INCREASED PROFITABILITY THROUGH PRODUCT DIVERSIFICATION AND IMPROVED SUGAR QUALITY

By

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Abstract

THE PROPOSED simplified Integrated Sugar Production Process (ISPP) using membrane technology would allow the sugar industry to produce new product streams and higher quality mill sugar with increased sugar extraction efficiency. Membrane filtration technology has proven to be a technically sound process to increase sugar quality. However commercial viability has been uncertain partly because the benefits to crystallisation and sugar quality have not outweighed the increased processing cost. This simplified ISPP produces additional value-added liquid streams to make the membrane fractionation process more financially viable and improve the profitability of sugar manufacture. An experimental study used pilot scale membrane fractionation of clarified mill juice confirmed the technical feasibility of separating inorganic salt and antioxidant rich fractions from cane juice. The paper presents details on the compositions of the liquid streams along with their potential uses, values and challenges in getting these products out to market.

Introduction

White cane sugar for consumption is mostly produced in a two-stage process, namely the production of raw sugar and the production of refined sugar. The raw sugar is typically produced at a sugar mill, where sugarcane stalks are crushed in a series of millings to extract the juice.

The juice is normally limed and clarified to remove suspended solids. The clarified juice is then evaporated to thick syrup, and crystallised in a vacuum pan. The washed crystal sugar separated from mother syrup is termed ‘raw sugar’. The syrup remaining after multiple stages of crystallisation and centrifugation is referred to as ‘cane mill molasses’.

Typically, 6–8% sugar present in the cane juice is lost in molasses at the mill operation. The raw sugar is then transferred to the sugar refinery for further purification. The refining process consists of affination, clarification, filtration, decolourisation (activated carbon or ion exchange), crystallisation and recovery. The intensity and the number of purification steps used depend on the quality of the raw sugar being processed. The syrup remaining after the multiple stages of crystallisation and centrifugation is referred to as ‘cane refinery molasses’.

This molasses produced in sugarcane mills and in subsequent refineries contains a substantial amount of sucrose. The conventional refinery process which is employed to produce refined white sugar is capital and energy intensive, though it is robust and reliable for mass production of very high quality white sugar.

The mixed juice extracted from cane is often considered to simply be a solution of sucrose in water. However, a variety of other extractable compounds that potentially have significant economic value are also present in the mixed juice. The typical composition of mixed juice extracted from sugarcane is detailed in Table 1. Sugarcane juice has also been reported to contain various bioactive compounds including phenolic acids and flavonoids (Singleton *et al*., 1999; Saska and Chou, 2002; Colombo *et al*., 2006; Duarte-Almeida *et al*., 2006).

Table 1—Cane juice composition based on solids (Walford, 1996).

Fraction	Component	Content (% w/v)
Sugars	Sucrose	81–87
	Reducing sugars	3–6
	Oligosaccharides	0.06–0.6
	Polysaccharides (including gums and dextrans)	0.2–0.8
Salts	Inorganic salts:	1.5–3.7
	Potassium (K_2O)	0.77–1.31
	Sodium (Na_2O)	0.01–0.04
	Magnesium (MgO)	0.10–0.39
Organic non-sugars	Organic acids	0.7–1.3
	Amino acids	0.5–2.5
	Dextrans	0.1–0.6
	Starch	0.11–0.5
	Gums	0.02–0.05
	Waxes, fats, phospholipids	0.05–0.15
	Colourants	0.1
Insolubles	Sand, bagasse, etc.	0.15–1.0

The total polyphenolics content of sugar cane juice was found to be as high as 695 mg/L (Colombo *et al*., 2006). In conventional mill processing operations these bioactive compounds undergo oxidative reactions and are partly converted to polymerised phenolics. They are mostly concentrated into the molasses fraction together with other remaining non-sugar organic compounds, salts, reducing sugars and oligosaccharides present in the clarified juice. Molasses is a by-product of the crystallisation process in both the sugar mill and refinery operations. Sugarcane molasses consists typically of 35% sucrose, 15% invert sugar, 10% ash, 5–10% non-sugar organic compounds and 18–25% water. It is primarily sold for low value applications such as cattle feed and for alcohol production (Lipnizki *et al*., 2006). The high concentration of non-crystallising sucrose and sucrose hydrolysis products reduces the sugar recovery from the sugarcane juice which is related to the inhibitory effects of ionic components in the ash and non-sucrose components. Furthermore, the adverse effects of high molecular mass components and increased viscosity on processing efficiency are also well documented (Jansen, 2009). Membrane processes have been suggested as an alternative approach to conventional mill processing to overcome these issues.

Membrane filtration processes

Membrane filtration is a powerful separation technique which is widely employed in water treatment, beet sugar processing and the dairy industry. Membrane filtration technology has been proven to be a technically sound process to improve the quality of clarified sugarcane juice and subsequently to increase the productivity of crystallisation and the quality of sugar production (Kwok, 1996; Fechter *et al*., 2000; Saska, 2000; Chung and Kwok, 2004; Fechter *et al*., 2004; Chou *et al*., 2006).

In contrast to the sugarcane industry, the beet sugar industry has long since successfully moved away from stand–alone refineries to produce white sugar directly from beet juice thanks to resin-based separation technologies such as demineralisation, softening, decolourisation and chromatography.

The application of similar technology to the sugarcane industry has resulted in a range of premium quality raw sugars for direct consumption. Some of the direct white sugar processes developed over the years are listed in Table 2 (Jensen, 2007). However, commercial application has not been financially viable because the benefits to crystallisation and sugar quality have not outweighed the increased processing costs.

Table 2—Comparison of the resin-based filtration processes for white sugar production.

	NAP Process	ARI Process	ABC Process	WSM Process
Reference	(Kwok, 1996)	(Kearney, 1996)	(Monclin, 1996)	(Fechter *et al*., 2001)
Softening	X	X		
Demineralisation				X
Decolouration	X			X
Chromatography		X		
Adsorption			X	

Simplified sugar production process

The ‘Integrated Sugar Production Process (ISPP) Concept Model’ (Wijesinghe *et al*., 2009) has been developed to overcome the cost issues associated with membrane applications. The approach is to use membrane filtration of cane juice to produce commercial, value added liquid streams while improving sugar yield and quality from the purified juice stream sent to crystallisation.

The objective of the ISPP is that the income from the value-added products will make the membrane filtration processes financially viable and improve the profitability of sugar manufacturers. A number of sequential membrane processes were incorporated into the model for progressive removal of high molecular weight to low molecular weight constituents in the juice that adversely affect sugar crystallisation and quality.

The ISPP model has been further simplified to result in more economically feasible options with fewer steps for the separation of select constituents for value adding. The simplified model is schematically presented in Figure 1, where it is compared with the traditional mill process and a patented membrane filtration process for white sugar production at the mill (Fechter *et al*., 2004).

In the proposed method the impure sugar juice extracted from clean cane billets would not be subjected to the conventional clarification process of heating, liming and settling. A brief heat treatment at 80^0C to control microbial and enzymatic activity followed by coarse filtration prior to microfiltration was found to be satisfactory to stabilise fresh cane juice for further processing. However lime clarified juice can also be used as the feed to the new process.

A number of direct white sugar production processes have used membrane filtration in combination with resin-based separation technology (Table 2). In all these processes the microfiltration (MF) membrane occurs after conventional clarification of raw cane juice. WSM technology, using membrane filtration and adsorption resins, was piloted successfully in South Africa in 2005.

It has been reported that the main component of the cost of production was associated with ion-exchange demineralisation. It also stressed that while the membrane filtration costs were not insignificant, it was the demineralisation chemical costs that governed the economics of the WSM process (Jensen, 2007). This suggests that membrane-based technology with no chemical usage could become competitive if the high investment cost associated with membranes and the performance (acceptable flux) issues can be mitigated.

The original ISPP model has been simplified to two membrane separation stages after pre-filtration of clarified juice to improve the economic viability of the process. The required pre-filtration could be achieved by 0.1 micron MF. The tubular stainless steel MF membranes have been successfully tested in the mill environment with up to 170 L/m^{2}h (Steindl and Doyle, 1999).

As shown in Figure 2, the MF permeate is directed to membrane concentration where it is concentrated to 25 Brix.

This level of concentration is easily achievable using reverse osmosis (RO) membranes under moderately low pressure of about 30 bar. Membrane concentration to 25 Brix offers three distinctive advantages over conventional evaporation in addition to potential energy saving when compared to conventional process.

1) By selecting appropriate RO or nano-filtration (NF) membranes with appropriate molecular-weight-cut-off (MWCO) it is possible to reduce the ash load in sugar syrup by about 30% and thereby effect substantial improvement in both the quality and crystallisation efficiency of the mill sugar.

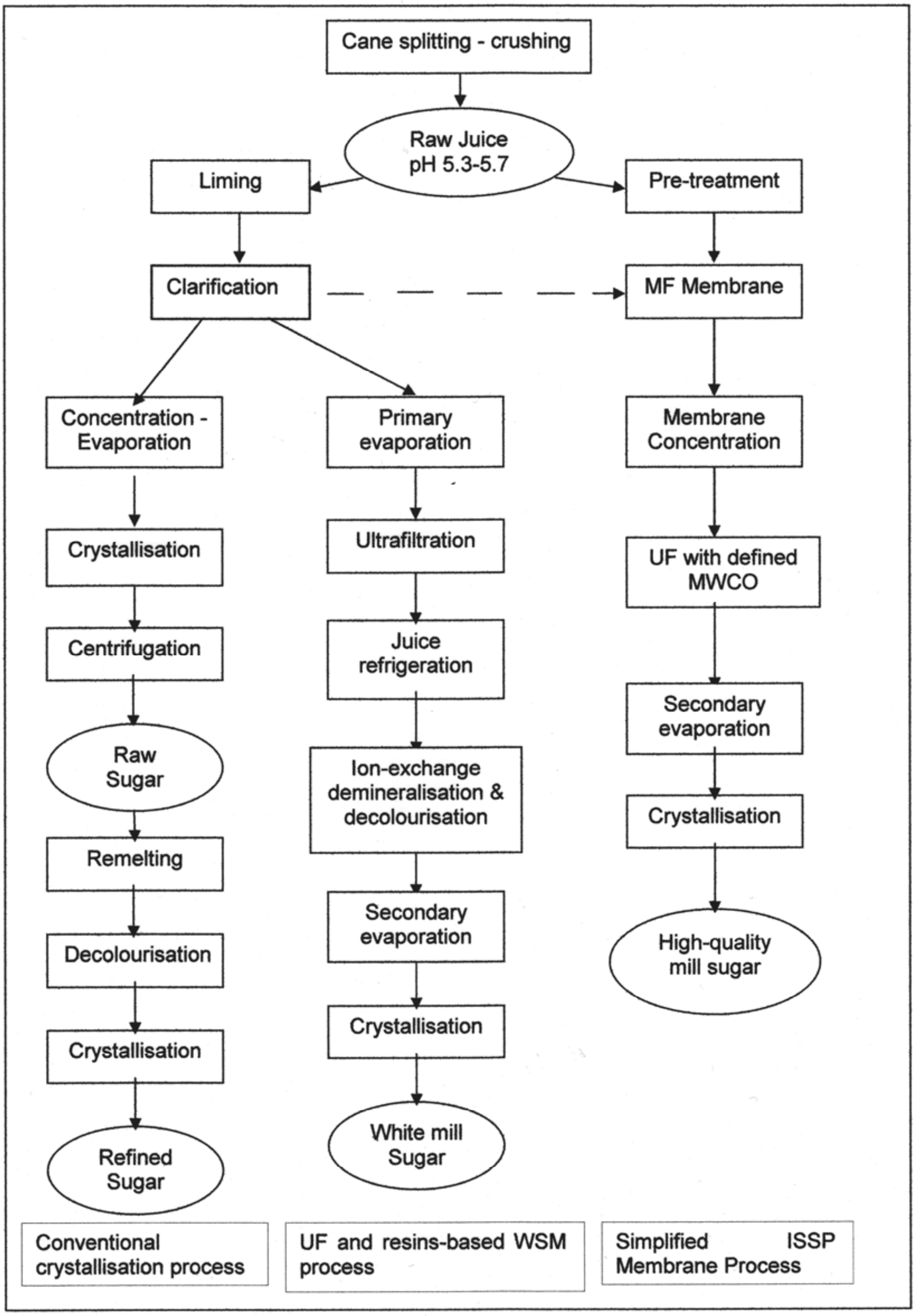

Fig. 1—Comparison of conventional, resin based and membrane processes.

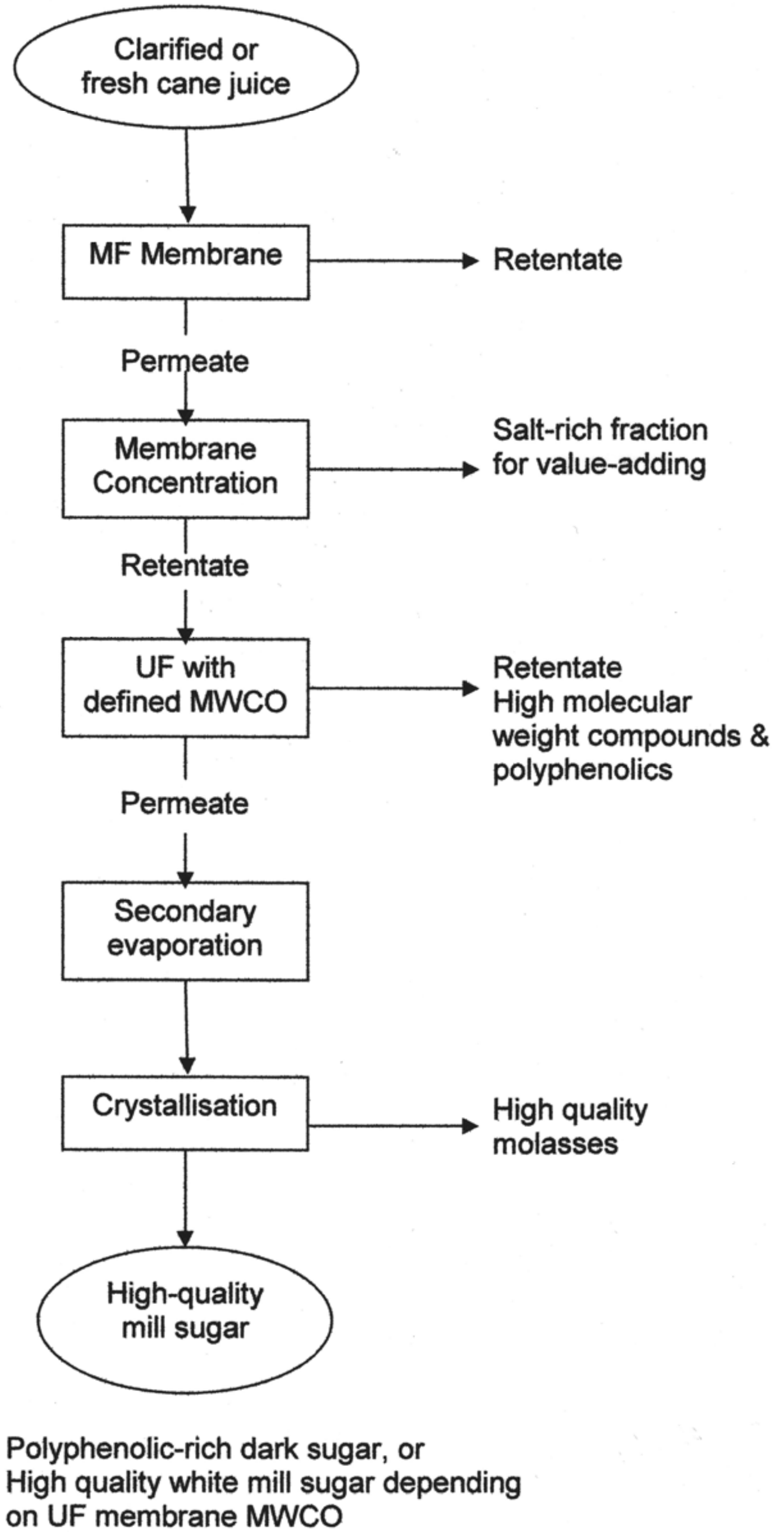

Fig. 2—Simplified ISSP membrane process details.

2) Having membrane concentration prior to RO could reduce the capital cost of the subsequent Ultra-Filtration (UF) module substantially due to the resulting throughput reduction. Mass balance calculations based on a throughput of 1000 kg/hr of clarified juice at 14.42 Brix given in Table 3 shows that the throughput is nearly halved (from 950 to 450 kg/hr).

3) The permeate fraction rich in potassium salts could be recovered to recycle the potassium for food or plant nutrient use.

Table 3—Mass balance computation for simplified membrane process depicted in Figure 2 (Basis: 1000 kg/hr clarified juice).

Flow/fraction description	Flow quantity process (kg/hr)	Total sugar content (kg/hr)	Total salt content (kg/hr)
Clarified juice	1000	144.2	1.2
MF retentate	50	7.2	0.06
MF permeate	950	135.1	1.16
RO retentate	450	126.7	0.72
RO permeate	500	7.75	0.44
UF retentate	23	6.3	0.04
UF permeate	427	120.4	0.68

The retentate from the membrane concentration unit is then fed into the UF. By selecting an appropriate UF membrane with a defined MWCO it is possible to remove all high molecular weight compounds and a maximum of 70% (compared to the RO concentrate) of the colouring material from the juice leaving high quality mill sugar syrup for further processing.

Alternatively a defined MWCO membrane could be used for selective removal of high molecular compounds and some of the colourants to result in the production of a polyphenolics-rich high quality mill sugar.

If the UF membranes are selected to achieve maximum colour removal, the permeate from UF has 40% less monovalent salts and 63% less colourants than the clarified juice. This semi-concentrated high quality sugarcane juice can be directed to secondary evaporation and subsequent crystallisation as in conventional mill process to yield high-quality mill sugar and molasses.

The molasses fraction can be subjected to diafiltration using defined MWCO membranes to remove about 50% of remaining monovalent salts and produce high quality sugar syrup for food applications.

Saleable liquid streams and economic feasibility

The simplified ISPP has fewer stages than any membrane integrated sugar production process known to us. It does not incorporate any resin-based separation processes, hence does not have any direct chemical usage. A further feature of the simplified ISPP is that it results in two distinct fractions that can be used as value-added ingredients in functional products. Important compositional features of these two fractions are given in Table 4.

Table 4—Important compositional information of saleable fractions.

	Clarified mill juice	Potassium–rich fraction	Polyphenolics–rich fraction
Sugar (% w/v)	14.42	1.55	25
Salts of interest: (mg/kg)			
Potassium	98.6	73.9	1.53
Sodium	10.0	10.0	20.0
Magnesium	1.23	3.3	2.6
Polyphenols (g Catechin Eq/L)	~1.222	0.072	1.483

Potassium–rich fraction: This is the largest fraction and represents about 45% of original mass of the cane juice but having only 1.55% of sugar and approximately 80% of the monovalent salts in the original juice. Membrane optimisation to eliminate the sugar and concentrate the salts would allow this fraction to be treated as a source of sugar-depleted natural potassium salts for beverage or plant nutrient applications with a corresponding value.

Polyphenolics–rich fraction: Sugarcane-derived products have been reported to contain various bioactive compounds including phenolic acids and flavonoids (Saska and Chou, 2002; Takara *et al*., 2002; Duarte-Almeida *et al*., 2006; Payet *et al*., 2006; Nakasone *et al*., 1996) which could account for certain antioxidant activity. Non-centrifuged cane juice extracts and blackstrap molasses have been found to have various physiological effects such as promotion of resistance against viral and bacterial infections, stimulation of immune response, protection against liver injuries and growth promotion in chickens (Koge *et al*., 2001, 2002; Nagai *et al*., 2001). Separation of these compounds from molasses and from sugarcane syrup has attracted considerable interest (Chou, 2002).

The role of dietary antioxidants in protecting tissues and cells against harmful effects of free radicals has been well publicised and numerous products extracted from natural sources are now available as dietary supplements. The market in developed countries for antioxidant rich supplements and fortified drinks and snacks has advanced well into the mainstream.

This suggests that sugar cane derived natural antioxidants could provide a way to broaden the market reach for sugar products within the increasingly health-conscious population.

Based on the typical compositional data of mixed juice and with conservative assumptions, a factory processing 1 million tonne of cane per year would produce saleable fractions worth up to approximately $34 million in addition to high quality mill sugar. Some details of the potential value to the millers are given below.

- The K-rich permeate fraction worth up to $ 29 million (Assumptions: K^+ content in mixed juice 0.845 g/kg mixed juice with 27% recovery; saleable volume of the fraction – 30% of original juice volume; value of the fraction as a beverage base $0.10 per L; correction for sugar loss to this fraction at $300/t of sugar). In 2007 *Beveragedaily.com* estimated that the energy drink market was expected to reach

US$ 39.2 billion in value by 2010. Potassium is one of the main ingredients in energy drinks with a premium expected for natural sources of this salt.

- The flavonoid rich fraction worth up to $ 6 million (Assumptions: flavonoid content in mixed juice ~ 0.600 g/kg; recovery of 30%; value of antioxidants $30/kg; no correction for sugar loss). Plant based flavonoids are the primary source of beverage antioxidants and used in nutraceutical formulations to boost health properties.

The major factors that affect economic feasibility of membrane applications in the cane sugar industry are cost of required membrane area (a function of throughput and average flux), membrane life, membrane cleaning frequency (dependent on membrane fouling), membrane replacement cost and high sugar recovery. The model was developed with the primary focus to produce saleable liquid streams for value adding to compensate most of the capital and membrane replacement cost. By introducing membrane concentration at the early stage the throughput of the subsequent membrane could be reduced substantially, resulting in a much smaller ultrafiltration module.

However, this necessitates using the MF as a pre-filtration process and adds another capital cost but gives turbidity-free permeate for further processing. Pilot trials conducted with MF permeate at 38^0C achieved acceptable permeate fluxes in subsequent filtration with RO and UF. In both cases average permeate fluxes remained constant at about 22 L/m^{2}h during a 4-hour trial with full recirculation. Membranes that can operate at higher temperature could further improve permeate fluxes.

Some sugar losses with the membrane fractions withdrawn from the main production stream are inevitable. However, the value of the sugar in these fractions should be compensated for in the sale of the side streams for added value purposes. Alternatively, most of the sugar lost with the fractions could be minimised in a number of ways.

Sugar loss in MF retentate could be totally recovered by recirculating it back to the clarifier. This should not create any major operational problem as the separation characteristics of the MF retentate fraction is not much different (in terms of suspended solids) to mixed juice entering the clarifier. The sugar lost with the largest fraction (RO permeate – Table 3) could be accounted for in costing of this fraction as shown above in potential value of potassium rich fraction. More than half of the sugar lost in polyphenolic rich fraction (UF retentate) could be easily recovered by diafiltration using water to wash the sugar from this stream.

One major advantage of the simplified ISPP model is its ability to completely eliminate the molasses fraction through the introduction of a diafiltration processes with NF filtration and subsequent concentration to produce high quality sugar syrup for the bakery industry. It should also be noted that the high quality raw sugar produced in this way could be comparable to refined sugar, but with the total elimination of cost associated with the refining process. Hence the value premium created would improve the bottom line of the mill processors.

All the above measures could make the ISPP and economically feasible option to improve the returns from sugar processing. However the validation of the approach can only be achieved through pilot trials in collaboration with manufacturers who can develop new marketable products from the alternative process streams.

Conclusion

A simplified ISPP Model has been developed using membrane filtration of cane juice to produce multiple value added liquid streams, coupled with the associated benefits of improved sugar yield and quality from the retained juice stream sent to crystallisation. The technical feasibility of the model was evaluated using clarified mill juice at pilot scale. The potential value, based on improved recovery efficiency determined from trial runs and assumptions on the values of phenolic and potassium rich product streams, indicates that the combined returns could make the membrane filtration processes financially viable and improve the profitability of sugar manufacturers.

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