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Integrated Modelling of Sugar Manufacturing Plant for Nigeria Cane Plantation

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ABSTRACT

Nigeria is a major importer of brown sugar, an important food source that can be manufactured from sugarcane locally available. To serve the purpose of designing a sugar manufacturing plant, this paper develops a plant-wide model for obtaining brown sugar from sugarcane. This model comprising material balance equations accounts for various processes involved in the manufacturing such as milling, filtration, evaporation, crystallization and drying. GAMS, an algebraic modelling tool, was employed to solve the model. From a basis of 100 tonnes of cane per day, a simulation result of 2000 tonnes of brown sugar per year compared excellently with literature. Therefore employing the model with a basis of 13 million tonnes of sugarcane, Nigeria's sugarcane plantation potential capacity, showed that the country can produce 500,000 tonnes per year, compared to the current capacity of less than 10,000.

Keywords: *GAMS, integrated modelling, sugarcane, sugar plant.*

1. INTRODUCTION

Globally, 176 million metric tons of sugar is consumed annually, an average of 25 kg of sugar is consumed per person. Out of this figure, Nigeria consumes about 1.5 million metric tonnes per year, about 7.5 kg per capita per year. However, domestic production is less than 1% (Shanbadeh, 2021; NSDC, 2021). Most sugar companies in Nigeria are into sugar refining, importing and refining brown sugar to produce white sugar. Sugar refining, however, translates to less than 20% value addition (OECD/FAO, 2016). To get 100% of the value, Nigeria must domesticate sugar technology, process sugarcane to brown sugar and then refine the latter into white sugar.

According to Wayas (2011), Nigeria has identified favourable landmasses potentially able to produce 13 million tonnes of cane plant (that is 250,000 Ha of land at a yield of 54.81 tonnes of cane per Ha). These cane plantations are located in twenty five States in the Federation, the States with the largest landmasses being Adamawa, Niger, Edo, and Jigawa States with 39,470, 39,350, 15,500 and 10,450 Ha, respectively. Since sugar manufacturing plants are sited near cane plantation (Jenkins, 1966), efforts should be geared towards designing and siting sugar production plants in various identified areas for intensive local sugar production, to increase local production of commercial sugar from sugarcane.

With mathematical modelling, a chemical plant can be designed and subsequently scaled up or down depending on the intended market and/or raw material availability. Design modelling involves employing descriptive equations of various processes encountered in a chemical plant and solving the equations for certain input and process conditions. Most chemical plants, especially those producing more than 1000 tonnes per year, operate largely on a continuous basis. Therefore continuous or steady state modelling can be employed in designing sugar production plant.

The objective of this paper is to derive a mathematical model for the description of brown sugar manufacturing from sugarcane. Processes involved in this manufacturing include cleaning, preparing sugar cane, juice milling, and juice purifying. Others include juice concentration, sugar crystallization, centrifugation and drying. As a methodology, material balance around each process and material partition among streams are mathematically described. The mathematical equations are then linked to form sugar manufacturing modelling. Then, this modelling will be applied and solved for a Nigerian mini raw sugar production plant processing 100 tonnes of cane per day. For model validation, simulated results will be compared with the plant brown sugar production capacity.

2. MATERIALS AND METHODS

Table 1 shows mass fraction ranges of sugarcane constituents: water, sucrose, hexoses, fiber, and others. A more detailed sugarcane composition is reported in Table A1 in the appendix. To produce commercial sugar, the juice must be extracted from cane and processed to isolate and crystallize sucrose from other soluble solids. The processes involved are milling juice from sugarcane, screening fibrous material from juice, and precipitation of dissolved impurities (i.e. others) and their removal by clarification, to produce purified juice. Other processes downstream include evaporation to concentrate the purified juice, crystallization to produce solid sucrose, centrifugation to separate the crystals and finally drying to reduce crystal moisture content. Figure 1 shows the process flow chart. As a methodology, material balance around each process and material partition among streams are mathematically described. The mathematical equations are then linked to form sugar manufacturing modelling.

Table 1: Constituents of Sugar cane (Jenkins, 1966)

Constituents	percent mass
Water	73-76
Sucrose	7-14
Hexoses	0.4-1.3
Fiber	11-16
Others	4-10.6

Hexoses comprise glucose and fructose while others comprise salts, acids and other non-sugars.

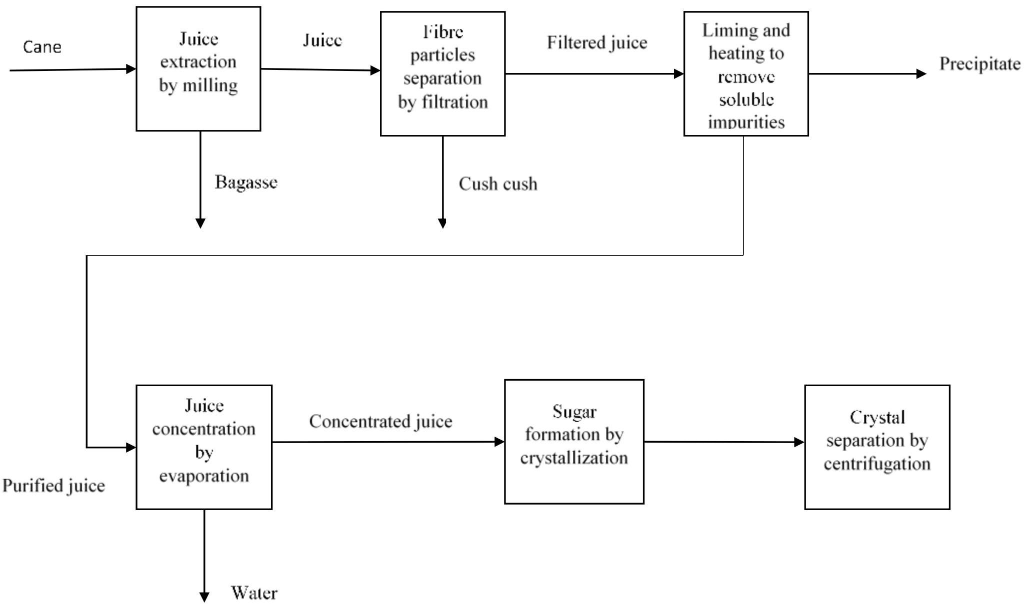

Figure 1 shows the process flow diagram for processing sugarcane into raw sugar.

In describing its continuous operation mathematically, the sugar manufacturing plant requires steady-state modelling. Each operation is mathematically described as follows. The components in Table 1 (sucrose, hexose, water, fibre and others) are denoted as c, h, w, f, and o, respectively.

Milling

The simplest type of milling is dry milling, which can reduce the fibre content to a maximum of 0.5 while extracting the juice. Thus, around a dry milling tandem, one inlet stream of sugarcane yields two outlet streams of concentrated juice and bagasse. The model is written as:

$$(m_i)_{S1} = (m_i)_{S2} + (m_i)_{S3} \qquad \forall\, i \tag{1}$$

$(m_i)_{S1}$ is the mass of component i in Stream 1, the sugarcane feed. Streams 2 and 3 are the product streams of bagasse and extracted juice, respectively. Entering and exiting the milling process through Streams 1 and 2, the fibre around the mill can be equated as:

$$x_{1f}M_{S1}^{T} = x_{2f}M_{S2}^{T};\; M_{S2}^{T} = \frac{x_{1f}}{x_{2f}}M_{S1}^{T} \tag{2}$$

where x_{1f} and x_{2f} are the mass fractions of fibre in streams 1 and 2. M_{S1}^{T} and M_{S2}^{T} are the total masses in streams 1 and 3.

Therefore, the total mass of juice extracted M_{S3}^{T} would be:

$$M_{S3}^{T} = M_{S1}^{T} - M_{S2}^{T}; \tag{3}$$

Using Eq. (2), Eq. (3) can be rewritten as:

$$M_{S3}^{T} = M_{S1}^{T}(1 - \frac{x_{1f}}{x_{2f}}) \qquad (4)$$

Fractional juice extracted e in the mill is written as:

$$e = \frac{M_{S1}^{T}(1-\frac{x_{1f}}{x_{2f}})}{M_{S1}^{T}(1-x_{1f})} = \frac{(1-\frac{x_{1f}}{x_{2f}})}{(1-x_{1f})} \qquad (5)$$

Using Eq. (1) and above analysis, the mass balance for fibre is written as:

$$(m_f)_{S1} = (m_f)_{S2} \qquad (6)$$

The mass balance for other components can be written as:

$$(m_i)_{S1} = (m_i)_{S2} + (m_i)_{S3} \qquad \forall\ i = w, c, h\ and\ o \qquad (7)$$

$$e = \frac{(m_i)_{S3}}{(m_i)_{S1}};\ \forall\ i = w, c, h\ and\ o \qquad (8)$$

The milling and crushing work on the bagasse, however, peel off some fibre (also known as bagacillio) into the extracted juice. Jenkins reports that one litre of extracted juice would contain about 10 g of fibre. With the juice density taken as 1.12 g per ml, on mass basis, it is 10 g of fibre per 1120 g of extracted juice. Eq. (6) can therefore be modified as:

$$(m_f)_{S1} = (m_f)_{S2} + (m_f)_{S3} \qquad (9)$$

where

$$(m_f)_{S3} = 0.89\%\ of\ [(m_c)_{S3} + (m_h)_{S3} + (m_w)_{S3} + (m_o)_{S3}] \qquad (10)$$

Screening, precipitation and clarification

The extracted juice passes through screens, reactors, and clarifiers. A combination of these units removes the bagacilio and other components such as gum, wax, and acids from the extracted juice, purifying it into a mixture of sucrose, hexoses and water. The other components exit through the waste stream. In the overall, one inlet stream (extracted juice) yields two outlet streams (clarified juice and waste). The model can be written as:

$$(m_i)_{S2} = (m_i)_{S4} + (m_i)_{S5} \qquad \forall\ i \qquad (11)$$

$$(m_i)_{S2} = (m_i)_{S5} \qquad \forall\ i = c, w, h \qquad (12)$$

$$(m_i)_{S2} = (m_i)_{S4} \qquad \forall\ i = o \qquad (13)$$

Evaporation

The clarified juice passes through an evaporator that heats up the solution to vaporise water, thereby concentrating the juice. The model can be written as:

$$(m_i)_{S5} = (m_i)_{S6} + (m_i)_{S7} \qquad \forall\ i \qquad (14)$$

Sucrose and hexose enter through Stream 5 (clarified juice) and exit Stream 7 (concentrated juice), the balance equation for sucrose around the evaporator can be written as:

$$x_{5s}M_{S5}^{T} = x_{7s}M_{S7}^{T}; \qquad (15)$$

where x_{5s} and x_{7s} are the mass fractions of sucrose in Streams 5 and 7. M_{S5}^{T} and M_{S7}^{T} are the total masses in Streams 5 and 7. The mass ratios of sucrose to hexose in Streams 5 and 7 remain the same; thus, a similar expression to Eq. (15) applies to hexose. The amount of water in Stream 6 to be evaporated can be calculated as:

$$M_{S5}^{T} = M_{S6}^{T} + M_{S7}^{T};\ M_{S6}^{T} = M_{S5}^{T} - M_{S7}^{T} \qquad (16)$$

Using Eq. (15), Eq. (16) becomes:

$$M_{S6}^{T} = M_{S5}^{T} - M_{S7}^{T} = \frac{(x_{7s} - x_{5s})}{x_{7s}} M_{S5}^{T} \tag{17}$$

Eq. (17) yields the amount of water to be evaporated from a clarified juice of x_{5s} to obtain a concentrated juice of x_{7s}. This water amount would be used in specifying the heating requirement of the evaporator.

Crystallization and centrifugation

Crystallization produces sugar crystals from the concentrated juice. In order to control crystal size, the process occurs by introducing into the concentrated solution seed mass, which grows from the seed size to the final crystal size, the growth mass being deposited by the solution. By growing the seeds, the technique prevents the nucleation step from occurring Regardless of the methods of crystallization _cooling, evaporation or solvent addition_, one of the objectives of crystallization is maximising the deposited growth mass. The maximum deposited mass is the product of solution volume and the difference between actual concentration and solubility concentration at the final temperature, given as

$$(m_c)_{S9} = \left(C_c - C_{ceq}\right)V \tag{18}$$

where C_c is the mass concentration of sucrose in the concentrated juice; C_{ceq} is the mass solubility of sucrose, which should be the same as the concentration of the molasses; and V is the volume of the crystallizer solution. By inspection, Eq. (18) is a component mass balance equation for sucrose, where:

$$(m_c)_{S7} = C_c V \tag{19}$$

and

$$(m_c)_{S8} = C_{ceq} V \tag{20}$$

A similar expression holds for hexoses. When compared to sucrose, the amount of hexose present in solution would not be sufficient to crystallize. Therefore, the crystals are primarily sucrose, which can then be removed from the molasses by centrifugation.

Drying

Although most of the water in the concentrated juice remains in the molasses, some water molecules find their way into the sugar crystals thus containing 1% of water. To bag and preserve the sugar crystals, the water content should be decreased to 0.1% by drying. A mass balance model similar to those of the evaporation process above applies:

$$(m_i)_{S9} = (m_i)_{S10} + (m_i)_{S11} \qquad \forall\, i = c \text{ } and \text{ } w \tag{21}$$

The balance equation for sucrose around the dryer can be written as:

$$x_{9c} M_{S9}^{T} = x_{11c} M_{S11}^{T}; \tag{22}$$

where x_{9c} and x_{11c} are the mass fractions of sucrose in Streams 9 and 11, given as 0.99 and 0.999, respectively. The amount of water in Stream 10 to be dried can be calculated as:

$$M_{S9}^{T} = M_{S10}^{T} + M_{S11}^{T};\ M_{S10}^{T} = M_{S9}^{T} - M_{S11}^{T} \tag{23}$$

Using Eq. (22), Eq. (23) becomes:

$$M_{S10}^{T} = \frac{(x_{11c} - x_{9c})}{x_{11c}} M_{S9}^{T} \tag{24}$$

Eq. (24) yields the amount of water to be dried from sucrose crystals to obtain raw sugar. The amount of water derived can be used in estimating the required air with specified humidity when designing a drier.

3. RESULTS AND DISCUSSION

To simulate a sugar manufacturing plant, Eqs. (7) – (13), (15), (17) – ((22), and (24) were lumped and implemented in a commercial code called GAMS, defined as General Algebraic Modelling System. This code can be used for formulating, solving and analysing mathematical problems. In solving the model, parameters must be specified. These parameters include the percentage of extracted juice from the bagasse, effectiveness of removing solid impurities, fraction of water evaporated from the dilute juice, solubility of sucrose, and the purity of raw sugar. Their values were extracted from Jenkins (1966). Dry milling yielded a maximum of 50 % extracted juice while a combination of filtration, screening, reactions and clarification of extracted juice removed all constituents except water, sucrose and hexoses. Evaporation increased the sucrose concentration from 30 to 70 Brix while the molasses exiting the combined setup of crystallization and centrifugation was 0.1 weight sucrose. Lastly, drying yielded raw sugar of 98.5% sucrose.

Also in solving the model, the amount of sugar cane as well as its composition must be specified as feed condition. Sucrose, water, fibre, and hexoses are classified as the major constituents while others are the minor constituents. Average percent values from the range reported in Table 1 were used for the major constituents while the remaining percent value was used for others. For the cane amount, Wayas (2011) reported a Nigerian mini raw sugar production plant processing 100 tonnes of cane per day into 2,000 tonnes of raw sugar per year.

Using this cane amount as input, the model yielded 1,323 tonnes of brown sugar per year, a shortfall of about 700 tonnes. This result is shown in Table 2, Simulation 1. (See the appendix Table A, Simulation 1 column, for the plant-wide complete results.) Uncertainties in many of the parameters may have led to this shortfall. With 9.2 % sucrose, the feed of 36,500 tonnes of cane has a maximum of 3,358 tonnes of sucrose. That means by adjusting parameters the model could actually yield 2,000 tonnes of sucrose. Some of the sucrose were however lost to bagasse in milling and the rest to molasses in crystallization and centrifugation. For example, the assumption of dry milling meant a maximum of 50% juice recovery. In most commercial sugar plants, however, wet milling by compound imbibition applies, extracting as high as 95 % of juice, albeit the heating requirement to concentrate the juice would be high (Jenkins, 1966). Changing the percent extraction in the model to 95% yielded 1,479 tonnes of brown sugar produced per year. In this case, the amount of sucrose escaped in the molasses was 1,525 tonnes per year. This result is shown in Table 2, Simulation 2. (See the appendix Table A, Simulation 2 column, for the plant-wide results). To further increase the yield of raw sugar to 2,000 tonnes per year, the amount of sucrose escaped in the molasses must be reduced by about one-third, realistic by decreasing the concentration of sucrose from 0.1 to 0.07 via further cooling crystallization. Doing this yields the amount of raw sugar produced as 1,972 tonnes per year. This result is shown in Table 2, Simulation 3 (complete results are reported in the appendix in Table A, Simulation 3 column). This value is 98.6 % accurate in comparison with 2,000 tonnes per year of brown sugar physically produced by the chemical plant.

Table 2: A combination of simulated sugar production results

	Sugarcane feed	Brown sugar	
		Simulated plant	Real plant
	tonnes		
Simulation 1	36,500	1,323	2,000
Simulation 2	36,500	1,525	2,000
Simulation 3	36,500	1,972	2,000
Simulation 4	1.35E+07	7.43E+05	na

With these updated parameters, the model can be used to predict the amount of raw sugar that can be produced in Nigeria. Wayas (2011) reported potential sugar cane plantation farms in Nigeria citing about eighty different locations to be 250,000 hectares of land, capable of producing 55 tonnes per hectare. From these data, Nigeria is capable of producing 13.75 million tonnes of sugar cane per year. Using this sugarcane production rate as feed and the updated parameters, the developed model simulated in GAMS yielded 0.743 million tonnes of raw sugar. This result is also shown in Table 2, Simulation 4 (see Table A, Simulation 4 column, for complete results). The sugar need of Nigeria as reported in 2008 was 1.58 million tonnes, 99% of which was imported. From the result, Nigeria can reduce sugar import by half. With the price of raw sugar taken as $342 per tonne, Nigeria would be saving about $254 million in foreign exchange annually.

4. CONCLUSIONS

This article reported model developments and applications for manufacturing brown sugar from sugarcane in Nigeria. The manufacturing processes include milling, filtration, decantation, evaporation, crystallization, centrifugation and drying. In the model developments, material balance models were employed to describe the processes. Linking these models resulted in integrated modelling for the entire sugar manufacturing plant. With a feed rate and model parameters, both obtained from literature, the model was solved using GAMS, an algebraic modelling solver.

The results, when compared with a sugar plant production capacity, revealed only about 75% production rate of brown sugar. Most of the sucrose escaped in the molasses. By adjusting the parameters, in particular the crystallization parameter, the production rate of brown sugar compared with literature. Using the potential sugarcane plantation in Nigeria along with adjusted parameters, the model revealed that the country could meet about 50% of its sugar demand, thereby saving more than $200 million in foreign exchange.

This model can be employed in designing, controlling and optimising sugar manufacturing in different parts of Nigeria and elsewhere.

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