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Minimization of Seasonal Sucrose Losses Across Robert's-Type Evaporators in Raw Sugar Manufacture by pH Optimization

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Factory staff must consider all costs to make sound economic decisions on how to improve the performance of evaporators, which includes knowing optimum pH levels to minimize sucrose losses. A factory study was conducted to determine the effects of target final evaporator syrup (FES) pH values across the season on sucrose losses. The factory operated Robert's type calandria evaporators, with two (2787 and 2322 m^2) preevaporators in parallel and three sets of triple-body evaporators (1148 m^2 each) in parallel; R_t values were 11.4 and 9.5 min in the two preevaporators, respectively, and increased from 10.0 to 21.8 min across the triple bodies. Gas chromatography was used to determine sucrose losses as Δ%glucose/%sucrose ratios on a °Brix basis. Most sucrose losses to acid hydrolysis occurred in the preevaporators. Increasing the target pH of the FES or clarified juice (CJ) systematically reduced losses of sucrose; however, scaling effects overrode pH effects in later bodies. Seasonal effects on evaporator sucrose losses were dramatic. In the early season when cane quality was lowest, higher amounts of impurities catalyzed further hydrolysis of sucrose. In the late season, resilient scale built-up across the season contributed to higher hydrolysis. An optimum target FES pH of ∼6.3−6.5 measured at room temperature (equivalent to a CJ pH of ∼7.1−7.3) is recommended, with a higher target FES pH in the early season or when processing immature cane, to reduce excessive losses. Across the evaporation station, the juice/syrup pH decreased up to the 2nd body with a consistent increase in the 3rd body due to evaporation of volatile acids into the condensate. Equations to assess the economic implications of evaporator sucrose losses are described. A target FES pH of 5.9 caused a season average sucrose loss of 0.55% equivalent to 1.52 lbs sucrose lost/ton of cane and a minimum U.S. $390400 loss in profits. In contrast, a target FES pH of 6.5 reduced this sucrose loss to 0.36% and 1.01 lbs sucrose lost/ton of cane and saved the factory a minimum of U.S. $131100.

KEYWORDS: Robert's-type evaporators; sugarcane processing; sucrose losses; factory target pH values

INTRODUCTION

Currently, in U.S. sugarcane factories, the evaporators of choice are Robert's-type conventional calandria evaporators, which are considered to be simple, robust, and easy to operate. However, the tubular heat exchangers in these evaporators cannot last the whole crop or grinding season without periodic cleanings because of scale build-up or fouling. This necessary cleaning, which is often referred to as a wash-out, is a strong rate-limiting step in the factory with respect to throughput. Average reports of the length of time between evaporator cleanings for Louisiana factories are approximately 8−10 days but 2.5 days have been reported in Florida factories (Mike Damms, personal communication).

Scale formation occurs primarily because of the concentration on nonsugars across the evaporator station, especially the later evaporators where some of the inorganic ions become supersaturated, precipitate out, and deposit on the heating surfaces (*1*). As inorganic ions vary from region to region, the nature of scalants varies too. Recently, Godshall and Wartelle (*2*) reported that scale in Louisiana was mostly calcium and silicate. Calcium was highest in 1st and 2nd effect evaporators, phosphorus peaked in the 2nd and 3rd effects, and silicate generally increased across the evaporator station (*2*). It is well-known that such scaling reduces the overall heat transfer coefficent (U) in multiple effect calandria evaporator stations, a factor that is decisive in the performance of these evaporators. A scale thickness of only 0.2 mm can reduce U to almost half (*3*), and silicate scale causes the highest reduction in heat transfer and is the most difficult to remove. Heat transfer coefficients are dependent on a number of other factors, including solution

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velocity, viscosity, and temperature (*4*). A high juice velocity can enhance heat transfer and retard scale formation (*4*). Scaling also has a very negative economic impact. Determining when to clean often requires striking a balance between maximizing the quantity of the finished product (raw sugar) from the process and the unit cost of the product. Factory staff must consider all costs to make reasonable economic decisions on when to clean the evaporators' heat exchangers, and this also should include the impact of fouling on sucrose losses. Optimization of the time between cleanings should also include when the mean hourly cost of sucrose losses achieves its minimum value (*5*).

In evaporators, sucrose is usually lost through thermally catalyzed acid hydrolysis (inversion) reactions or physically by vapor entrainment, although the latter is much less than the former. Acid hydrolysis of sucrose is a misnomer because it can occur up to ~pH 8.3 (*6*). It can also be accelerated by the presence of glucose or fructose (*7*) and/or salts (*7*−*8*), and this is becoming a bigger problem with the worldwide change to green cane from burnt cane, which has greater amounts of such associated impurities. Generally, in the few sucrose loss studies that have been undertaken across Robert's and a few Kestner evaporators in South Africa (*9*−*10*), the United States (*11*−*12*), and Mauritius (*13*), it was reported that most hydrolysis occurred in the preevaporators. This is not surprising as the highest temperatures and lowest °Brix values occur there, which are both conducive to higher hydrolysis rates. Preevaporators are usually larger to produce vapor for juice heaters and vacuum pans. However, Purchase et al. (*10*) found a positive correlation between the relative size of the preevaporators and losses. Recently, Eggleston and Monge (*12*) reported that scaling has a dramatic effect on increasing sucrose losses. Generally, sucrose losses in Robert's preevaporators increased with time between evaporator cleanings but only occurred late in the cleaning cycle in later bodies (*12*). To the best of our knowledge, there have been no reports on the effect of varying the target final evaporator syrup (FES) pH or seasonal effects on sucrose losses across evaporators.

The measurement of sucrose losses across unit processes in the sugar industry is notoriously difficult and has meant that very limited diagnosis of process problems contributing to sucrose losses has occurred. Sucrose concentrations are traditionally measured at the factory using polarization or optical rotation purity measurements. However, polarimetry cannot be used to measure small sucrose losses as the formation of degradation products with a high positive polarization suppresses the overall polarization changes due to losses (*8*). Even using the more accurate techniques of high-performance liquid chromatography and gas chromatography (GC) are difficult (*9*−*11*, *13*) because actual sucrose loss may be smaller than the experimental error of the technique being used. Consequently, sucrose losses are more easily measured indirectly from increases in glucose/°Brix or glucose/sucrose ratios (*9*) because low concentrations of glucose (glucose and fructose are the primary degradation product of sucrose, but glucose is preferred because it is more acid and heat stable than fructose) can be measured much more accurately and precisely than the relatively higher concentrations of sucrose.

$$\%\ \text{sucrose lost} = \frac{\left[\frac{(\%\text{Glc})_{out}}{°\text{Brix}}\right] - \left[\frac{(\%\text{Glc})_{in}}{°\text{Brix}}\right]}{\left[\frac{(\%\text{Sucr})_{in}}{°\text{Brix}}\right] \times \text{MW}_{Glc}} \times \text{MW}_{Sucr} \times 100 \quad (1)$$

where MW = molecular weight, Sucr = sucrose, and Glc = glucose.

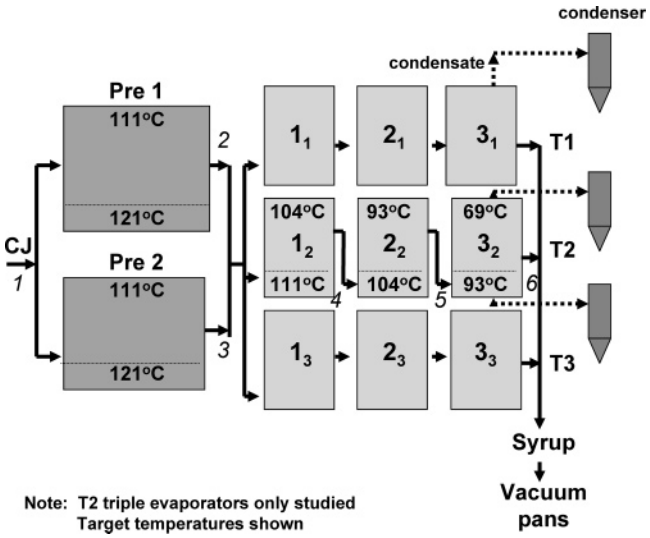

Figure 1. Configuration of Robert's-type evaporators at Cora Texas factory, Louisiana. Sample points are numbered in italics.

In sucrose loss measurements, chloride has also been used as a reference marker instead of °Brix (% dissolved solids) because some dissolved solids may be destroyed (*9*, *13*). For example, in syrup phosphatation clarification where >1% losses were measured (*14*), °Brix was preferentially destroyed relative to chloride; therefore, chloride was the reference marker. However, Wong Sak Hoi and Tse Chi Shum (*13*) observed that, for evaporator juices and syrups, there was a constant °Brix/chloride ratio, which implied that °Brix is not preferentially destroyed relative to chloride; therefore, either °Brix or chloride can be used as a marker. Measurements of sucrose losses across evaporators based on increases in glucose/sucrose ratios, however, are still underestimates. This is because they are based on the assumption that no glucose is degraded, although Schaffler et al. (*9*) reported that even under adverse acid conditions compensation for glucose degradation increased sucrose losses by only 0.03%, but this may vary with factory and region. Overall then, up to the present time, there has been no better marker than glucose reported for the determination of sucrose losses across evaporators, but only minimum losses are given. Furthermore, as factory flow rates fluctuate constantly, studies of sucrose losses across factory processes require large amounts of samples to obtain precise averages, and only trends are given.

This large factory study was undertaken to determine the effect of varying the target FES pH on sucrose losses across a multiple-body evaporation station to find the optimum target pH range, the effect of the seasonal changes in juice quality on losses, and to investigate the interaction, if any, of time between evaporator cleanings and pH on sucrose losses.

MATERIALS AND METHODS

Factory Conditions. This study was conducted during the 2001 grinding season at the Cora Texas factory in Louisiana. The season average cane grinding and flowput rates were 13845 metric tons (15230 short tons)/h and 2105 L (547 gallons)/min, respectively, and 100% of the green billeted cane was processed. The factory operated a hot lime clarification process (*15*). The factory evaporator station (**Figure 1**) consisted of Robert's-type calandria evaporators, with two preevaporators in parallel, followed by three sets of 1st, 2nd, and 3rd triple effect evaporators in parallel. Only the second set of triple effect evaporators was studied. The evaporators were equipped with automatic level (height) and °Brix controls in the last (3rd) evaporators, to help maintain the °Brix of the FES. The two preevaporators fed vapors to

Table 1. Evaporator Body Sizes and Retention Times[a,b]

	evaporator bodies				
	in parallel[c]		second series of factory triples in parallel[c]		
	preE1	preE2	1st	2nd	3rd
size (m^2) [ft^2]	2787 [30000]	2322 [25000]	1148 [12500]	1148 [12500]	1148 [12500]
retention time[d] (min)	11.4[e]	9.5[e]	10.0[f]	13.5[f]	21.8[f]

[a] Factory flow rate = ~11636 metric tons (12800 short tons)/day. Calculated according to Honig (*1*). [b] Full table can be seen in Eggleston and Monge (*12*). [c] See **Figure 1**. [d] 60% level of juice in tubes is assumed. [e] The flow into parallel preevaporators was 55% into Pre-E1 and 45% into Pre-E2. [f] The flow into the T2 factory triple set of 1st, 2nd, and 3rd evaporators was 40% of the total flow imput.

the triple effect evaporators, juice heaters, and vacuum pans. There was no bleed off the triple effects. The factory staff aimed for 9 days maximum between cleanings of individual evaporators. Cleaning occurred by using HCl (2.5−3.5% concentration, which was dependent on the evaporator body) for 2 h. Evaporator sizes and calculated retention times (R_t values) are listed in **Table 1**. R_t values in each evaporator body were calculated from the juice volumetric flow rates, evaporator body volumes, and average masses of °Brix in each body according to Honig (*1*); assumptions could only be made regarding volumetric flow rates because they change constantly in a factory (*15*).

Sampling. To investigate the effect of pH, the factory was first run for approximately 2 h at the target pH of the FES from the 3rd body before sampling began across the evaporation station. The target FES pH was obtained by varying the pH of the hot limed juice (which depends on the cane quality) and clarified juice (CJ). Sampling was repeated every 10 min on five consecutive occasions to constitute a sampling period. The effect of three different target FES pHs was studied in 1 day, and the factory was flushed out at the target FES pH at least 2 h before the next sampling period. Each sampling period was repeated three times across the grinding season: early (Oct 2), mid (Nov 6), and late (Dec 11) season, for adequate coverage of environmental variation in cane quality. Sometimes, the target pH of the FES was not achieved but the pH obtained was taken.

CJ and evaporator juice/syrup entering and exiting each evaporator body were collected taking into account the calculated R_t values (**Table 1**), and sampling points are shown on **Figure 1**. To prevent flashing on sampling and for safety reasons, cooling heat exchangers were installed at the sampling points situated at the bottom of the two preevaporators and 1st evaporator body. Condensates were also collected as the composite of two samples taken across each sampling period. Because the factory had two preevaporators in parallel and three series of triple bodies in parallel, it did not clean all of the evaporators at once but was able to stagger the cleaning of individual evaporators over a 9 day cleaning cycle. As a consequence on any given day of sampling, each evaporator body was at a different time between cleanings, and these were noted.

Evaporator Cleanings Were Staggered over 9 Days:

day	1	2	3	4	5	6	7	8	9
evaporator	PreE1	PreE2	–	triple 1	–	triple 2	–	triple	–

Evaporator juices and syrups were carefully stored to prevent further chemical degradation reactions and/or microbial growth. Each sample was first collected in a large (250 mL) container, and then, ~25 mL was immediately poured into a 50 mL container. The two containers were immediately placed in dry ice before transportation to the Southern Regional Research Center laboratory in New Orleans, LA. The samples were stored in a −80 °C laboratory freezer until laboratory analyses. Glucose, fructose, and sucrose concentrations were measured in juice from the small containers, usually the next day. All other analyses were measured in juice from the large containers.

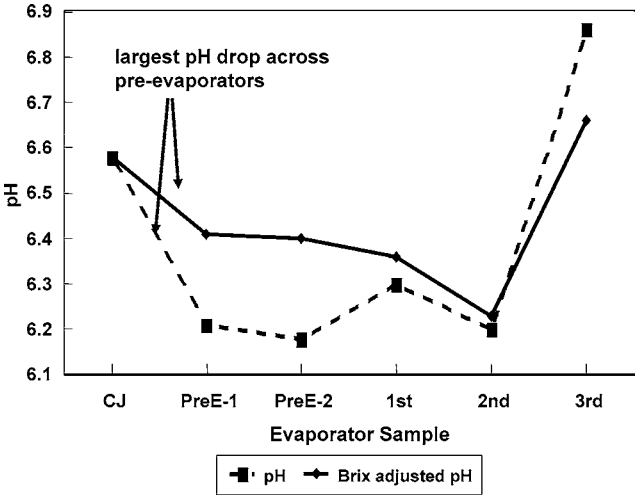

Figure 2. Typical effect of adjusting evaporator station samples to the CJ °Brix on pH at 25 °C.

Measurement of Sucrose Hydrolysis in Evaporator Juices and Syrups. pH at room temperature (~25 °C) was measured after the juice/syrup °Brix's had been diluted to the °Brix of the associated CJ. The pH was measured using an Ingold combination pH electrode calibrated at room temperature using two different pH buffers (pH 7 and 10). The electrode was connected to a Metrohm 716 DMS pH meter. The condensate juices were not diluted.

°Brix (% Dissolved Solids). The mean °Brix of triplicate samples was measured using a an Index Instruments TCR 15-30 temperature-controlled refractometer, accurate to ∀ 0.01°Brix.

Sucrose, Glucose, and Fructose. Sucrose, glucose, and fructose in cane juice were determined by GC, based on ICUMSA method GS7/4−22 (1998) with modifications (*12*). Duplicate analyses were undertaken of three, randomly chosen samples from each sampling period.

Color. Color was measured as the absorbance at 420 nm and calculated according to the official ICUMSA method GS2/3-9 (1994). Samples were first diluted to the approximate °Brix of the CJ sample and then diluted in triethanolamine/HCl buffer (pH 7) and filtered through a 0.45 μm filter.

Statistics. Pearson correlation coefficients were calculated to investigate relationships among the various deterioration criteria using PC-SAS 6.12 (SAS Institute, Cary, NC). Season analysis of FES target pH values was undertaken using PROC GLM in SAS 9.0. Mean separation of % glucose values was done using Duncan's New Multiple Range Test at the 5% probability level.

RESULTS AND DISCUSSION

°Brix Adjusted Sample pH vs Nonadjusted Sample pH. For comparison purposes in this study, sample pH values were measured at room temperature. However, at the higher processing temperatures, the pH values are always lower because the dissociation of water and sugars provides more H^+ ions. It is known that pH usually drops across evaporator stations. There are four contributing factors to this drop: (i) the precipitation of alkaline salts, in particular calcium, silicon, and magnesium salts; (ii) the formation of acids from sugar degradation reactions, (iii) the increasing °Brix concentrations, which concentrate H^+ ions; and (iv) the release of small quantities of ammonia from amino compounds. To remove the strong effect of °Brix concentration, we measured the pH of each sample at the °Brix of the associated CJ. Purchase et al. (*10*) stated that an indirect indication of sucrose hydrolysis is the pH decline across the evaporators as long as the pH is measured at the °Brix of the CJ and at ambient temperature. The typical effect of adjusting the °Brix of the sample on pH is shown in **Figure 2**. As expected, the °Brix-adjusted pH was higher than the

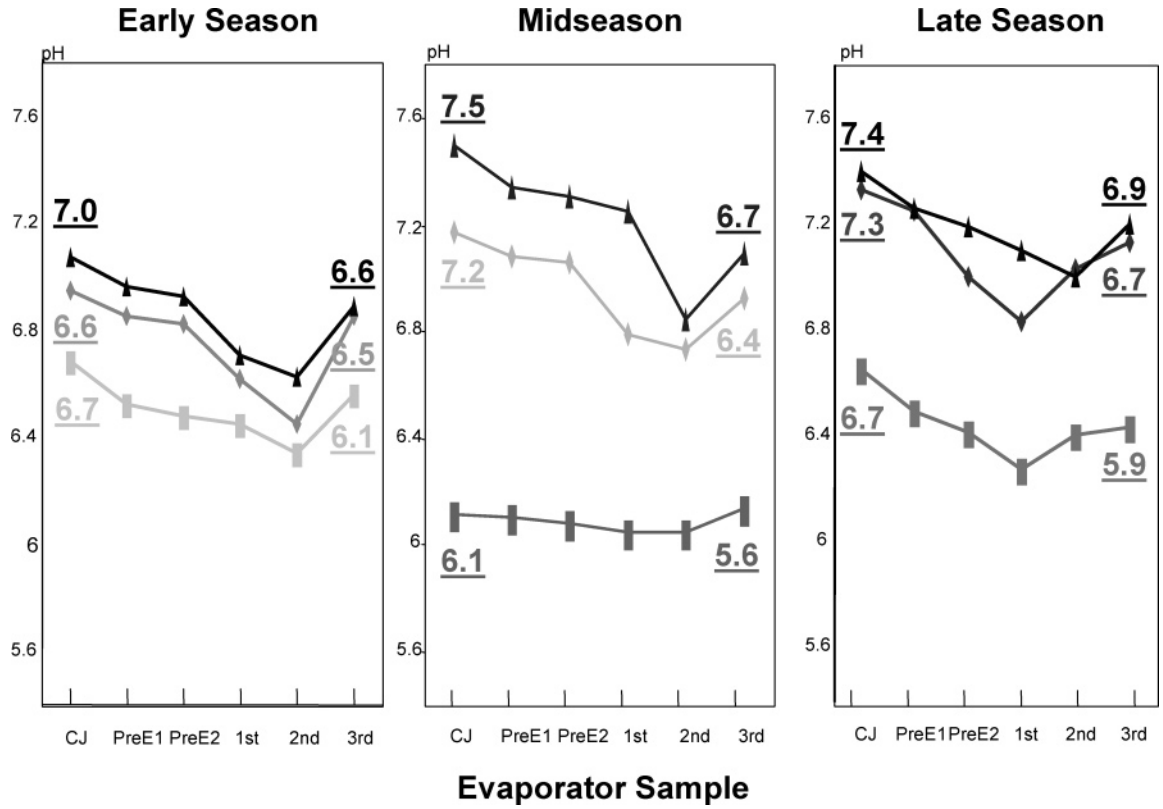

Figure 3. Effects of changing the target FES pH and season on °Brix-adjusted profiles. Unadjusted CJ and FES (third body) pH values are underlined.

Table 2. Example Condensate pH Values in the Late Season

evaporator body	condensate pH value		
target FES pH	5.9	6.7	6.9
preE1	6.40	6.29	5.8
preE2	6.01	6.39	6.52
1st body	5.53	5.31	5.53
2nd body	5.75	5.72	5.83
3rd body	5.59	6.59[a]	5.33

[a] Anomalous value.

nonadjusted sample pH. However, this difference usually decreased across the station up to the 2nd body (the increase in the pH of the non-°Brix-adjusted 1st evaporator sample was anomalous), suggesting that contributors to the pH decline other than the °Brix concentration effect, that is, the precipitation of alkaline salts, became continuously more important.

A surprising but very consistent phenomenon occurred in the 3rd and last evaporator (**Figures 2** and **3**). The pH dramatically increased, and as can be seen in **Figure 2**, this was not because of °Brix concentration effects. A comparative measurement of the condensate pH values from this body often showed a marked decrease (examples are listed in **Table 2**), which strongly indicates that this pH increase in the last body is because of the evaporation of volatile acids. Day (*16*), in the same grinding season at another Louisiana factory, reported that the concentration of volatile acids (formic and acetic) was greater in the condensate of the penultimate evaporator body and was even worse in condensate from the last body to the condenser as major pipe corrosion problems occurred there. The major source of these acids has been reported (*16*) to be the microbial quality of sugarcane wash water. This phenomenon (**Figure 2**) has not been reported before in other geographical areas, which may be because the presence of volatile acids is lower, or a simpler explanation is that it has not been studied.

Effect of Different Target FES pH Values on Evaporator Station pH Profiles. The effect of changing the target pH of the FES on the evaporator station pH profiles across the season is shown in **Figure 3**. The major factor affecting the pH of the FES was the pH of the CJ. The phenomenon of the dramatic pH increase in the last body was consistent across the whole season. The pH of the juice exiting the second preevaporator (preE2) was usually lower than from the first preevaporator (preE1), which may be because the preE2 was not functioning properly. The largest drops in pH occurred in the preevaporators and in the 1st body (**Figure 3**), indicating that the most hydrolysis occurred there.

Target pH and Seasonal Effects on Glucose Concentrations in CJs. The effect of changing the target pH of the FES on average glucose concentrations in CJs is illustrated in **Figure 4**. On a given sampling date, as expected, there was a significant ($P < 0.05$) decrease in glucose with an increase in the target FES, because of reduced sucrose hydrolysis. However, the CJ glucose also decreased across the season irrespective of the target FES pH, which can be attributed to the quality of the sugarcane supply. The quality of the sugarcane supply is lowest in the early season in Louisiana (*17*) because of immature cane, which contains high amounts of invertase (*18*), and, consequently, the glucose and fructose produced from the enzymatic hydrolysis of sucrose. The relatively higher glucose in the early season has implications on the extent of sucrose losses that occur, as glucose along with pH can further induce the nonenzymatic hydrolysis of sucrose at high temperatures (*7*).

Effects of pH on Sucrose Losses. The effects of pH on sucrose losses are illustrated in **Figure 5**, using histograms of glucose changes across individual evaporator bodies and the season. Glucose formation that indicates that the hydrolysis of sucrose occurred is depicted by histogram bars above the zero

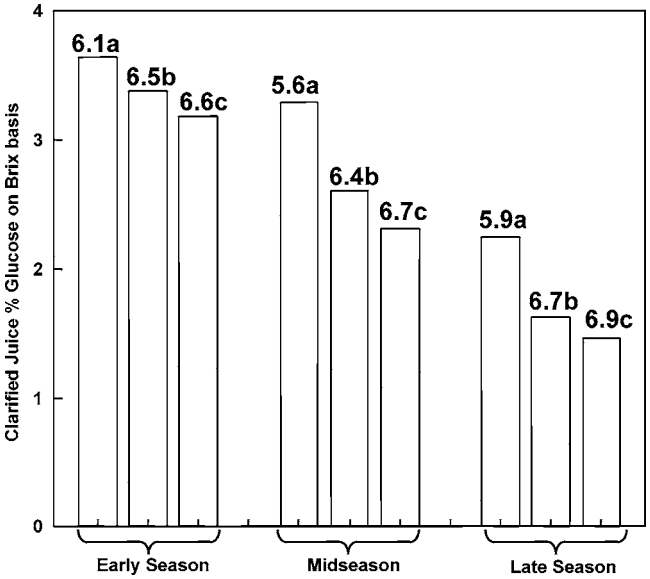

Figure 4. Effect of target FES pH on glucose in CJs across the season. Numbers on the histogram bars denote the average FES pH. Lower case letters represent significant differences ($P < 0.05$) among the three target FES pH values for each part of the season.

line. Glucose reduction is depicted by bars below the zero line and can only occur if glucose is either precipitated out or degraded.

Sucrose Losses in the Early Season. We had the most difficulties, in the early season, to achieve the required target FES pH values for this study, and the range achieved was only pH 6.1−6.6. Sucrose acid hydrolysis occurs up to pH 8.3 (*6*), and the lower the pH, the more hydrolysis occurs. Overall, across the whole season, as the FES target pH increased, hydrolysis usually decreased although results were the most anomalous in the early season (compare **Figure 5a** with **Figure 5b**,**c**). These anomalies are most likely attributed to the occurrence of the lowest quality and most immature sugarcane in early season. The higher glucose (**Figure 4**) and fructose levels alone would have worked synergistically with the pH effect to further induce the hydrolysis of sucrose (*7*). However, even in the early season, it was still observed that most hydrolysis occurred in preE1 and preE2, where the temperature and °Brix were the highest and lowest, respectively; this is in agreement with the pH results (**Figure 3**). In general, glucose reduction occurred in the 1st and 2nd bodies, and this was affected by pH (**Figure 5a**). As acid degradation of glucose was expected to be small (*9*), the most likely explanation for glucose reduction was that glucose precipitated out with larger, insoluble molecules. Because pH had a marked effect on glucose reduction, the latter effect was most likely the major effect and this was especially true for the mid (**Figure 5b**) and late seasons (**Figure 5c**). Also in the early season, a relatively small amount of sucrose hydrolysis was detected in the last (3rd) evaporator (there was no significant difference in glucose changes in the last evaporator among the three target FES pH values), which was surprising as the lowest temperatures and highest °Brix's occurred here. Because hydrolysis was not detected in this last body in either the mid (**Figure 5b**) or the late (**Figure 5c**) seasons, it is most likely that this slight hydrolysis was caused by the higher amounts of glucose and fructose and other impurities catalyzing hydrolysis. However, another explanation may be that in the mid or late seasons, glucose was degraded or precipitated out in more amount than was produced by hydrolysis.

Sucrose Losses in the Midseason. In the midseason, we were able to obtain a wider range of target FES pH values from pH 5.6 to 6.7. It is not recommended that factories target the FES pH at 5.6, but this sometimes occurs (*17*). As the FES target pH increased from pH 5.6 to 6.7, hydrolysis usually decreased significantly ($P < 0.05$), especially in the preevaporators, which is similar to the early season. The higher hydrolysis in preE1 was most likely because it was less clean, i.e., 5 days after the last clean (**Figure 5b**) as compared to the preE2, which had been cleaned 2 days before. Eggleston and Monge (*12*) previously observed that hydrolysis increased across certain evaporator bodies with time after the last cleaning. This is because scale that has formed causes increases in retention times due to decreased heat transfer coefficients and flow rates, and rises in the temperature of the heating juice to partially compensate for the decreased rate of heat transfer in scaled tubes (*12*). This scaling effect on hydrolysis also occurred in the late season (**Figure 5c**) but was not as apparent in the early season (**Figure 5a**), which suggests that sugarcane quality may have a greater effect than the scaling effect. In the midseason, by FES pH 6.7, sucrose hydrolysis was relatively low ($P < 0.05$) in preE1 and not even detected in preE2 (**Figure 5b**). The only other evaporator where hydrolysis was detected was in the 2nd evaporator. Seven days had elapsed after the last cleaning of the 2nd and the 1st and 3rd evaporators, and the scale build-up caused hydrolysis to occur (*12*). The large amount of hydrolysis at FES pH 6.4 seemed anomalous, as usually hydrolysis decreased with increased pH (**Figure 5b**); furthermore, there was no significant difference with hydrolysis at pH 5.6 or 6.7. However, as glucose formation and, consequently, sucrose losses still occurred in the 2nd body at FES pH 6.7, this strongly further suggests that scaling effects can override pH effects. In contrast, glucose reduction occurred in the 1st and 3rd bodies, and this was affected by pH (**Figure 5b**).

Sucrose Losses in the Late Season. In the late season, the range of FES target pH values was from pH 5.9 to 6.9. Up until the 2001 grinding season, many factories in Louisiana were indirectly targeting FES syrups ∼pH 6.0 through target CJ pH values, but this often gave actual FES pH values of 5.9 and lower (*17*). Similar to the early and midseason results, most hydrolysis occurred in the preevaporators. However, unlike the midseason results, more hydrolysis generally occurred in preE2 than preE1 (**Figure 5c**) because on this sampling date the preE2 was less clean than preE1 (**Figure 5c**). This further confirms that, with respect to sucrose losses in evaporators, scaling effects override pH effects. Hydrolysis was only detected in the 1st evaporator body in late season, but this was relatively high and, as expected, decreased systematically ($P < 0.05$) with an increase in the target FES pH.

Sucrose Loss Calculations. The dramatic, seasonal effects of changing the target FES pH on calculations of % sucrose losses, based on the formula of Schaffler et al. (*9*), are shown in **Table 3**, as well as the lbs of sucrose lost per ton of cane. As expected, the lower the pH, the higher the losses are and vice versa. Although a FES target pH of 5.6 is not targeted in factories because of associated high hydrolysis (**Table 3**), it sometimes occurs when deteriorated cane is being processed or factory problems occur. In 2000, many Louisiana factories had a target CJ pH of ∼6.7 to give a FES pH of ∼6.0, although pH values of 5.9 in the FES often occurred (*17*). Results in **Table 3** show that by increasing the target FES pH to at least pH 6.3 causes a marked decrease in losses, particularly in the mid and late seasons. Sugar industry personnel in the United States are concerned that increasing target pH values and lime usage will

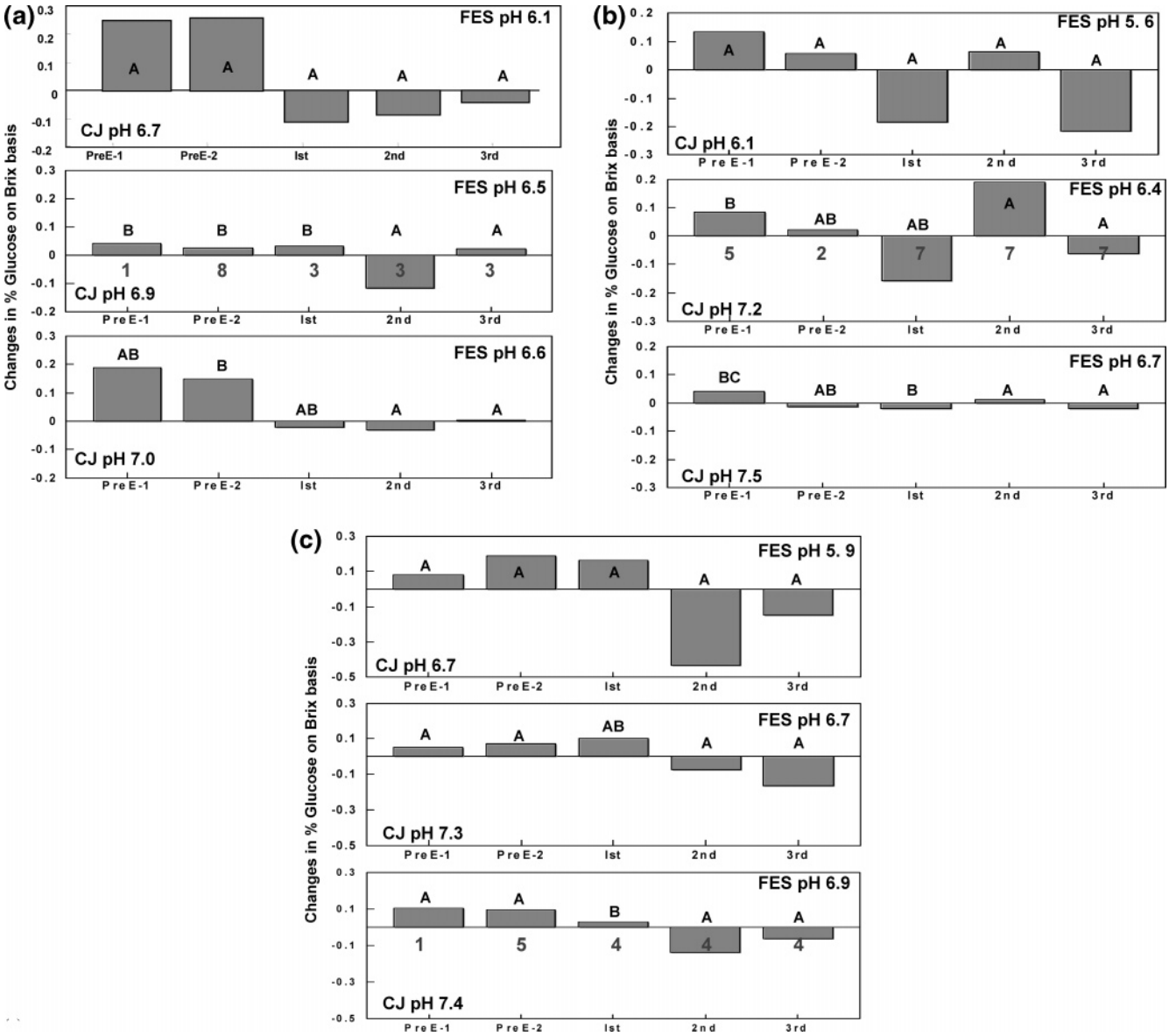

Figure 5. (**a**) Effect of changing the target FES pH on sucrose losses. Early season data are shown. Numbers on the histogram bars denote days after the last clean-out. Upper case letters represent significant differences ($P < 0.05$) among the three target FES pH values for each evaporator body. (**b**) Effect of changing the target FES pH on sucrose losses. Midseason data are shown. Numbers on the histogram bars denote days after the last clean-out. Upper case letters represent significant differences ($P < 0.05$) among the three target FES pH values for each evaporator body. (**c**) Effect of changing the target FES pH on sucrose losses. Late season data are shown. Numbers on the histogram bars denote days after the last clean-out. Upper case letters represent significant differences ($P < 0.05$) among the three target FES pH values for each evaporator body.

Table 3. Effect of Target FES pH Values on Calculated % Sucrose Losses and Lbs Sucrose Lost Per Ton of Cane

target pH		% sucrose losses[a,b]				lbs sucrose lost/ton cane			
final evaporator syrup (FES)	clarified juice	early	mid	late	season average	early	mid	late	season average
5.6	~6.1–6.3	0.81	0.31	0.86	0.66	2.27	0.86	2.39	1.84
5.9	~6.7	0.69	0.28	0.67	0.55	1.93	0.77	1.87	1.52
6.3	~7.1	0.53	0.24	0.59	0.45	1.49	0.66	1.65	1.26
6.7	~7.4	0.37	0.08	0.37	0.27	1.04	0.21	1.04	0.76

[a] On the basis of the formula of Schaffler et al. (*9*)—See the Materials and Methods. [b] Some % loss data were obtained as extrapolations from graphed data.

cause more scale, but the worst scale to remove and the one that reduces heat transfer the most (*3*) is silicate, which is mostly associated with soil in the cane supply. However, even though the least hydrolysis occurred at FES pH 6.7 (equivalent to a CJ pH ~7.4), this pH is still not recommended because too much lime would be consumed and the potential for more scale formation would be unacceptably high. Overall, a compromise FES pH range of 6.3−6.5 (equivalent to a CJ pH range of 7.1−7.3) is recommended to reduce sucrose losses.

Seasonal effects of sucrose losses across evaporators were also dramatic (**Table 3**). Sucrose losses were much lower in the midseason when the highest sugarcane quality occurs (*17*).

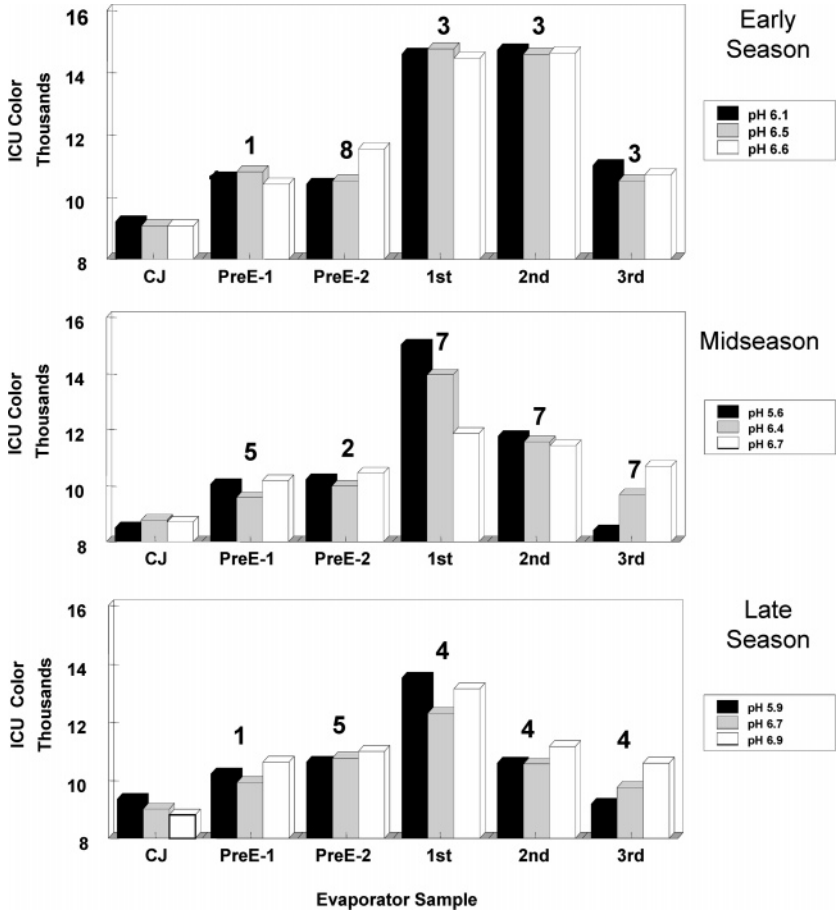

Figure 6. Effect of changing the target FES pH on color formation and removal. Numbers on graph denote days after last clean-out.

The higher losses in the early season can be attributed mostly to the lowest quality of cane (**Figure 4**), as the evaporators were comprehensively cleaned in the off-season before grinding began. Greater amounts of impurities, including glucose (**Figure 4**), fructose, acids, and salts, would have further catalyzed the hydrolysis of sucrose. Some of the highest sucrose losses also occurred in the late season (**Table 3**). Although cane quality decreases again in the latter season (but not to the extent of the early season; *17*), these increased losses are most likely because of the build-up of scale resistant to cleaning in the later bodies after the preevaporators, which becomes worse as the season endures. This is further evidenced by the considerable improvement of overall losses in late season, if the losses in the 1st body were removed. This resilient scale most likely contains silicate, which is the most difficult type of scale to remove and which is more predominant in the later bodies of Louisiana factories (*2*).

Color Formation Across Evaporators. Although there has been a general lack of interest in color formation across evaporators in Louisiana because there are seldom any penalties by the refinery for color in raw sugar, color formation is still an indication of sugar degradation, and color reduces the quality of raw sugar. Color character across evaporators varies with factory (*1*). There have been different reports of the nature of color formation across sugarcane factory evaporators in the literature. Honig (*1*) reported that color formation is mostly related to the iron content of the juice. Edye and Clarke (*11*) stated that color formation is due to "condensation reactions of color precursors (e.g., 5-hydroxymethyl-2-furaldehyde) and colored compounds" and "occurs under conditions where sucrose is likely to decompose". Schaffler et al. (*9*) observed a general color increase across an evaporator station, which was attributed to fructose degradation. The effects of different target FES pH values and seasonal dates on color formation and removal are shown in **Figure 6**. There were no statistical differences among color measurements in the different evaporators, which makes drawing absolute conclusions difficult. However, in general, across the season, some color formed across the preevaporators and scaling had little effect (**Figure 6**). As the highest temperatures and hydrolysis occurred in the preevaporators (**Figure 5**), this color formation is most likely because of thermal sugar degradation reactions. Irrespective of target pH or season date, the most color formation occurred in the 1st evaporator in this factory (**Figure 6**). We have no full explanation for this, although the lower the pH the more color formed, which suggests that color reactions were acid induced. Flakes of iron were also noticed in the samples from the first body, which suggest that acid−iron reactions occurred. Overall, there were no significant correlations of either fructose, glucose, or sucrose with color, which suggests that color formation across the evaporator station was complex and not just associated with sugar degradation as previously described (*9*, *11*).

Except in the early season, color was generally removed in the 2nd body with no apparent affect of pH (**Figure 6**). Furthermore, for the whole season, color was generally removed in the last (3rd) body, although color formation has been reported by others (*9*, *11*). As for glucose and fructose, color can be simultaneously formed and removed/destroyed in an evaporator, and the measurements shown in **Figure 6** are only a cumulative glimpse of these multiple physicochemical occurrences. Therefore, the color removal in the 3rd body may represent overall removal of color over color formation. As most precipitation of insoluble scale compounds occurs in the last body, removal of color by precipitation is the most likely cause.

Table 4. Calculation of Minimum U.S. Dollar Losses Across the Season[a]

final evaporator syrup (FES)	clarified juice (CJ)	calculated U.S. dollar losses across the season[b]
5.6	~6.1–6.3	470630
5.9	~6.7	390400
6.3	~7.1	323780
6.7	~7.4	194840

[a] Minimum losses are conservative. [b] U.S. dollar losses calculated according to eqs 2 and 3 in the text.

Effect of Target pH Values on Minimum Economic Costs. The minimum amount of U.S. dollars that are lost because of the suboptimization of target FES or CJ pH values was calculated according to the following equations:

$$\mathrm{CG} \times \frac{\mathrm{E}}{100} \times \frac{\mathrm{CJP}}{100} \times \frac{\mathrm{L}}{100} = \mathrm{S} \quad (2)$$

then

$$\left\{\frac{\mathrm{S}}{\mathrm{RSS}} \times 100\right\} \times 2000 \times \mathrm{RSP} = \$\text{U.S. lost per season} \quad (3)$$

where CG = tons of sugarcane ground for the whole grinding season, E = % extraction of juice in cane, CJP = % sucrose in CJ (season average based on pol), L = sucrose loss (%), S = tons of sucrose lost, RSS = % sucrose in raw sugar (season average based on pol), and RSP = price per lb of raw sugar in U.S. dollars in 2001 (i.e., 20 cents per lb).

The calculated results are shown in **Table 4**. Even though dollar losses are only minimal and conservative, considerable costs were still incurred by the factory because of unwanted sucrose losses across the evaporators. Although much less profit losses occurred at FES pH 6.7, this target pH it is still not recommended. A compromise in target CJ or FES pH has to be achieved by any factory to ensure no excessive lime addition occurs and, even worse, more calcium scale and color formation.

Recommendations from This Study. (1) Control of the FES (FES) pH is recommended to minimize sucrose losses in the clarifiers and evaporators. The authors recommend a target FES pH of 6.3−6.5 (equivalent to a target CJ pH of ~7.0−7.2), as measured at room temperature. (2) The target FES and CJ pH values need to be higher at the beginning of the season, to compensate for the lower quality sugarcane and reduce excessive hydrolysis losses. A higher target pH at the end of the season is not recommended as resilient scale was shown to override increased target pH values. (3) Predictor equations of evaporator sucrose losses currently being used in the sugar industry (*20*, *21*) need to incorporate a scaling component to improve estimations. (4) Future investigations of sucrose losses across evaporators in the sugar industry need to take into account the "cleaning/scaling status" of the evaporator bodies and seasonal affects. (5) More factory studies on other low retention time, high heat transfer evaporators (*19*) are warranted to reduce sucrose hydrolysis, especially in the preevaporators. (6) Further studies on scale reducers or inhibitors are warranted.

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