An integrated approach for the optimal preliminary design of a malt drink production plant from sorghum

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Un enfoque integrado para el diseño preliminar óptimo de una planta de producción de malta a partir de sorgo

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ABSTRACT

With the aim of finding friendly celiac food, sorghum is presented as a cereal with a high content of nutrients, which has several beneficial properties, especially for those countries that lack other traditional cereals such as wheat, corn, or rice. In addition, sorghum cultivation is economically profitable and it does not contain the proteins that affect celiac patients. In the last years, a variety of "free gluten" food products were developed for improving the celiac diet, as well as sorghum beers, which are frequently produced in a home-made manner on a very small scale by individual brewers. However, to the best of our knowledge, there is not a non-alcoholic beverage from sorghum. In this work, a mathematical model for the optimal design of a batch plant for producing malt drink from sorghum at industrial level is proposed. The model is formulated as a mixed integer linear problem, which is implemented and solved in GAMS using the CPLEX solver. Through experimental results, design and operation model parameters are obtained in order to develop real-fit formulation. The investment cost is minimized, and a technical-social-economical analysis is presented in order to evaluate the more profitable and sustainable option to produce malt drink from sorghum. For a production of 5,000 L/d, the payback period is equal to 4.8 years and the unit cost per bottle of 300 mL is $ 0.312. The obtained malt drink with technology presented in this work, meets the physical and organoleptics requirements established for its consumption according with the comparison reported by Nieblas [1], with two malt drinks from barley commercialized in Cuba, Bucanero and Tínima malt drink.

Keywords: Malt drink; modeling; optimization; process design; sorghum.

RESUMEN

Con el objetivo de encontrar alimentos amigables para celíacos, el sorgo se presenta como un cereal con un alto contenido de nutrientes, que tiene varias propiedades beneficiosas, especialmente para aquellos países que carecen de otros cereales tradicionales como el trigo, el maíz o el arroz. Además, el cultivo del sorgo es económicamente rentable y no contiene las proteínas que afectan a los pacientes celíacos. En los últimos años, se ha desarrollado una variedad de productos alimenticios de "libre de gluten" para mejorar la dieta de los celíacos, como cervezas de sorgo, que a menudo son producidas de forma artesanal y a muy pequeña escala por cerveceros individuales. Sin embargo, hasta donde se conoce, no existe una bebida no alcohólica a base de sorgo. En este trabajo se propone un modelo matemático para el diseño óptimo de una planta discontinua de producción de malta a partir de sorgo a nivel industrial. El modelo se formula como un problema mixto entero lineal, el cual se implementa y resuelve en GAMS utilizando el resolvedor CPLEX. A través de resultados experimentales, se obtienen los parámetros de diseño y operación del modelo para desarrollar una formulación de ajuste real. Se minimiza el costo de inversión y se presenta un análisis técnico-social-económico con el objetivo de evaluar la opción más rentable y sostenible de pro-

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ducir malta a partir de sorgo. Para una producción de 5.000 L/d, el período de pago es de 4,8 años y el costo unitario por botella de 300 mL es de $ 0,312. La bebida de malta, obtenida con la tecnología presentada en este trabajo, cumple con los requisitos físicos y organolépticos establecidos para su consumo de acuerdo con la comparación reportada por Nieblas [1], con dos maltas de cebada comercializadas en Cuba malta Bucanero y Tínima.

Palabras clave: Malta; modelación; optimización; diseño de procesos; sorgo.

RESUM

Amb l'objectiu de trobar aliments amigables per a celíacs, la sorgo es presenta com un cereal amb un alt contingut de nutrients, que té diverses propietats beneficioses, especialment per a aquells països que no tenen altres cereals tradicionals com el blat, el blat de moro o l'arròs. A més, el cultiu del sorgo és econòmicament rendible i no conté les proteïnes que afecten els pacients celíacs. En els últims anys, s'ha desenvolupat una varietat de productes alimentaris "lliure de gluten" per millorar la dieta dels celíacs, com cerveses de sorgo, que sovint són produïdes de forma artesanal i a molt petita escala per cervesers individuals. No obstant això, fins on es coneix, no existeix una beguda no alcohòlica a base de sorgo. En aquest treball es proposa un model matemàtic per al disseny òptim d'una planta discontínua de producció de malta a partir de sorgo a nivell industrial. El model es formula com un problema mixt sencer lineal, el qual s'implementa i resol en GAMS utilitzant el resolvedor CPLEX. A través de resultats experimentals, s'obtenen els paràmetres de disseny i operació del model per desenvolupar una formulació d'ajust real. Es minimitza el cost d'inversió i es presenta una anàlisi tècnica-social-econòmica amb l'objectiu d'avaluar l'opció més rendible i sostenible de produir malta a partir de sorgo. Per a una producció de 5.000 L/d, el període de pagament és de 4,8 anys i el cost unitari per ampolla de 300 ml és de 0,312 $. La beguda de malta, obtinguda amb la tecnologia presentada en aquest treball, compleix amb els requisits físics i organolèptics establerts per al seu consum d'acord amb la comparació reportada per Nieblas[1], amb dos maltes d'ordi comercialitzades a Cuba malta Bucanero i Tínima.

Paraules clau: Malta, modelació, optimització, disseny de processos, sorgo.

1. INTRODUCTION

The prevalence of celiac disease (CD) has been increasing worldwide, most likely because of greater awareness and better testing [2]. CD is an autoimmune enteropathy characterized by permanent intolerance to gluten [3] that causes damage to the small intestinal mucosa when gluten, found in wheat, barley, and rye, is ingested, which only occurs in genetically susceptible individuals [4]. The sensitivity to innate and adaptive gluten and autoimmunity are crucial in the development of CD [5]. Wheat ingestion was first recognized as the cause of CD by Willem Karel Dicke in 1950 [6].

CD affects 0.3-1.0% of the world population. It is believed to be presented in up to 1 in 100 of the population although only about 10-15% of affected people are clinically diagnosed [7].

The mainstay of treatment is a strict lifelong adherence to a gluten-free diet. Current adherence to gluten-free diet depends on many factors, such as patient age, absence of symptoms that would maintain the patient aware of his/her illness, cost of the diet without gluten, food label information [8], cross-contamination during the processing steps and gluten-free products available on the market.

Sorghum (*Sorghum bicolor(L) Moench*) is a high biomass, sugar-yielding crop [9]. It is considered a safe food for celiac patients, because it is more closely related to maize than to wheat, rye and barley [10].

This cereal is gluten free grain, and represents an important source of energy and protein for a large segment of the human population in the semi-arid and arid tropics, where weather is too hot and dry for successful wheat and maize production. In countries, such as Australia, United States and Brazil, this cereal is mainly used for animal feed production. In contrast, sorghum is produced and used for human consumption in countries of Africa, Asia and other semi-arid regions of the world [11]. Sorghum is a drought-resistant and is the second most important cereal food in Africa and Asia after maize. The sorghum production is primarily grown under rainfed conditions [12] and the growing period length is mainly a function of the date of the first rains, which is delayed with latitude and varies widely from year-to-year. Sorghum is a short day photoperiod sensitive crop, and its flowering progress accelerates as the daily sunny period decreases. The favorable conditions for sorghum cultivation extend from May to November corresponding with the wet season and with the majority of the growth cycle occurring under decreasing day length, explaining why cycle duration shortens when sowingis delayed [13]. Sorghum has a lower cost and its production process is easier than maize, and until recently it has not been used for snacks and breakfast cereal [14]. Sorghum is a profitable cereal for the national and international market, based on its low production cost, rusticity characteristics, resistance to drought and the short harvest periods. This cereal has a lower cost than barley and other cereals used as beer adjuncts, and it has demonstrated its potential as a crop [15]. Sorghum could be used as a substitute for conventional cereals due to its high bioactive compounds, minerals, dietary fiber, vitamin E and carotenoids content, and it's potential to promote health and prevent diseases [15].

Some laboratories studies employing UDG-10 sorghum was made in Cuba, mainly, in beverages (malt drink and beer) from celiac patients [1, 12, 16].

The malt is the results of germination and drying, during determined times and temperatures of cereals grains [1, 17, 18]. On the other hand, beer is traditional produced using barley and wheat, which results toxic for celiac patients. Moreover, as beer is a beverage obtaining from fermentation process using selected yeast [17] it alcoholic graduation must be at least 3% mass and the primitive dry extract must be lower to 11% mass. Therefore, this is an alcoholic drink, which is not suitable for celiac patients due to the contamination risk.

According to Albanese [19], production and marketing of very low gluten content (< 100 mg/L) or gluten-free (< 20 mg/L) beers is still in its starting phase and the projected market value in Europe is estimated on the order of several billion Euros per year [20]. Most gluten-free beers foresee the use of at least a fraction of malts derived from cereals and pseudo-cereals not containing gluten or its precursors, such as sorghum, buckwheat, quinoa, and amaranth [21].

Sorghum is increasingly incorporated into snack foods and bakery products, being an attractive alternative for wheat allergy sufferers. This growing demand from celiac has led to sorghum being commercially available in gluten free bread, pasta, cookies, cereal, beer and bakery mixes for brownies, cakes, and pancakes [18]. In Cuba, different types of bread, toasts and confectionery using the sorghum flour, are elaborated, which is known as "Gluten Free Breading" [15, 22].

Malt drink is a nutritive beverage, obtaining from a broth preparing from grains. The difference from beer is that it is not subjected to fermentation process; therefore it lacks alcoholic graduation [1]. In Nigeria sorghum also was using in combination with other cereals as millet and maize to produce a Kunu, a non alcoholic cereal beverages [23], but this technology and the characteristics of main products are different to malt drink. The works of Felipe [24] and Belén [25] reveal that in Cuba there are 1,200 children and more of 450,000 adults with celiac disease. Supply this power nutrient food for celiac population can improve their life quality and diet. However, no malt drink production plant from sorghum exists to fulfill this necessary required beverage and research about its production and consumption has not been published.

The availability of diverse food to Cuban celiac individuals should be increased and be cheaper, and the gluten-free malt drink is also a product that celiac patients should consume. Nevertheless, the malt drink process production from cereals different to barley has not yet been well established, despite some recent encouraging results [26].

In this work a preliminary batch process design for producing malt drink from sorghum is proposed. Experimental results [27, 28, 29] are used to define the model parameters, like fixed size factors and processing times. The design model considers out-of-phase unit duplication in order to reduce the production cycletime and idle times while improving the process performance. The problem is formulated as a mixed integer programming model (MILP) for which the minimum investment cost is obtained and the global solution can be assured. This type of optimization model was previously used for successfully designing and planning batch and semicontinuous process [30]. As optimization results, the number of units and sizes for maceration, filtration, cooking, and clarification stages, are determined. The production planning along the time horizon of one year is also decided, given by the number of batches to be processed and its size. The model is implemented and solved in GAMS [31] and different production scenarios are analyzed, for which the investment cost is minimized, the economic profitability indicators are calculated, and the progress in this free-gluten food is evaluated. The contribution of this work is to obtain feasible plant design for implementing this new and healthy beverage for a celiac population with limited drink options.

2. MATERIALS AND METHODS

With the aim of obtaining preliminary process design for a sorghum malt drink plant, some steps are performed. First, the malt production process is studied and defined for the present work. Then, the mixed integer linear model for obtaining the optimal design of the process is stated. This formulation is adapted for malt drink from sorghum, but is a well known formulation in the classical process systems engineering literature (see [30] and [32]). This mathematical model is then implemented and solved in GAMS (General Algebraic Modeling System) [31] for the different studied cases in order to evaluate the economic feasibility through the usual mathematical method for profitability evaluation[33]. In the following sections, each step is described.

2.1. Process description

The raw material, the milled UDG-110 sorghum malt, is prepared considering one hundred grams of milled sorghum malt per liter of malt that is going to be produced [28]. The first stage is the maceration, where the water is heated until 38 ± 1 °C (the acidification temperature), so that the organic phosphates are activated, decreasing the pH and the endobeta-glucanase enzyme, which catalyzes the decrease of beta-glucan gums [29]. Ten liters of water per Kg of sorghum malt are used. At that point, the grain is added and the process is agitated to avoid lumps formation. Afterwards, a stepwise process, where the temperature is iteratively increased and maintained, is started. The sample is placed in a jacketed reactor in order to regulate the temperature. First, the temperature is fixed at 38 ± 1 °C for half an hour, and then it is increased to 63 ± 1 °C. In that period, the proteolysis occurs to degrade the proteins into simpler proteins and amino acids. This temperature is maintained for 45 minutes, and after this period, it is again increment to 71 ± 1 °C during 30 minutes. Finally, the temperature arrives at 78 ± 1°C and during 10 minutes, the broth is shaking at longer intervals. Figure 1 shows the maceration stage performance. This performance presents a great similarity with the first maceration reported by De Meo [21].

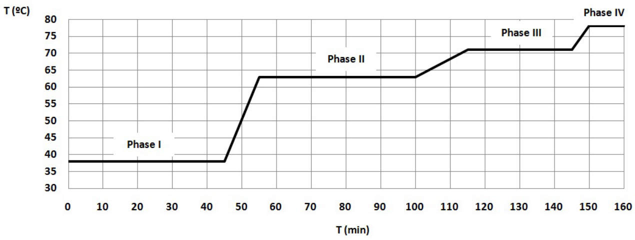

Figure 1. *Maceration stage performance*

The liquid extraction that becomes in malt drink begins in the filtration stage, separating the clear must from the bran by leaching out. The whole mixture is placed on a filter, keeping the liquid in one container and the grain in another. The amount of water used in the filtration is equal to 50% of the water utilized in the maceration stage. When the total broth is strained, hot water is added to the bran in the filter for extracting the remaining sugars. The temperature for this step is 70 °C and it is stirred to keep dissolved the sugar. After a few minutes the previous step is repeated, straining the grain [34]. The obtained bran represents 42% of the product from the maceration. After the extraction process, the bran, rich in nutritive elements, is pumped into a tank and sold as animal feed.

The broth cooking is the following stage, with the aim of inactivating the enzymes of the macerate, sterilizing the must, solubilizing and isomerizing the bitter substances of the hops, especially the alpha-acids that form tannin-soluble proteins at high temperatures and insoluble at lower temperatures, and concentrate the most [29]. This stage is carried out in a tank, which contains the whole liquid, and the temperature has to be higher than 100˚C. This should boil for half an hour, and caramel color and refined sugar is added. This stage has 18 % loss regarding to the total broth that enters to the filtration.

The most adequate levels to carry out the process for obtaining malt drink are between 100-120 g/L of total malt/solution ratio.

The last considered stage is the clarification process, where 4% of the stage input broth is lost. Finally, the malt drink is pumping to a bottling plant.

2.2. Problem statement

The design model for maceration, filtration, cooking and clarification stages is presented in this section. The objective is to develop a batch design and planning approach in order to implement this technology for producing malt drink from sorghum. The fixed size factors and time formulation is used for this purpose [35]. A key issue in this approach is the size factor calculation. For this task, experimental data from [27, 28] and [29], were used for obtaining the streams involved in the process and describing the mass balances. Let t_j be the processing time and S_j the size factor for stage j. It is worth to mention that during the processing time, no materials enter or leave the process unit, and the size factor represents the size needed at stage j to produce one mass unit of final product. Following the usual procurement policy, unit sizes are restricted to take values from a set of available discrete sizes, $SV_j = \{VF_{j1}, VF_{j2}, ..., VF_{jPj}\}$, where P_j is the number of available standard sizes for stage j. In this work, j = 1, …, 4 corresponds to maceration, filtration, cooking and clarification stages respectively. The problem consists in determining the number of batches of malt drink, Nb, its size, B, and the optimal design for the involved stages, i.e. number of duplicated unit per stage, N_j, and its size, V_j, in order to reach the required production Q in the horizon time H at a minimum cost.

2.3. Model formulation

In this section, the mathematical model for the optimal design is presented. According to Grossmann and Sargent [32], the unit size for stage j, is calculated by:

$$V_j \geq S_j B \qquad (1)$$

As previously mentioned, the unit size for each stage is selected from a set of discrete sizes, where VF_{jp} correspond to the p-th element (unit size) of stage j. These values are provided from standard sizes as is shown in the Cases section. Then, the definition of unit size is given by the Eq. (2):

$$V_j = \sum_{p=1}^{P_{jf}} VF_{jp} y_{jp} \qquad \forall j \qquad (2)$$

The binary variable y_{jp} is used for selecting the size of unit j. It is assumed that all units for each stage are identical; therefore, only one size is chosen for each stage:

$$\sum_{p=1}^{P_j^{UP}} y_{jp} = 1 \qquad \forall j \qquad (3)$$

P_j^{UP} represents the maximum number of different unit sizes.

In this type of process, there is a time bottleneck stage. In order to reduce the process cycle time and consequently improve the process performance, unit duplication out of phase is proposed. Let x_{jk} be the binary variable equal to 1 if k parallel units are selected in stage j, then:

$$N_j = \sum_{k=1}^{N_j^{UP}} k\, x_{jk} \qquad (4)$$

Thus, the number of duplicated units is defined by N_j, and N_j^{UP} represents the maximum number of parallel units for stage j. Again, only one option of duplication is selected for each stage as states Eq.(5):

$$\sum_{j=1}^{N_j^{UP}} x_{jk} = 1 \qquad (5)$$

The production planning along the horizon time H is also a decision embedded in the model. Let CT be the cycle time of the process, i.e. the required time to finish one batch of product, then the total production must be fulfilled in the horizon time:

$$Nb\ CT \leq H \qquad (6)$$

Eq.(6) is a non linear equation, so in order to formulate a linear expression the variable w_i that indicates if i batches of product are produced is defined.

$$Nb = \sum_{i=I^{LO}}^{I^{UP}} i \ w_i \tag{7}$$

$$\sum_{i=I^{LO}}^{I^{UP}} w_i = 1 \tag{8}$$

I^{LO} and I^{UP} represent suitable lower and upper bounds for the number of batches. This bound can be calculated from model data as processing times, total amount of product to be produced, etc.

Therefore, using Eq.(7) into Eq.(6), a new expression for the horizon time constraint is reached:

$$\sum_{i=I^{LO}}^{I^{UP}} i \ w_i \ CT \ \leq H \tag{9}$$

With the aim of avoiding nonlinear constraint, the product between the binary variable, w_i, and the continuous variable, CT, is reformulated as a new continuous variable, CTw_i.

$$\sum_{i=I^{LO}}^{I^{UP}} i \ \ CTw_i \ \leq H \tag{10}$$

This new variable must fulfill the following conditions:

$$CTw_i \leq H \ w_i \qquad \forall i \tag{11}$$

$$CTw_i \leq CT \qquad \forall i \tag{12}$$

$$CTw_i \geq CT - H(1 - w_i) \tag{13}$$

$$\sum_{i=I^{LO}}^{I^{UP}} CTw_i = CT \tag{14}$$

On the other hand, the CT corresponds to the time needed to complete batch, and it is calculated as the biggest quotient of the processing time and the number parallel units of each stage, as is stated by Eq. (15):

$$CT \geq \frac{t_j}{N_j} \qquad \forall j \tag{15}$$

Again, in order to avoid nonlinear expressions, Eq.(15) is reformulated using the definition of N_j:

$$CT \geq \sum_{k=1}^{N_j^{UP}} \frac{t_j}{k} x_{jk} \qquad \forall j \tag{16}$$

Finally, the required production, which is calculated as the number of produced batches by its size, must be fulfilled. This condition is stated by Eq. (17):

$$\sum_{i=I^{LO}}^{I^{UP}} i \ w_i \ B \ = Q \tag{17}$$

Analogously to Eq.(9), this expression is linearized using a new continuous variable, Bw_i representing the product of B and w_i:

$$\sum_{i=I^{LO}}^{I^{UP}} i \ Bw_i \ = Q \tag{18}$$

and this variable Bw_i must satisfy the following conditions:

$$Bw_i \leq Q \ w_i \qquad \forall i \tag{19}$$

$$Bw_i \leq B \qquad \forall i \tag{20}$$

$$Bw_i \geq B - Q(1 - w_i) \qquad \forall i \tag{21}$$

$$\sum_{i=I^{LO}}^{I^{UP}} Bw_i = B \tag{22}$$

The objective function involves the investment cost minimization given by Eq.(23):

$$Cinv = C_{ann} \sum_{j=1}^{4} N_j \alpha_j V_j^{\beta_j} \tag{23}$$

C_{ann} is a model parameter that involves the capital charge factor and the annualized and maintenance cost.

Replacing N_j and V_j variables by their discrete expressions, the previous equation reaches:

$$Cinv = C_{ann} \sum_{j=1}^{4} \sum_{k=1}^{N_j^{UP}} \sum_{p=1}^{P_j^{UP}} k \ x_{jk} \ \alpha_j VF_j^{\beta_j} \ y_{jp} \tag{24}$$

In this last equation, the product of binary variables $x_{jk}.y_{jp}$ is presented, which is reformulated through a new variable z_{jpk} defined as follows:

$$z_{jpk} \leq x_{jk} \qquad \forall j, p, k \tag{25}$$

$$z_{jpk} \leq y_{jp} \qquad \forall j, p, k \tag{26}$$

$$z_{jpk} \geq x_{jk} + y_{jp} - 1 \qquad \forall j, p, k \tag{27}$$

Therefore, the total investment cost is calculated by:

$$Cinv = C_{ann} \sum_{j=1}^{4} \sum_{k=1}^{N_j^{UP}} \sum_{p=1}^{P_j^{UP}} k \ \alpha_j VF_j^{\beta_j} \ z_{jpk} \tag{28}$$

Summarizing, the mathematical model for the optimal design and planning for the batch stages considered in this work for producing malt drink involve the minimization of Eq. (28) subject to Eqs. (2)-(5), (7), (8), (10)-(14), (16), and (18)-(22).

All the cases were implemented and solved in GAMS (General Algebraic Modeling System) [31].

2.4. Economic evaluation

The economical evaluation was made through the traditional methodology of Peters and Timmerhaus [33].

3. RESULTS AND DISCUSSION

According to the process description previously presented, Figure 2 shows the stages involved in malt drink production process from milled sorghum malt considered in this work. These are: maceration, filtration, cooking and clarification, also according to Nieblas [1]. As the sorghum malt drink plant will be installed near or in the same site that a brewery, malt drink is pumped to the existing bottling plant, which is appropriately disinfected and cleaned. For this reason the bottling plant are not considered in the design model.

Through mass balances, the size factors were calculated. Table 1 resumes the experimental obtained data for the different stages.

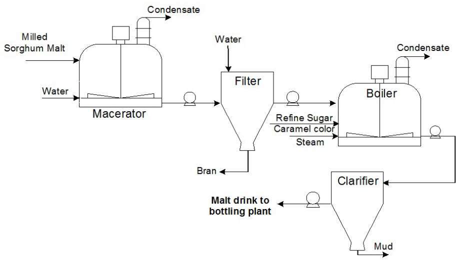

Figure 2. *Stages considered in the design model.*

Table 1. *Experimental data obtained from [27, 28] and [29] describing the mass balances for size factor calculation*

Stage	Inlet flow	Amount (Kg/d)	Outlet flow	Amount (Kg/d)
Maceration	Milled sorghum malt	49.5	-	-
	Water	496	-	-
Filtration	Macerated malt	545.5	Bran	229.1
	Water	248.0	-	-
Cooking	Filtrated	564.39	Loss	101.59
	Caramel	46.5	-	-
	Sugar	37.58	-	-
Clarification	Most	546.88	Loss	21.88
	-	-	*Malt drink*	525 Kg/d

The model parameters for each stage are summarized in table 2. The C_{ann} is equal to 0.1375 and the economic factors were obtained from [36] and updated with proper cost indexes given by the Economic Indicators [37].

In the process under study, the clarification is a time limit stage as can be observed from table 2. The processing time for this stage is more than 36 times longer than the others. Therefore, the unit duplication for this stage is only considered in this work. It is assumed that a maximum number of 20 units working in parallel out of phase is a reasonable amount from the design point of view; therefore, N_4^{UP} = 20 and N_j^{UP} = 1 for j =1, 2, and 3, is proposed.

The unit sizes are simultaneously determined with the number of parallel units. These sizes are selected from the discrete values proposed in table 3.

Table 2. *Model parameters for process design*

Stage (j)	SF_j (m^3/kg)	t_j (h)	α_j	β_j
Maceration	$9.17{\cdot}10^{-4}$	2.583	10338.59	0.72
Filtration	$6.30{\cdot}10^{-4}$	0.5	46193.7	0.51
Cooking	$7.71{\cdot}10^{-4}$	2	10338.59	0.72
Clarification	$9.14{\cdot}10^{-4}$	96	46193.7	0.51

Table 3. *Discrete unit sizes (m^3)*

Stage (j)	VF_{j1}	VF_{j2}	VF_{j3}	VF_{j4}	VF_{j5}	VF_{j6}
Maceration	0.1	0.2	0.3	0.4	0.5	0.6
Filtration	0.18	0.32	0.46	0.6	0.72	0.98
Cooking	0.1	0.2	0.3	0.4	0.5	0.6
Clarification	0.1	0.2	0.3	0.4	0.5	0.6

Considering the time horizon equal to 7,200 hours, the minimum and maximum number of batches can be calculated. Assuming that no units are duplicated, the cycle time is equal to the longer stage time, i.e. 96 hours. Therefore, the minimum number of batches to be produced is equal to 7,200/96 = 75 (I^{LO} = 75). On the other hand, if the total of parallel units are used, i.e. 20, the cycle time is equal to 4.8 h, and therefore the maximum number of batches is equal to 7,200/4.8 = 1,500 (I^{UP} = 1,500).

With these model parameters, the following cases are analyzed, where the required amount of malt drink is varied. For the different cases, societal needs for celiac patients, economic feasibility and preliminary design are assessed.

The number of equations, binary and continuous variables depends on the model characteristics, i.e. maximum number of parallel units, number of proposed discrete sizes for unit, minimum and maximum number of batch, among others. For the parameters previously presented, the model involves 10,022 equations, 3,396 continuous variables and 1,473 discrete variables, and the resolution time is around 3 CPU s.

3.1. Case 1 (production of 500 L/d of malt drink).

In this first case, the annual production is fixed to 150,000 liters per year. This amount was used in the experimental analysis from which model parameters were adjusted.

The optimal design in this case selects 4 unit duplicated out of phase for the clarification stage. This establishes a cycle time equal to 24 hour, which represents the production of one batch per day. The unit sizes are 0.5 m^3, 0.46 m^3, 0.5 m^3 and 0.5 m^3 for maceration, filtration, cooking, and clarification stages respectively. The batch size is equal to 500 L of malt drink, and 295 batches are produced occupying 7,080 hours of the time horizon, i.e. less than the total available time horizon. Figure 3 shows the production planning. It can be noted from the figure that long idle times are reached for maceration, filtration and cooking units. Therefore, the process performance is not efficient. The reason is that the required production amount is small and it can be generated using four units duplicated out of phase for the clarification stage.

The total investment cost for is equal to \$19,546. Then, the economical analysis according to Peters and Timmerhaus [33] is made in order to determine if the production of 500 liters per day is profitable. In table 4 these results are summarized, where it can be noted that this production amount is not profitable (NPV is a negative amount). For this production, the unitary cost for a bottle of 300 mL is \$0.3884, for which no values are reached for the internal Rate of Return and Payback Period. These economic results are reasonable taking into account the small production scale. It is worth to mention that the economic analysis includes the malting process investment cost for obtain the needed raw material.

In order to determine a suitable production amount of malt drink, from the economical point of view, a sensitivity analysis varying the annual produced amount

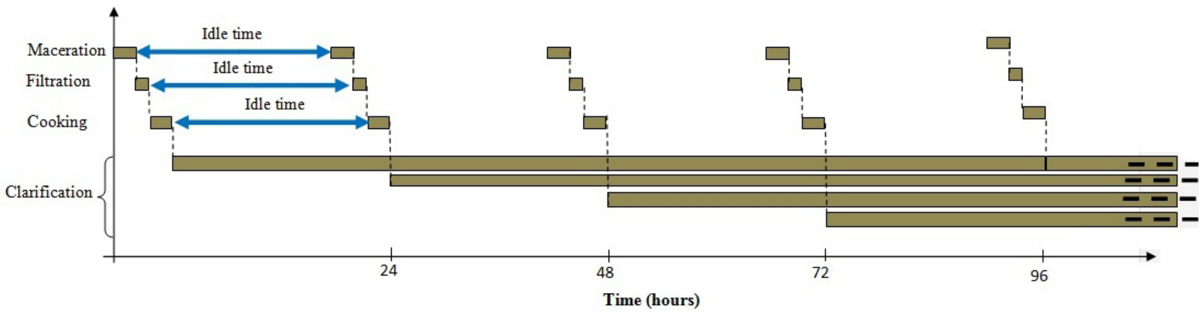

Figure 3. *Production planning for 500 L/day of malt drink*

is made. The main results are summarized in Figure 4, where the equilibrium point is a reached around the production of 530 L/d. Also, the unit cost for each bottle of 300 mL is obtained for the different amounts of produced malt drink, which is shown in Figure 5. From this information the selling price is analyzed, highlighting that for values greater than 10,000 L per day, the reduction is asymptotic.

Table 4. *Economical analysis for 500 L/d of malt drink*

Economic values	
Net Present Value ($)	-$185,014.14
Internal Rate of Return (%)	-
Payback Period (years)	-
Profitability ($/year)	- 9,405.66
Total production cost ($/year)	194,214.34
Unitary cost ($/bottle)	0.3884

From the design point of view, the proposed set of possible unit sizes is varied in order to obtain feasible design. In other words, the data of table 3 is modified in such way that for greater production amount, bigger unit sizes are provided. Figure 6 shows the number and size of units for clarification stage obtained for the optimal design of each case in the sensitivity analysis.

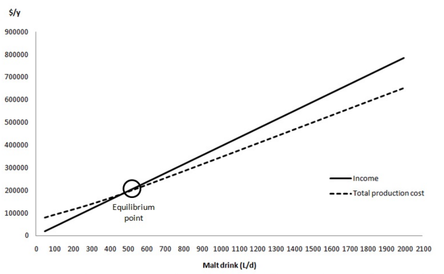

Figure 4. *Economical results for the sensitivity analysis varying produced amount*

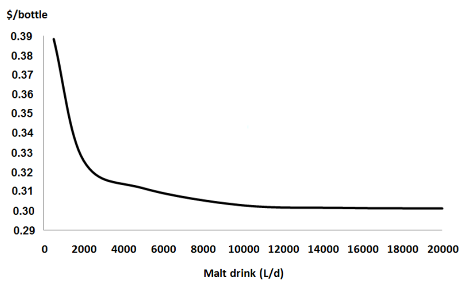

Figure 5. *Sensitivity analysis: unit price for bottle of malt drink vs. produced malt drink*

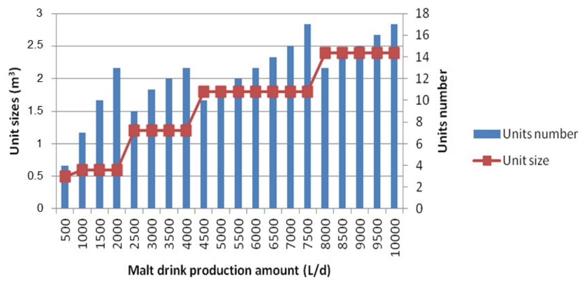

Figure 6. *Sensitivity analysis: design of clarification stage*

3.2. Case 2 (production of 5,000 L/d of malt drink).

As was previously mentioned, the celiac population in Cuba involves 1,200 children and more of 450,000 adults. According to the sensitivity analysis previously presented, the number of patients, and the different plant designs obtained for each studied case, it is assumed that a production plant of 5,000 L/d can suitably fulfill the demand around the region where the facility will be located.

For a daily production of 5,000 L of malt drink, the optimal solution selects 11 units out of phase for the clarification stage, reducing the cycle time to 8.73 h, and consequently decrementing the idle time of the other stages. The investment cost in this case is $81,409, and Figure 7 displays the cumulative cash position along the years and show that this case is profitable. In tables 5 and 6 some design and economical results are presented, respectively. The occupied volume in each unit is given on order to assess the equipment use and process performance.

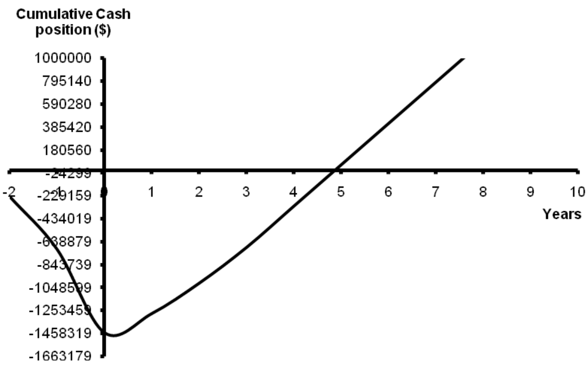

Figure 7. *Cumulative Cash Position evolution for 5,000 L/d production*

The unit cost per bottle of 300 mL of malt drink is equal to $0.312, which is a reasonable value for the local habitants.

In Abdulraheem [38], a technology with certain similarities to those studied in this article was used, since malted sorghum is used as raw material for the "Mucamalt" malt drink. They obtained a total production cost of 12,876.68 $/day, producing 160 hL/day, which leads to a unit cost of 80.47 $/hL. In the present work, 0.312 $ per bottle of 300 mL represents a cost of 104 $/hL of malt drink. Taking into account the characteristics of the technology analyzed in this work and costs updating, the difference of 23.53 $/hL corroborates that, in addition to the social impact that it has on celiac patients, it is also an economically promising technology.

On the other hand, the payback period of 4.8 years represents a good inversion for the brewer sector, which can take advance of their installation and add the necessary units and cleaning processes for producing malt drink from sorghum. Finally, it is worth to highlight that this represents an alcohol-free drink, not only nutritious for celiac patient, but also for all the people who want a healthier lifestyle.

Table 5. *Process design for producing 5,000 L/d of malt drink*

Stage	Number of parallel units	Size (m^3)	Occupied Volume (m^3)
Maceration	1	1.8	1.78
Filtration	1	1.38	1.22
Cooking	1	1.5	1.5
Clarification	11	1.8	1.78
Number of produced batches per year		825	
Cycle time (h)		8.73	
Batch size (Kg)		1,944.5	

Table 6. *Economical analysis for 5,000 L/d of malt drink*

Economic values	
Net Present Value ($)	1,139,331.7
Internal Rate of Return (%)	38.3
Payback Period (years)	4.8
Profitability ($/year)	358,986.5
Total production cost ($/year)	1,557,905
Unit cost ($/bottle)	0.312

3.3. Physical characteristics of malt drink from sorghum.

From the physical aspect, the obtained malt drink with the technology proposed in this work, meets the established requirements for its consumption. Table 7 was taken from [1], which compares the malt drink from malted sorghum obtained in a pilot scale trial using the technology presented in this work, and two malt drinks from barley widely commercialized in Cuba: Bucanero and Tínima malt drink.

Table 7. *Malt drinks comparison of physical and organoleptic parameters*

Malt drink	°Bx	pH	ρ (kg/m^3)	Viscosity (cP)	Color and Taste	Smell
Sorghum	*16.3*	*3.72*	*1,054*	*1.72*	*Appropriate**	*Characteristic**
Bucanero	13.0	4.06	1,040	1.63	-	-
Tínima	14.5	4.78	1,050	1.65	-	-

**People appreciation in comparison with Bucanero and Tínima malt drink.*

Density, viscosity, acidity, pH, extract and organoleptic characteristics (color, taste and smell) are within the reported parameters for this drink and closed to the barley malt drinks sold in Cuba, Bucanero and Tínima [1].

6. CONCLUSIONS

In this work, a MILP formulation for the optimal preliminary design of a malt drink plant from sorghum was presented. The traditional constant size factors and time approach was implemented taken into account the proper process information. The experimental cooperation work allowed the model parameters calculation, which represent a key aspect to the suitable representation of the problem. Moreover, the production process design of this free gluten beverage represents a novel development to the best of our knowledge.

A sensitivity analysis was presented in order to state the tradeoffs between economical indicator and social sustainability. According to this analysis, different scenarios can be performed for maximizing the number of celiac patients accessing to malt drink at minimum plant investment cost. Starting around 520 liter of malt drink per day, its production is feasible from the economical point of view. However, in order to reach a reasonable unit cost per bottle and suitable production to fulfill the demand for celiac patients, a greater amount of product is proposed. It was shown that for a production of 5,000 L/d, the payback period is equal to 4.8 years, the unit cost per bottle is $ 0.312, and the obtained plant design improves the plant performance.

The obtained malt drink with the technology presented in this work meets the established physical requirements for its consumption.

The presented approach serves as a tool for evaluating a healthy drink plant installation, needed to cover the lack of food options for celiac patient.

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