AP AGRO PRODUCTIVIDAD

Colegio de Postgraduados

Factors influencing caking of cane sugar

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ABSTRACT
Objective: To identify variables that influence the cane sugar caking process in order to develop a path diagram showing the possible cause-effect relationship between caking and the factors leading to it.
Design/methodology/approach: The methodological work was based on a literature review of the subject following a search through the databases of indexed scientific journals.
Results: Based on the literature review, the most cited causal factors of cane sugar caking are physicochemical properties, packaging, and storage conditions. These factors were used in constructing the path diagram of the caking phenomenon.
Study limitations/implications: Studies carried out on the cause-effect relationship behind this phenomenon have been very limited as evidenced by the small number of scientific papers found on this subject in the search. Additionally, most of these articles are not recent.
Findings/Conclusions: The main factors affecting the development of caking in cane sugar can be classified as: physicochemical (moisture, product temperature and particle size), packaging (liner) and storage conditions (ambient relative humidity and temperature).

Keywords: Lumpiness, sugar, path diagrams.

Citation: Hernández- Reyes, M. L., Hidalgo-Contreras, J. V., Hernández-Cázares, A. S. & Pascual-Ramírez, J. (2022). Factors influencing caking of cane sugar. *Agro Productividad*. https://doi.org/ 10.32854/agrop.v15i4.1992

Editor in Chief: Dr. Jorge Cadena Iñiguez

Received: April 8, 2021.
Accepted: February 19, 2022.
Published on-line: April 1, 2022.

Agro Productividad, 15(3). March. 2022. pp: 13-19.

INTRODUCTION

The sugar industry is considered one of the oldest in the world. One of the first technologies that gave way to what we know today as mills were trapiches, which used animal power to grind sugar cane to obtain panela, an unrefined whole cane sugar. Later, sugar mills emerged (Von Wobeser, 1988). Currently, Mexico has 51 sugar mills, distributed in 7 regions and 15 states (CONADESUCA, 2019).

During the 2020-2021 harvest in Mexico, 49 of the 51 mills in the country were in operation, industrializing a total of 790,000 ha of sugarcane and milling 51 million tons of sugarcane resulting in 5.7 million tons of sugar (CONADESUCA, 2021). The state of Veracruz is home to 18 of the 51 above-mentioned mills, which produced around 2,499,011 tons of sugar, of which 461,725 tons correspond to refined sugar produced by only 4 of the 18 mills in the state (CONADESUCA, 2021). In addition, the sugar agroindustry in Mexico has a very important social weight, providing at least 2 million jobs directly or indirectly to people engaged in activities within the chain (Aguilar-Rivera *et al.*, 2017).

Against this background, it is of the utmost importance to conduct relevant research that can benefit each of the seven links in the value chain, including cultivation and harvesting, transportation of sugarcane from the field to the factory where it is transformed into sugar, direct or indirect marketing, transportation for sugar distribution, and marketing of the product for direct use, industrial use, and, lastly, the final consumer (Aguilar-Rivera *et al.*, 2017).

According to Aguilar-Rivera (2014), the sugar agroindustry has competitiveness problems because it is not energy self-sufficient. As a result, Mexico does not have the capacity to be a sugar exporter. For this reason, the domestic market becomes the basis for the sugar trade. Therefore, the objectives should be focused on reducing field, factory and administration costs (Aguilar-Rivera N., 2010).

Sugar caking is a phenomenon that affects the marketing of the product because it does not allow its fluidity during industrial use, making it difficult to apply as a raw material in the food industry. Therefore, this study uses causal analysis to contribute to the identification and quantification of the factors that cause it, which could subsequently contribute to a better understanding of the phenomenon. This study aimed to contribute to improving the competitiveness of the sugar agroindustry by identifying the most relevant factors involved in caking, which has a direct impact on the quality of the final product.

MATERIALS AND METHODS

Path analysis is the predecessor model to structural equations. These analyses had their origin in 1917 when the American geneticist Sewall G. Wright designed a model with which he intended to explain the genetic influence between littermates. The relationships found by Wright were represented in a path diagram. In the early 1970s this methodology was taken up and improved by economists and sociologists, making it much more effective, the so-called path analysis, today known as structural equation modeling (Garcia V., 2011). Path analysis is a methodology that facilitates the study of a system of structural equations and is based on three essential components: the path diagram, the identification of correlations and covariance, and the distinction between direct and indirect effects. These diagrams enable visualizing the theory being proposed, since doing so with mathematical equations would make it difficult to understand (Medrano & Muñoz-Navarro, 2017). Figure 1 shows what a path diagram consists of. Through it, direct and indirect effects can be identified; for example, physicochemical properties have a direct effect on caking, but also have an indirect effect on this phenomenon through packaging. The structural equation representing the path diagram in Figure 1 is:

$$Caking=\lambda_{11}Physicochemical\ properties+\lambda_{21}Packaging+\lambda_{31}Storage+E$$

where: λ_{ij} correspond to the correlations associated with the i-th effect of the j-th causal and E is the random error.

To carry out the structural equation methodology, Cupani (2012) recommends following six stages: specification, identification, parameter estimation, fit evaluation, model respecification and, finally, interpretation of the results (Cupani, 2012). In this sense, this work shows the specification stage, in which knowledge and understanding of the theory related to the phenomenon to be studied, in this case, caking, is a priority. To achieve this specification, an exhaustive literature review of previous research and theories related to the phenomenon must be carried out. If this stage is not carried out properly, the results may lead to situations where the expected parameters are not correctly assigned.

In this study, a search was carried out in the bibliographic databases of the *Colegio de Postgraduados* and Google Scholar, which in turn directed us to various journals such as the Journal of Food engineering, Advanced Power Technology, and Procedia Engineering. The keywords used in the search were *aterronamiento de azúcar* and *compactación de azúcar*. In order to broaden the search, sugar lump, lump, and caking sugar were used, which provided better results. The search was conducted on the basis of research published over the previous ten years; a long time span due to the fact that very few studies have been carried out on this phenomenon. Once the studies were reviewed, a table divided into three columns was drawn up containing the name of the author and the date of his/her work, the research work carried out and finally the causes that led to the caking found by the authors, with the aim of identifying and classifying the causes. Subsequently, the path diagram was made. It should be noted that for this stage there is no methodology as such, but rather the diagrams are built based on the understanding of the phenomenon shown by the researchers, the interaction, and the direction between the variables.

RESULTS AND DISCUSSION

Caking is a phenomenon that can be observed during the storage and distribution stages. It is due to the sensitivity of sugar to environmental conditions and grain size. These conditions promote the formation of a crystalline interface and liquid bridges between sugar grains that form a conglomerate unable to flow, which can only be reversed by mechanical means (Castrillon *et al.*, 2011). Sugar is mainly used for domestic consumption and as a raw material for industry. When the lumpiness characteristic is present, its use becomes difficult, and this is a reason for rejecting the product (Pascual-Ramirez *et al.*, 2016).

Christakis *et al.* (2006) explain caking as the exchange of surface water between product particles. When this exchange occurs, the particles absorb moisture and join by means of liquid bridges and when they dry out, they become solid. These bridges can have different strengths related to water activity (Aw) conditions. At an Aw of 0.8, solid bridges become two to three times stronger than liquid bridges (Billings *et al.*, 2006).

Regarding this phenomenon, useful research has been carried out for sugar manufacturers in order to minimize this defect in sugar, as well as its negative repercussions. Tait *et al.* (2010) placed sugar in a dryer in which the air flow was mainly modified, preserving most of the parts of the original machinery but changing the location of some of them for storage in a silo, thus achieving great advances in minimizing the appearance of lumps in the finished product and thereby avoiding the use of machinery provided for the decompaction of packaged sugar. Chitprasert *et al.* (2006) carried out studies on the effects of grain size, reducing sugar content, temperature, and pressure on caking of cane sugar. Using water vapor adsorption isoterms and scanning electron microscopy, they found that grain size has the largest influence on the hygroscopic properties of raw sugar and that the ideal storage conditions to prevent caking are a grain size greater than 0.425 mm and relative humidity of less than 67.89% at 30 °C.

Another factor associated with caking is the moisture that migrates from the inside of the grain to the outside, forming a crust together with the fine particles on the outside of the grain (Freeman *et al.*, 2015), because when the crystals are smaller there is a larger contact surface between the particles. Pascual-Ramirez *et al.* (2016) propose sieving sugar under controlled relative humidity and temperature conditions, since it has been observed that small particles are the ones that mostly initiate moisture adsorption, triggering caking. This study also recommends that the weight of the pallets should not exceed 10 tons; once this limit is exceeded, caking occurs due to the effect of the pressure to which the sugar crystals are subjected.

In order to understand the caking phenomenon, it is necessary to understand how a particle behaves individually and how it interacts when it is packaged in bulk. Among the mechanisms that should be considered ln studying the caking phenomenon, Zafar *et al.* (2017) states that van der Waals, electrostatic and liquid bridge forces, as well as contact mechanisms, such as elastic and plastic deformation, surface roughness, formation of liquid and solid bridges and amorphous powders, are the key to preventing caking.

Based on the results of the studies presented above, Table 1 was prepared in order to facilitate the organization of information for the subsequent construction of the path analysis diagram (Figure 1).

Table 1. Variables of importance in sugar caking.

Author	Research	Contribution
Rogé & Mathlouti (2003)	Water vapor sorption isotherms	Particle size (F-Q) Ambient temperature (A) Ambient relative humidity (A)
Billings *et al.* (2006)	Capillary condensation	Ambient relative humidity (A) Product moisture (F-Q) Product temperature (F-Q) Particle size (F-Q)
Christakis *et al.* (2006)	Numerical simulation	Ambient relative humidity (A)
Chitprasert *et al.* (2006)	Effect of grain size, reducing sugars and pressure	Grain size (F-Q) Ambient relative humidity (A) Ambient temperature (A)
Castrillón *et al.* (2011)	Influence of drying conditions	Storage temperature (A) Packaging (E) Fine particles (F-Q)
Pascual *et al.* (2016)	Characterization of the phenomenon	Ambient relative humidity (A) Grain size (F-Q) Packaging (E) Storage temperature (A)
Zafar *et al.* (2017)	Bulk powders	Particle size (F-Q) Product moisture (F-Q)

Source: author-made based on the literature review. F-Q represents physicochemical variables, A variables are attributed to the environment and E variables are related to packaging.

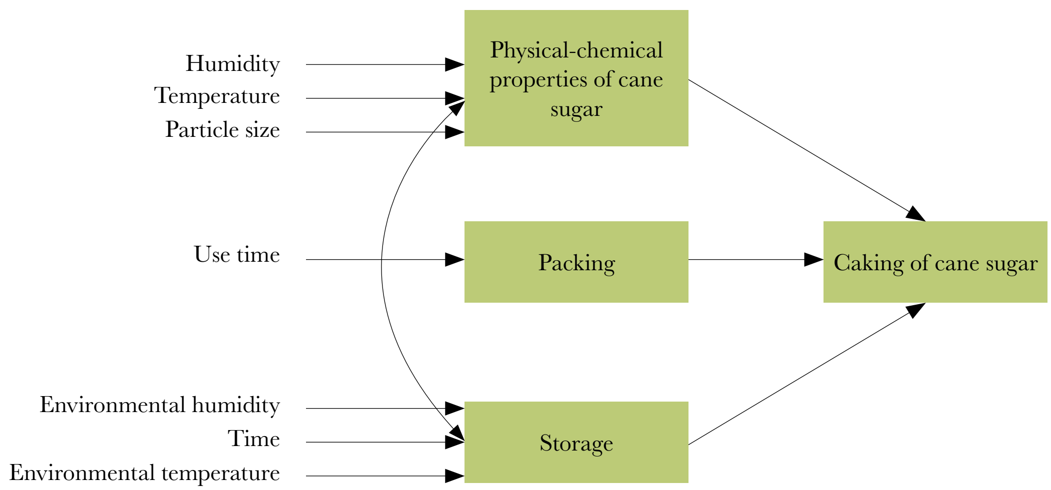

Figure 1. Path analysis diagram of the cause-effect phenomenon of cane sugar caking.

Based on the information in Table 1, a path diagram was constructed (Figure 1) showing the relationship between the variables that influence the formation of sugar lumping: physicochemical properties (moisture, temperature, and particle size), packaging (use time of the bags) and storage (ambient relative humidity, time spent in the warehouse and ambient temperature). In the diagram these variables are inside a rectangle; this is because they are called observed variables and are defined as such since they can be measured directly (Manzano, 2017). These rectangles are linked by straight single-headed arrows, indicating that the arrow has its origin in the variable that exerts the influence (independent variable) and ends in the variable that is predicted (dependent variable), which in this case corresponds to caking. In the case of the double-headed arrows, they represent a covariation between the variables.

For a phenomenon to be considered causal, it must meet the condition that variable X is the cause of variable Y; therefore, when X occurs, Y appears. Variable Y cannot occur without the previous occurrence of X (Caballero, 2006). Under this condition it can be seen in the path diagram that:

- All of the three observable variables, namely physicochemical properties (PP), packaging and storage, have a direct effect on caking, since each one arises at a date that points to the dependent variable (caking).
- Physicochemical properties have an indirect effect on caking through packaging, *i.e.*, the effect of physicochemical properties on caking is affected through packaging. For example, if the moisture content of the sugar is high, it will be affected in its migration to the environment, which can lead to conditions for caking to occur.
- It is also possible to observe the indirect effect of PP on caking through storage conditions. For example, several studies have pointed out that the environmental conditions (ambient temperature and relative humidity) present inside warehouses are factors that influence the caking phenomenon (Rogé & Mathlouti, 2003, Billings *et al.*,

2006, Christakis *et al.*, 2006, Chitprasert *et al.*, 2006, Castrillón *et al.*, 2011, Pascual *et al.*, 2016 and Zafar *et al.*, 2017).

- Regarding packaging, Castrillón *et al.* (2011) pointed out that it acts as a barrier against the migration of moisture and the internal temperature of the product. Its effect, for example, in slowing down the migration speed of moisture can lead to caking, especially in polypropylene packaging with an internal liner, which acts as a protection against product contamination. This finding coincides with the perception of those who handle packaging presentations with greater product containment (1 and 1.5 tons), called jumbo bags. These bags are reused for 8 to 10 periods (harvests), unlike 50 kg bags that are used only once; the reuse of jumbo bags leads to wear of the internal liner.

The path diagram (Figure 1) represents in a schematic way the causal phenomenon of cane sugar caking, in which the magnitudes and statistical significance of these independent variables (physicochemical, packaging and storage) with respect to the dependent variable (caking) can be evaluated through structural equation modeling (SEM). This multivariate statistical technique can be used to measure the effect (weight) and its significance on the phenomenon under study.

CONCLUSIONS

Based on the few published studies related to cane sugar caking, variables related to this phenomenon were identified, namely physicochemical properties (moisture, temperature and particle size), polypropylene packaging (liner) and storage conditions (ambient relative humidity and temperature). The direct and indirect effects of these variables can lead to the formation of association structures between the sugar crystals, thus generating the formation of lumps. The analysis of the variables that promote caking, found through the study of the different publications, allows for a graphic representation of the phenomenon, represented as a path analysis diagram, which will be useful for the decision-making and approaches of future studies, especially those related to the quantification of the magnitude with which these factors induce caking in cane sugar.

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