SILAGE PRODUCTION FROM THE RESIDUES OF PLANTAIN (M*usa* AAB Simmonds): A NUTRITIONAL ANALYSIS THROUGH PROCESS SIMULATION

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KEYWORDS

Agriculture; Computer software; Manufacturing; Scheduling; Simulators.

ABSTRACT

Sustainable processes are required to decrease the environmental and economic impact of residues and wastes. Therefore, the agro-industrial waste upcycling, as substitutes of substrate, is of paramount relevance. In this work, the nutritional value of silage from fresh residues of plantain agro-industry was evaluated by process simulation, as an alternative of dairy cattle feed. Several databases were accessed to design the process. SuperPro Designer V10 simulator was used. Results showed that fresh plantain residues mixed with 97.14% pseudo total, 0.24% rejection banana and 1.63% of rachis are not recommended for dairy cattle consumption due to its high moisture content (>90%), fiber neutral detergent (>50%) and acid detergent fiber (>30%). Simulation techniques have shown to be a powerful tool when making decisions on investment projects that involve technologies for waste utilization in order to find the more appropriate process configuration reducing experimentation requirements.

INTRODUCTION

The global production of agricultural waste was projected at approximately 368,3 million tonnes for 2016 (Gómez, Sánchez, and Matallana, 2019). Plantain waste production was about 241.3 million tonnes, considering a worldwide plantain production of 39.2 million tonnes, in 2017 (Escalante, Orduz, Zapata, Cardona, and Duarte, 2009; FAO, 2019). Plantain waste are mostly made up of rachis, rejected plantain, and pseudostem (Escalante et al., 2009). Dominico–Hartón clone (*Musa* AAB *Simmonds*) is among the varieties of greatest economic interest in Colombia. Most of plantain waste in Colombia is left in the plantations or treated as urban solid waste (Mazzeo, Díaz, and Mejía, 2015; Mazzeo, León, Mejía, Guerrero, and Botero, 2010).

The physicochemical composition of *musaceae* waste (plantain and banana) is variable and has a significant biological value (Agama, Sañudo, Vélez De La Rocha, González, and Bello, 2015; Botero and Mazzeo, 2009; Mohapatra, Mishra, and Sutar, 2010). Thus, plantain waste seems a good alternative as dairy cattle feeding. The aim of this work was to design and evaluate the process of silage production from fresh plantain waste, considering nutritional criteria, by process simulation. The viability of dairy cattle feed production was evaluated.

METHODS AND MATERIALS

Information Collection

Waste and process information was collected from the databases of Scopus, Web of Science and Google Scholar. The search strings were as follows: 1) Plantain AND use * AND waste *; 2) (Process * OR transformation OR use *) AND waste AND (plantain OR banana) AND silage. The methodology of Pérez and Muñoz (2014) was used to identify the amount of documents to be analyzed. The information in each document was exported to a spreadsheet matrix in MS Excel for analysis.

Design and simulation of silage production processes

Batch size processing

Batch size of the plantain waste to be processed in the simulation was calculated from the historical plantain production between 2007 and 2018 in Caldas province, Colombia (Agronet, 2019). Forecasting tools such as linear regression analysis, simple moving average, weighted moving average and exponential smoothing were used (Holt, 2004; Jacobs and Chase, 2008; Winters, 1960). The silage formulation described by Chiba, Chiba, and M (2005) was used (see Table 1).

Table 1: Silage formulation for 100 kg Product (dry basis)

Component	Quantity (kg)
Molasses solution 50% (w/v)	3
Urea	2
Plantain waste	95

Design and simulation procedure

The design and simulation of the ensilage process was carried out using the SuperPro Designer v10 simulator licensed to the Universidad de Caldas (see Figure 1). The values of the main physical-chemical properties of the compounds (molecular weight, enthalpy of formation, normal boiling point and normal freezing point, among others) were consulted in specialized databases (U.S. National Library of Medicine, 2020), software's (Royal Society of Chemistry, 2015) and bibliographic sources (Aix-Marseille Université, 2019; Kanehisa Laboratories, 2019; Yaws, 2008, 2015).

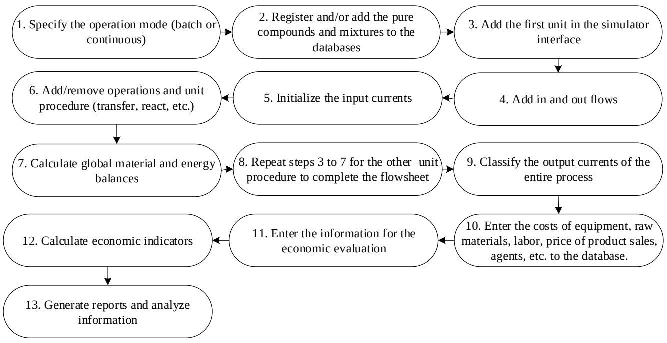

Figure 1: Simulation Procedure Using SuperPro Designer

Nutritional analysis.

The content of Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF) in the products was calculated from the composition reported by the process simulator used in this work and using the procedure described by Van Soest and McQueen (1973). A correction factor of 0.15 was used for fat, protein and ash content, and 0.98 as digestibility factor (Goering and Van Soest, 1970):

$$Hemicellulose = \%NDF - \%ADF \quad (1)$$

$$Cellulose = \%ADF - \%lignin \quad (2)$$

The content of Non–Fibre Carbohydrate (NFC), Digestible Energy (DE) and Metabolizable Energy (ME) was calculated according to the procedure described by the National Academy of Sciences (2001), considering that the fat content was replaced by the content of the ethereal extract:

$$NFC = 100 - (\%NDF + \%\ crude\ protein + \%\ fat + \%\ ash) \quad (3)$$

$$DE\ (Mcal/kg) = 0.04409 \times \%TDN \quad (4)$$

$$ME\ (Mcal/kg) = 1.01 \times DE\ (Mcal/kg) - 0.45 \quad (5)$$

The content of Total Digestible Nutrient (TDN) and net Energy for Lactation (NE_L) was calculated using the procedure described by Schroeder (1994):

$$TDN = 88.9 - (\%ADF \times 0.779) \quad (6)$$

$$NEL\ (Mcal/lb) = (\%TDN \times 0.01114) - 0.054 \quad (7)$$

The reference ranges of the nutritional parameters used in the compositional evaluation of the simulated products are presented in Table 2.

Table 2: Reference Range of the Nutritional Parameters for Silage

Parameter	Values in DM	Reference
Moisture	<50%	National Academy of Sciences (2001)
NDF	25% minimum	
ADF	17% minimum	
NFC	44% maximum	
Crude protein	>13.8%	
Silica	<0.2%	
Parameter	**Values in DM**	**Reference**

Calcium	0.6%–0.7%	FEDNA (2009)
Phosphorus	0.3%–0.4%	
Potassium	1.0%–1.5%	
Magnesium	0.18%–0.21%	
NE_L/kg DM	>1.37 Mcal	

DM: dry matter

RESULTS AND DISCUSSION

Description of the process for silage production

The block diagram of the silage production process is shown in Figure 2. In the silage production process, the particle size is important. A particle size of 3 mm is suggested to provide an adequate size to the food and avoid ruminal acidosis (National Academy of Sciences, 2001).

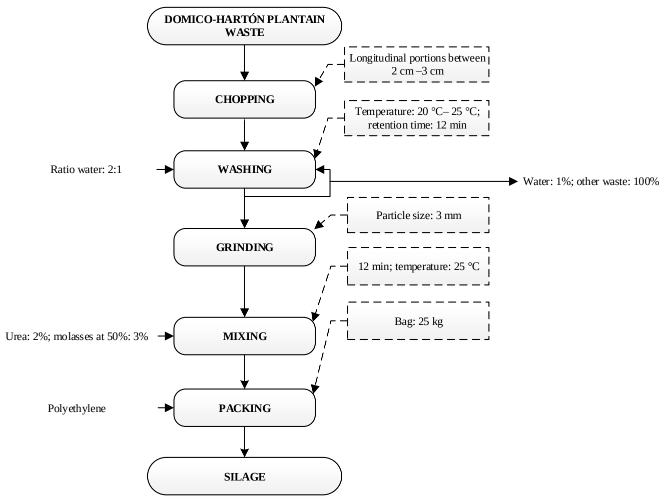

Figure 2: Block diagram of the Silage Production Process

Batch size processing

The projection method presented by the lower Mean Absolute Deviation (MAD) was the weighted moving average with a value of 20,254 tonne. This method projected a plantain production of 264,122 tonne for the year 2019 (see Figure 3). Table 3 shows the average amount of fresh fruit and waste obtained from the harvest of the Dominico–Hartón plantain plants evaluated at the Montelindo Farm and the projection of the production of fruit and waste for the Caldas province in 2019.

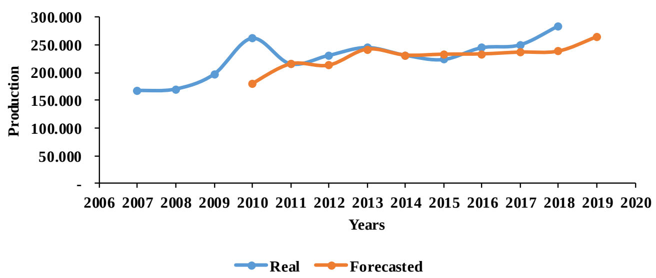

Figure 3. Forecast of Dominico-Hartón plantain production for Caldas province

Table 3 shows that the leaf sheaths, a lignocellulosic material, comprises about 57% of waste, while the material with higher starch content, represented mostly by rejected fruit, is less than 2%. The high content of NDF and ADF in the residues, specifically represented by leaf sheaths and leaves, and the low amount of starch that the rejected plantain can provide, can have a negative effect on the formulation of feed for dairy cattle. Energy intake is generally one of the limiting factors in milk production and depends, among other factors, on the relationship between fibrous and non-fibrous carbohydrates (FEDNA, 2009). The National Academy of Sciences (2001) recommends that the content of NDF be 25% as long as 19% comes from fodder. The forage has a considerable amount of starch and protein (FEDNA, 2019) that can balance the relationship between fibrous and non-fibrous carbohydrates in plantain residues to be used in the feeding of dairy cattle.

Table 3: Plantain fruit and waste yields obtained at experimental Montelindo Farm and estimated waste production extrapolated for Caldas province in 2019

Part	Measured mass (kg)	Share (%)	Quantity calculated for 2019 (tonne/year)
Floral stalk	15.50	19.94	321,080
Leaf sheaths	44.15	56.78	914,561
Rachis	1.00	1.29	20,714
Fruit	12.00	15.43	264,122
Rejected fruit	0.90	1.16	3,099
Leaves	4.20	5.40	87,002
Total	**77.75**	**100.00**	**1,610,580**

Table 4 shows the quantity (kg/day) of the selected waste and the percentage of participation calculated from the global plantain data produced in the studied region and the measurements of the waste generated in the Montelindo Farm. From the total amount of waste chosen, a batch size of 132,640 tonne/year (approximately 360,000 kg/day) was defined.

Table 4. Selected Waste Streams from Plantain Agro-industry

Waste	Quantity (kg/day)	Share (%)
Pseudostem	3,385,319	97.14
Rejected fruit	8,492	0.24
Rachis	56,753	1.63
Other waste	34,505	0.99
Total	**3,485,071**	**100.00**

Design and simulation of silage production process

Figure 4 shows the flowsheet for silage production from fresh plantain waste. The process was designed for processing an inlet mass flowrate of 8,000 kg/h. The installation of a system for decanting solids (E–03) and recovering wash water (E–04) in equipment E–02 was included in the simulated process flowsheet. This configuration allowed to reduce water consumption to a ratio of 2 parts to 1 waste. In the mixing stage, a constant automatic dosing system was included based on the mass flowrate consisting of valves (from E–07 to E–09). This system allowed to eliminate the manual loading of the additives in the equipment E–14, E–13 and E–10 of the process flowsheet.

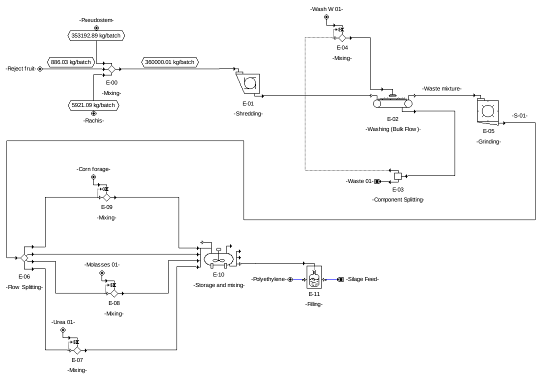

Figure 4: Process Flowsheet for Silage Production

Figure 5 shows the corresponding Gantt chart. It should be highlighted that the E-11 equipment (packing) represents the bottleneck of the silage process. The operation time in the bottleneck, being greater than the process times of all the units making up the flowsheet within a batch, represents the limiting stage of the entire process and defines the time required to start the next processing batch (cycle time). The cycle time corresponds to the usage time of the bottleneck unit, which is, in turn, the minimum possible time between productive cycles.

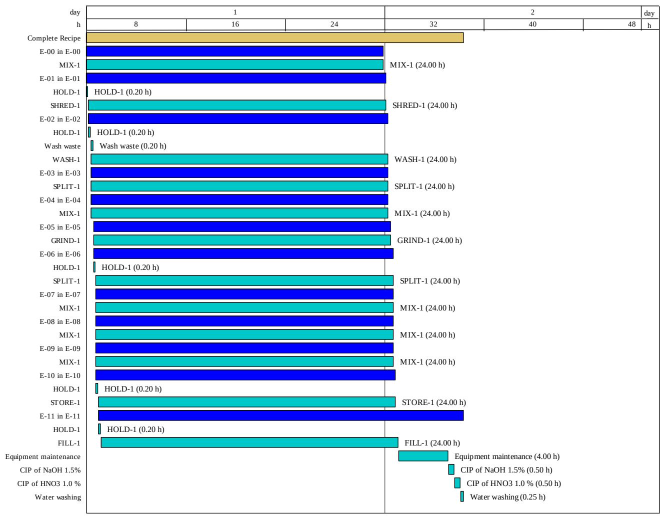

Figure 5. Gantt Chart of the Process for Producing Silage

The start of the operation of each equipment in the flowsheet was made with 12 minutes of difference between one equipment and the next. This programming allowed the flowrate of material entering the equipment to be processed in a semi-continuous mode in order to process a greater amount of feedstocks per unit of time. The silage process had an available time of 8,520 h with a batch time of 30.45 h, a cycle time of 29.45 h, and a number of batches per year of 289.

Table 5 shows the silage composition obtained by simulating the flowsheet for the production of the silage formulation defined. These results indicate that the original silage formulation (see Table 1) did not significantly improve the nutritional composition. On the other hand, the contents of NDF and ADF in the silage decreased to a lesser extent. The amount of NFC increased in the silage due to the addition of sucrose, fructose and glucose from the molasses. The above effect may be influenced by the amount of additives and their DM content. In this sense, the additives disperse the original compounds of the initial mixture of the waste.

Table 5: Compositional Product Analysis Obtained from the Simulation (dry basis)

Component	Traditional blocks
Fibers	
NDF	40.74
ADF	24.91
Proximal analysis	
Moisture	91.02
Ethereal extract	0.30
Crude protein	2.89
Cellulose	18.43
Hemicellulose	13.62
Lignin	3.56
NFC	28.49
Starch	18.09
Glucose	1.09
Fructose	1.40
Sucrose	5.84
Urea	21.00
Ash	11.71
Silica	0.22
Calcium	0.01
Phosphorus	0.00
Potassium	0.05
Magnesium	0.00
Others	11.44
TDN	69.50
Energy	
NE_L (kcal/kg)	1,586

CONCLUSIONS

Considering the available literature, computer-assisted simulation was used for the first time to design and evaluate nutritionally the production of silage for feeding dairy cattle from plantain residues. This work allowed comparing the composition of fresh plantain waste according to different international standards (FEDNA, 2009; National Academy of Sciences, 2001), managing to analyze the nutritional value of a mixture of these residues as a source of energy for dairy cattle, considering the NDF, ADF and NFC. Based on the results of the simulations, it is proposed to study an alternative technology for the reduction of moisture from plantain waste, as well as a reformulation of the products, which may be the key to improving the profitability indicators of these processes for waste valorization. In this way, the process simulation represents a powerful tool for the design of the different stages for producing different types of food products for ruminants, taking into account their specific requirements and the possibility of using agro–industry waste of wide availability in the context of each country.

FUTURE WORK

In future work, the design and evaluation of the production processes of blocks and silage from residues of the plantain agro-industry will be approached under the concept of biorefineries.

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REFERENCES

Agama E., Sañudo, J., Vélez De La Rocha, R., González, G., Bello, L., 2015. Potential of plantain peels flour (*Musa paradisiaca* L.) as a source of dietary fiber and antioxidant compound. CyTA - Journal of Food, 14(1), 117-123. doi:http://dx.doi.org/10.1080/19476337.2015.1055306

Agronet, 2019. Área, Producción y Rendimiento Nacional por Cultivo (Area, Production and National Yield by Cultivation, in Spanish). https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=1. (accessed Octuber 12 2019).

Aix-Marseille Université, 2019. Carbohydrate-Active enZYmes Database (CAZy). http://www.cazy.org/Welcome-to-the-Carbohydrate-Active.html. (accessed June 19, 2019).

Botero L., Mazzeo, M., 2009. Obtención de harina de ráquis del plátano dominico hartón, y evaluación de su calidad con fines de industrialización (Obtainment of rachis flour from Dominico–Hartón plantain, and its quality evaluation with industrialization purposes, in Spanish). Vector, 4, 83-94.

Chiba S., Chiba, H., M, Y., 2005. A guide for silage making and utilization in the tropical regions. http://jlta.lin.gr.jp/report/detail_oversea_pdf/kaigai_m039.pdf.

Escalante H., Orduz, J., Zapata, H., Cardona, M., Duarte, M., 2009. Atlas del potencial energético de la biomasa residual en Colombia (Atlas of the energy potential of the residual biomass in Colombia, in Spanish). https://bdigital.upme.gov.co/handle/001/1058.

FAO, 2019. FAOSTAT: Food and agriculture data. http://www.fao.org/faostat/es/#data. (accessed 2 de junio 2019).

FEDNA. 2009. Necesidades Nutricionales para Rumiantes de Leche (Nutritional Requirements for Dairy Cattle, in Spanish). Fundación Española para el Desarrollo de la Nutrición Animal (FEDNA), Madrid.

FEDNA, 2019. Ensilado de maíz (Corn silage, in Spanish). http://www.fundacionfedna.org/forrajes/ensilado-de-ma%C3%ADz. (accessed July 18, 2019).

Goering H., Van Soest, P., 1970. Forage fiber analyses (apparatus, reagents, procedures, and some applications)

Gómez J., Sánchez, Ó., Matallana, L., 2019. Residuos urbanos, agrícolas y pecuarios en el contexto de las biorrefinerías (Urban, agricultural and livestock waste in the context of

biorefineries, in Spanish). Revista Facultad de Ingeniería, 28(53), 7-32. doi:https://doi.org/10.19053/01211129.v28.n53.2019.9705
Holt C., 2004. Forecasting seasonals and trends by exponentially weighted moving averages. International Journal of Forecasting, 20(1), 5-10. doi:https://doi.org/10.1016/j.ijforecast.2003.09.015
Jacobs F., Chase, R., 2008. Operations and Supply Management: The Core. McGraw-Hill/Irwin, New York.
Kanehisa Laboratories, 2019. KEGG: Kyoto Encyclopedia of Genes and Genomes. https://www.genome.jp/kegg/. (accessed June 19, 2019).
Mazzeo M., Díaz, F., Mejía, L., 2015. Aprovechamiento de Residuos de Cosecha y Poscosecha del Plátano (Use of Harvest and Post-harvest Residues of Plantain, in Spanish). Universidad de Caldas, Manizales, Colombia.
Mazzeo M., León, L., Mejía, L., Guerrero, L., Botero, J., 2010. Aprovechamiento industrial de residuos de cosecha y poscosecha del plátano en el departamento de Caldas (Industrial use of plantain harvest and post-harvest waste in the department of Caldas, in Spanish). Revista de Educación en Ingeniería, 5(9), 128-139. doi:http://dx.doi.org/10.26507/rei.v5n9.14
Mohapatra D., Mishra, S., Sutar, N., 2010. Banana and its by-product utilisation: an overview. Journal of Scientific & Industrial Research, 69, 323-329.
National Academy of Sciences. 2001. Nutrient Requirements of Dairy Cattle, Vol. 7. The National Academy of Sciences, Washington.
Pérez J., Muñoz, L., 2014. What can't be ignored in service quality evaluation: Application contexts, tools and factors. Revista Facultad de Ingeniería Universidad de Antioquia, 72, 145-160.
Royal Society of Chemistry, 2015. ChemSpider. http://www.chemspider.com/. (accessed March 13, 2019).
Schroeder J., 1994. Interpreting forage analysis. https://library.ndsu.edu/ir/bitstream/handle/10365/9133/AS-1080-1994.pdf?sequence=2.
U.S. National Library of Medicine, 2020. PubChem. https://pubchem.ncbi.nlm.nih.gov/. (accessed March 13, 2020).
Van Soest P., McQueen, R., 1973. The chemistry and estimation of fibre. Proceedings of the Nutrition Society, 32(3), 123-130. doi:https://doi.org/10.1079/PNS19730029
Winters P., 1960. Forecasting sales by exponentially weighted moving averages. Management Science, 6(3), 324-342. doi:https://doi.org/10.1287/mnsc.6.3.324
Yaws C., 2008. Thermophysical Properties of Chemicals and Hydrocarbons. William Andrew Publishing, Beaumont.
Yaws C., 2015. The Yaws Handbook of Vapor Pressure. Elsevier, Oxford.

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