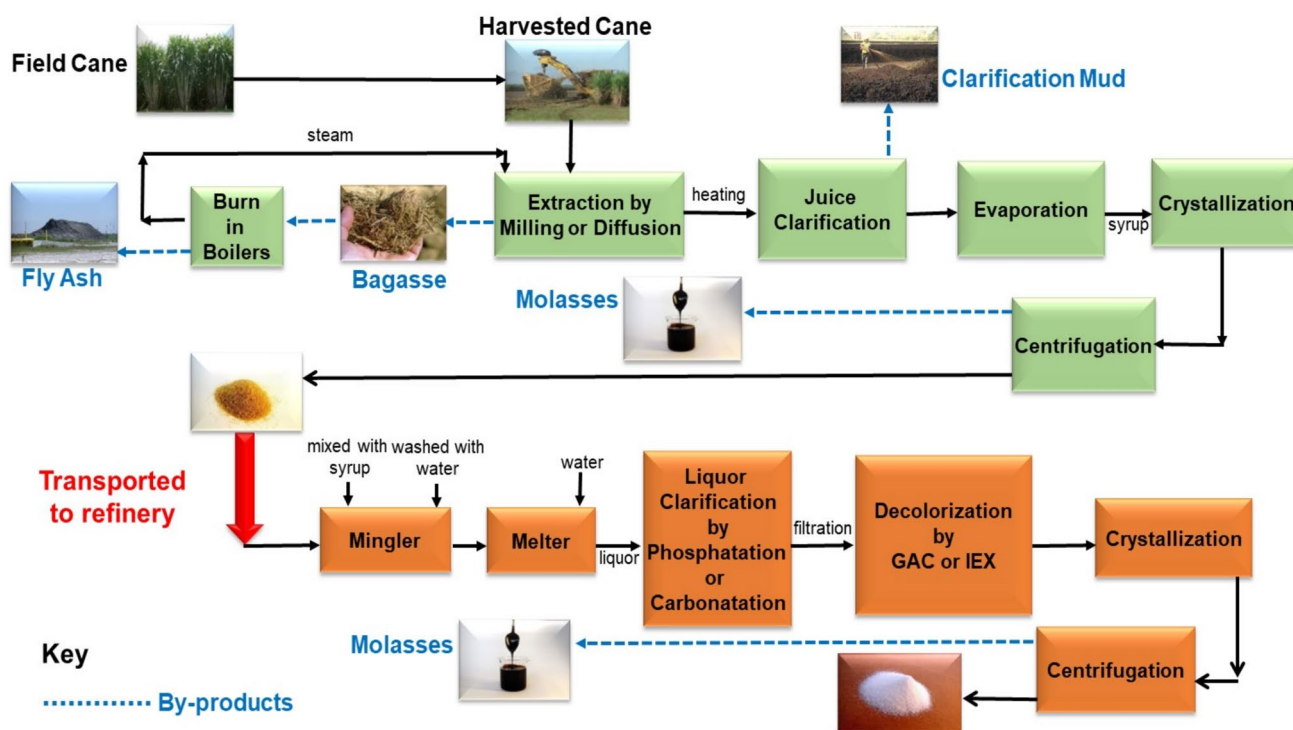


Fig. 4 Production flow scheme for raw sugar at a factory and refined sugar at a refinery. GAC=granular-activated carbon and IEX=ion exchange resins

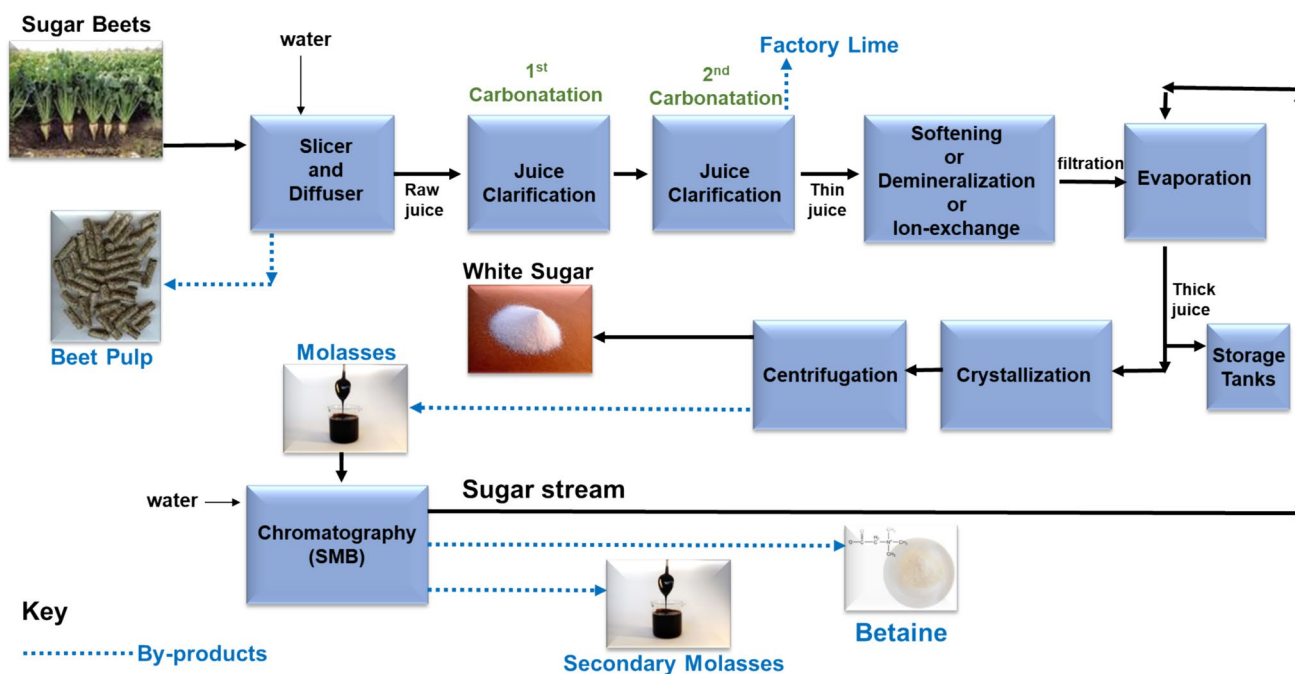


Fig. 5 Production scheme for white sugar manufacture at a sugar beet factory. SMB = simulated moving bed chromatography

Table 3 Key manufacturing values for the large-scale processing of sugarcane and sugar beets

Production parameter	Sugarcane	Sugar beet
Final syrup purity (%) [*]	80–90	90–95
A-sugar color (ICU)	120–1500	22–45
Overall sucrose recovery (%)	80–85	84–90
CaO consumption (% on cane or beet)	0.04–0.08	1.2–2.0
Steam consumption (% on cane or beet)	35–65	20–30
Electrical power consumption (kW h/t)	12–30	22–30
Manning level in factory (No. of persons)	~150–1000	~150–300

Most but not all values are from Avram-Waganoff and Morgenroth (2019). The stated values will vary from country to country

These are typical values found in the worldwide sugar industry. Avram-Waganoff and Morgenroth (2019), however, did not state the geographical sources of the values

^{*}This is known as thick juice in sugar beet processing

to the areas of consumption (Eggleson et al. 2017). Generalized flow schemes for the processes at the sugarcane factory and refinery are illustrated in Fig. 4. To summarize, juice is extracted from the harvested sugarcane with either tandem roller mills or a diffuser; the juice is clarified with heat and lime, concentrated with vacuum evaporation, crystallized, and centrifuged. The final product of raw sugar is subsequently transported to a refinery, melted, and subjected to similar unit processes with an additional decolorization polishing step after syrup clarification, to produce white, refined sugar (Fig. 4). For more details of these unit processes the

reader is referred to Eggleson et al. (2017), Chou and Chen (1993), and Van der Poel et al. (1998).

The main unit processes of sugar beet processing are similar to those for sugarcane (compare Figs. 4 and 5), but, unlike for sugarcane, white sugar production is a one-stage, direct process. In summary, sugar beet processing includes the storage of harvested beets until needed, washing, slicing, and extraction of juice by diffusion only. The juice is then clarified using lime and carbon dioxide, filtered, concentrated with vacuum evaporation, crystallized, and centrifuged. A major difference to sugarcane is that often a portion of the thick juice (final evaporator syrup) from sugar beet processing is diverted for storage in large tanks to extend the beet campaign (Fig. 5). The alkaline nature of thick juice and lower invert concentrations, when compared to sugarcane syrup, make it more conducive to storage, but treatments such as surface sealants are still required (Hatch et al. 2013).

Another major difference to sugarcane processing is that during sugar beet processing, the resulting molasses after centrifugation is subjected to an industrial, ion exchange chromatography procedure, e.g., simulated moving bed chromatography (SMB), to recover additional sucrose. Molasses desugarization using ion exchange chromatography is usually continuous and up to 90% of the sucrose in the beet molasses can be recovered as well as other valuable products, e.g., betaine (Eggleson et al. 2017). The recovered sucrose fraction named “extract” is subsequently sent to the crystallization pans, mixed with thick juice, and crystallized or is further purified and sold as liquid sugar (Fig. 5). In

strong contrast, desugarization of cane molasses does not occur because it is more technically difficult and less economical for several reasons. First, it has a lower content of sucrose (~35% on a dry basis) than beet molasses (~60% on a dry basis). Second, sugarcane molasses contains a markedly higher amount of glucose and fructose sugars. Thirdly, sugarcane molasses is more viscous than beet molasses due to a greater amount of impurities, especially polysaccharides. Fourthly, cane molasses contains a lot more suspended material. Fifthly, cane molasses contains higher salt and calcium concentrations which have to be “softened” before being added to the chromatography resin (Eggleston et al. 2017).

As stated earlier in this article, most sweet sorghum is currently used for the small-scale production of syrup and a flow chart of this uncomplicated process is illustrated in Fig. 6a. Processing is relatively simple with the harvested sweet sorghum (usually whole stalks) being passed (single or double pass for additional juice extraction) through a small roller mill to extract the juice. The resulting juice is clarified by the action of heat, which forms a scum that is skimmed off the surface during open-pan evaporation (Fig. 6a). A small amount of research and development has gone into the creation of a larger-scale syrup manufacturing industry for sweet sorghum, to exploit the syrup as a feedstock for the subsequent production of food and non-food grade bioproducts and biofuels, shown in Fig. 6b (Eggleston et al. 2016). The relatively large amount of starch in the sweet

sorghum presents a major technical problem at the large-scale (Eggleston et al. 2016). Unfortunately, adding amylase to control the starch is not recommended since most of the troublesome starch is in the insoluble form. Eggleston et al. (2016) unequivocally showed that multiple process strategies for the physical removal of starch can reduce the concentration of insoluble starch to a satisfactory level. An initial strategy is to remove the starch-rich seed heads while harvesting. Settling of coarsely filtered juice, previously de-aerated with a vacuum pump, can precipitate out some, but not all the insoluble starch (Fig. 6b). Subsequent clarification of the settled juice at 80 °C, liming to ~pH 6.5 (temperature and pH are lower than in sugarcane juice clarification to preserve the sugars), and addition of a small dose (5 mg/L) of polyanionic flocculant can precipitate out further starch in the mud. A final filtering of the clarified juice through simple sand filters will ensure no problems with starch during vacuum evaporation (Fig. 6b). An additional benefit of the large-scale clarification process in Fig. 6b is that the resulting clarified juice is stable for a minimum of 48 h which gives much needed process flexibility (Eggleston et al. 2016). Cost-effective, long-term storage, and transport technologies are also available for the storage of bulk syrup to extend the year-round supply; this includes vegetable oils and candelilla wax (Eggleston et al. 2015).

Since sugar beets, sugarcane, and sweet sorghum are rich sources of simple sugars, they are all susceptible to microbial deterioration when injured, e.g., after cutting

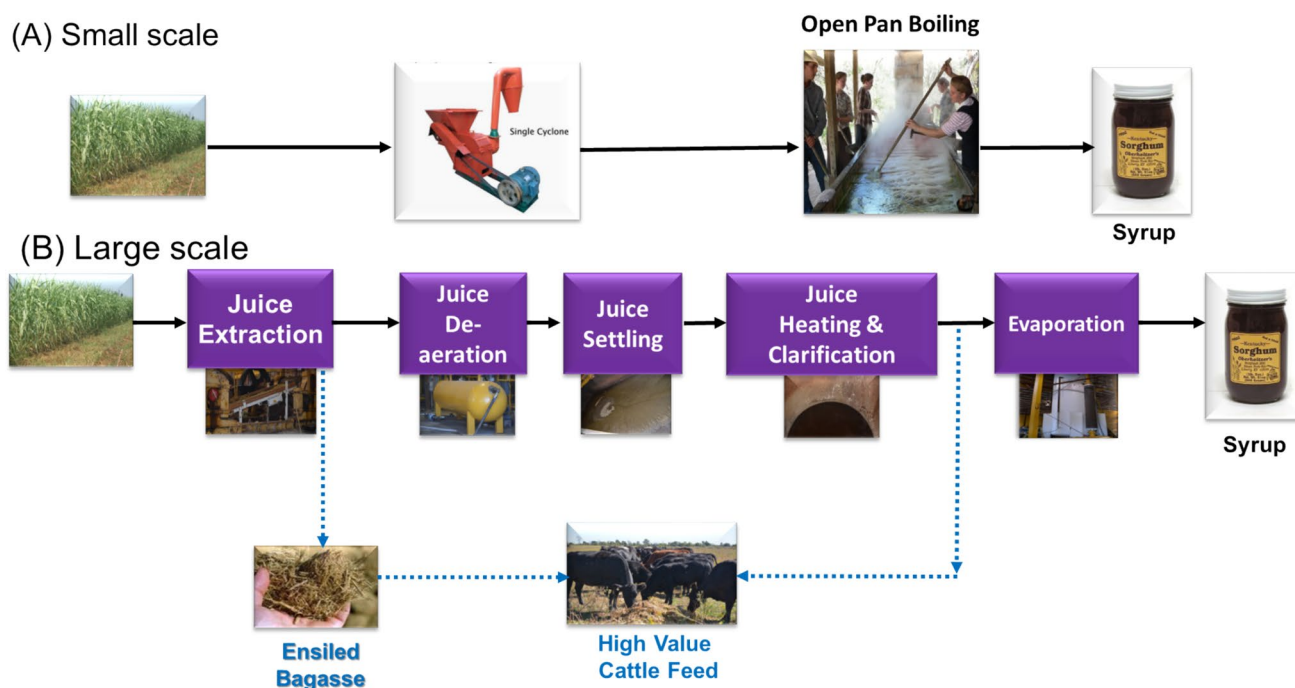


Fig. 6 Processing of sweet sorghum for syrup production on a **a** small scale and **b** large scale. The large-scale processing information was taken from Eggleston et al. (2016) with permission

during harvesting or during storage, particularly (but not solely) from *Leuconostoc* sp. lactic acid bacteria (Eggleston 2002; Eggleston and Huet 2012; Lingle et al. 2012; Qi et al. 2023; Malick et al. 2024). Not only does microbial activity cause the loss of valuable sugars but deterioration products which form can negatively affect processing, e.g., dextran (α -1 $\rightarrow$ 6-D-glucan) that can detrimentally affect crystallization rates and crystal shapes (Eggleston 2002). The application of dextranase can mitigate the negative effects of dextran, and this is an area of research which has overlapped both sugarcane and sugar beet industries (Eggleston and Huet 2012). To the best of the author's knowledge there are no known publications on the use of dextranase in sweet sorghum processing, most likely because there is no large-scale industry for this crop yet.

Integrated or Dual Production of Sugar from Sugar Beets and Sugarcane

In recent years, the integrated processing of sugar beets and cane for the manufacture of refined sugar has been investigated in select countries where both crops can be grown, and are now a reality, for example, in Pakistan (Avram et al. 2007; Avram-Waganoff and Morgenroth 2019). At least two impetuses for this are: (i) water scarcity and (ii) extending the annual operating time of the factory which in turn increases profits (Avram-Waganoff and Morgenroth 2019). As shown in Table 1, sugar beet requires ~ 50–60% less water than is necessary for sugarcane cultivation which allows it to be considered as an alternative or complementary crop in select regions (Avram-Waganoff and Morgenroth 2019). Another advantage for sugar beet as a complementary crop is its higher sugar and lower impurity contents (Tables 2 and 3). An example of a successfully integrated, dual-use factory for the processing of sugarcane and sugar beets is Al Moiz factory in Western Pakistan, which processes sugarcane from December to March then sugar beets from April to June annually for the production of refined sugar (≤ 45 ICU). Maximum use is made of the equipment for dual use, e.g., same diffuser for the extraction of juice and downstream equipment after the evaporation station (Avram-Waganoff and Morgenroth 2019). Excess bagasse from the initial sugarcane crop is used as fuel for cane refining and beet processing, with enough left over for some cogeneration of electricity. More technical details can be found in Avram et al. (2007). Such a dual-use plant has allowed for the increased production of sugar, molasses, sale of electricity, and beet pulp as a valuable animal fodder (Avram-Waganoff and Morgenroth 2019).

Fibrous By-products of Sugar Crops

For all three sugar crops, there is a fibrous by-product after juice is extracted (Figs. 4, 5, 6). Since sugarcane and sweet sorghum are both grasses, their fibrous by-product is named bagasse, while the fibrous residue from sugar beet is named pulp. In general, sugarcane, sugar beet, and sweet sorghum field plants contain ~ 13.5, 6.1, and 16.4% fiber/pulp, respectively. Most beet pulp is pelletized and used for animal (cattle) feed. In contrast, most of the sugarcane bagasse is burnt in boilers at the factory to produce steam energy which drives the factory (Fig. 4). Boilers are becoming more efficient meaning that surplus quantities of bagasse are on the rise. Nowadays, in quite a few countries and regions, e.g., Brazil, Mauritius, and Florida (USA), sugarcane bagasse is also used for the cogeneration of electricity, with some electricity sold to the local utilities grid, but this is very much reliant on local and national economics. When cogeneration is not possible, other value-added uses for the bagasse can be investigated; some re-use and conversion technologies were published in a recent review by Lima and Beacorn (2022a,b). It must be noted that beet pulp can be burnt in the same way as bagasse to produce all the energy for the factory, but it is worth more as an animal feed and, therefore, an important part of the human food chain.

As listed in Table 4, there are major differences in the composition of these fibrous by-products which dictate their final end use. Compared to sugarcane, sweet sorghum bagasse and sugar beet pulp contain considerably more protein, making these by-products more valuable as animal feed. The relatively high protein content of sweet sorghum also suggests that it may be too valuable to be burnt. Sugar beet pulp contains valuable pectin polysaccharides with unique functionalities which have been explored as food ingredients (Hotchkiss et al. 2010). Other polysaccharides including alkaline soluble polysaccharides (ASP) and cellulose have also been extracted sequentially with a microwave heating source under pressure. ASP has potential as a bioactive food ingredient, and the cellulose can be converted to carboxymethyl-cellulose (CMC) which has markets in adhesives, paper products, battery manufacture, drug delivery, dairy substitutes, fat replacement, antibiotic stabilizer, and laxatives (Hotchkiss et al. 2010).

In 2020, Crown van Gelder and Cosun Beet Company in Europe announced a new method to make paper and packaging materials from beet pulp as a sustainable alternative to wood fibers, and Cosun Beet will use the sugar beet paper to pack its 25-kg industrial bags of sugar (Anon 2020). This fits well into the circular sustainability of this crop as illustrated in Fig. 2. Moreover, food and beverage companies, in their sustainability improvements, see packaging as an easy, initial step with “reduce, reuse, and recycle” being their mantra for many years (Hanacek 2024).

Table 4 Approximate compositions of the fibrous by-products from sugarcane, sugar beet, and sweet sorghum

Component	Sugarcane bagasse % dry weight	Sugar beet pulp	Sweet sorghum bagasse	References
Cellulose	26–57	18–52	27–45	Kim and Day (2011), Cronewitz et al. (1998), Appiah-Nkansa et al. (2019), Chen (1993)
Hemicellulose	19–33	18–32	25–27	Kim and Day (2011), Cronewitz et al. (1998), Appiah-Nkansa et al. (2019), Chen (1993)
Lignin	14–32	3–16	11–25	Kim and Day (2011), Cronewitz et al. (1998), Appiah-Nkansa et al. (2019), Chen (1993)
Pectin	0	15–32	Unknown	Eggleston et al. (2020), van der Poel et al. (1998)
Protein	≤ 0.2	5–10.4	7–12	Kurella et al. (2022), Cronewitz et al. (1998)
Ash	1–8	3–12	0.4–3.2	Kim and Day (2011), Lima et al. (2017), Cronewitz et al. (1998), Appiah-Nkansa et al. (2019), Chen (1993)
Residual sugar*	~ 1.1	2–6	Unknown	
Fuel value MJ/kg (low and high heating fuel values)	15–17	7–18	4.2–19.2	Cutz and Santana (2014); Lima et al. (2017), Appiah-Nkansa et al. (2019)

*The amount of residual sugar left in the fibrous by-product is highly dependent on processing efficiency

The other major by-products of sugarcane and sugar beet processing are molasses. Beet molasses is typically sold for animal feed, and sugarcane molasses is sold for animal feed and as a fermentation feedstock because it contains considerably more sugar than beet molasses after sucrose recovery. Other, less major by-products are also created during sugar manufacture, i.e., clarification mud and fly ash at the sugarcane factory, and construction products, biogas, lime fertilizer, and heating at the beet factory. A full discussion of all these by-products is outside the scope of this paper, but the reader is referred to Van der Poel et al. (1998), Godshall (2010), Parkin and De Bruijn (2010), and Aita et al. (2024).

Other Quality Differences

Refined, white sugar produced from sugarcane and sugar beets is very similar in quality as both are approximately 99.9% pure (Eggleston et al. 2017). Unlike for sugar beets, a large variety of brown centrifuged or non-centrifuged sugars are manufactured from sugarcane around the world, which offer greater nutritional and health profiles to consumers when compared to refined sugar (Eggleston et al. 2021a, b; Azlan et al. 2022). Such less-refined sugars contain more natural phytochemicals (typically natural phenolic colorants that have originated in the field sugarcane) and fiber (Wahlqvist et al. 1998) that slowly digest and reduce glycemic responses in humans (Ebadi and Azlan 2021; Jaffe 2012). Consumers are increasingly demanding these types of natural sugars for both nutritional and sustainability reasons. Azlan et al. (2022) reported a study comparing the human effects of cane brown sugar BS, minimally refined (cane) brown sugar MRBS, refined sugar RS, and glucose.

Results allowed the authors to categorize BS and MRBS as low GI (glycemic index) and RS as medium GI (but still significantly lower than glucose). Additionally, BS and MRBS had better satiety and total antioxidant capacities (TAC) than RS. It is interesting to note that in a recent study of common food grade syrups in the USA by Eggleston et al. (2021a, b), sweet sorghum syrups were observed to be comparatively rich dietary sources of phenolic antioxidant colorants, even greater than sugarcane syrups. Such phenolic antioxidants in both sugarcane and sweet sorghum need to be further exploited.

Conclusions

Sustainability is a multi-faceted concept involving the three pillars of the environment, society and social responsibility, and economic viability, all of which are interdependent and have to be balanced. For instance, the economic sustainability that can be derived by reducing sugar and quality losses from cut-to-crushing (harvesting-to-processing) by both growers and processors, can represent new opportunities to further invest in environmental sustainability practices. Ultimately, for each sugar crop (sugarcane, sugar beets, and sweet sorghum) the understanding of their similarities and differences is fundamental for the implementation of tailored sustainable practices for the benefit of the grower, processor, refiner, and consumer.

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Data Availability The datasets used during the current review study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no conflicts of interest.

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