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Conceptual Design of the Vinasse-Based Livestock Feed Supply Chain

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Abstract. This article presents a conceptual model of the livestock feed supply chain that used the vinasses generated by the ethanol industry. To define this new supply chain, we designed a causal loop diagram, which is a tool of the systems dynamic's methodology. The causal loop diagram identified the key variables of livestock feed supply chain, as well as the main interactions between the variables.

Keywords: Vinasses, system dynamics, supply chain, conceptual design.

1 Introduction

The sugar industry is one of the most important industries worldwide, and it usually applies the principles of circular economy and waste reduction [1]. That is, the various types of waste generated during sugar production are often used to create new products, such as biofuels and biochemicals. According to the Organization for Economic Co-operation and Development (OECD) and the US Food Agriculture Organization (FAO) [2], trends in sugar production indicate that by 2023 sugarcane will remain the dominant sugar crop (about 86%), while only a little amount of global sugar production will come from sugar beet.

According to [3], the commercial fate of ethanol and molasses from the sugar industry is uncertain due to the latest COVID-19 (SARS-CoV-2) pandemic. In Mexico, higher sugar prices due to uncertainty in the market can have a positive impact on the price of sugarcane, which in turn can benefit local farmers but also cause instability economic.

As one of the many byproducts of sugar production, molasses plays a key role in ethanol production and is commonly used to develop animal feed [4].

According to [5], sugarcane molasses is an important source of energy, since it contains components such as sucralose, glucose, fructose, and lactic acid, among others.

The production of ethanol from sugarcane molasses generates vinasse, a liquid residue rich in organic materials and minerals that can be used for fertirrigation.

However, since untreated vinasse can harm crops significantly [6], the scientific and industrial communities have found other applications for vinasse, including energy generation, soil fertilization [8], and livestock feed (LF) production. Unfortunately, the viability of using vinasse to produce animal feed is not sufficiently explored. Hence, in this research, we propose a conceptual model to analyze the potential of sugarcane vinasse as the raw material for the LF supply chain.

The remainder of this paper is structured as follows: section 2 discusses the state of the art on the multiple applications of vinasse, including energy generation and soil fertilization, among others. Section 3 introduces our research methodology, and Section 4 details how we followed said method. Finally, section 5 discusses the research conclusions and our suggestions for future work.

2 Background

This section discusses the most common industrial applications of sugarcane vinasse.

2.1 Vinasse for Energy Production

The anaerobic digestion of vinasse generates considerable amounts of biogas, which can be used to produce electricity. In [9], authors compared the potential of vinasse biogas to that of oil power plants in terms of energy generation, costs, and greenhouse gas (GHG) emissions in Brazil. In the end, the authors found that vinasse could be a viable alternative to generate electricity in the country.

Also, in [10], the authors performed an economic analysis of vinasse biogas for electricity generation in Sao Paulo.

The analysis calculated the amount of sugarcane and volume of vinasse produced in the region. The study concluded that in Sao Paolo biogas from vinasse could help generate a total of 659 GWh/year of electric power, to be supplied to 295,702 inhabitants and covering 0.45% of the state’s energy demands.

Finally, according to [11], global vinasse production is estimated to be of 22.4 gigaliters, which have the potential to produce 407.68 gigaliters of biogas. In this sense, vinasse is a potential source of renewable energy.

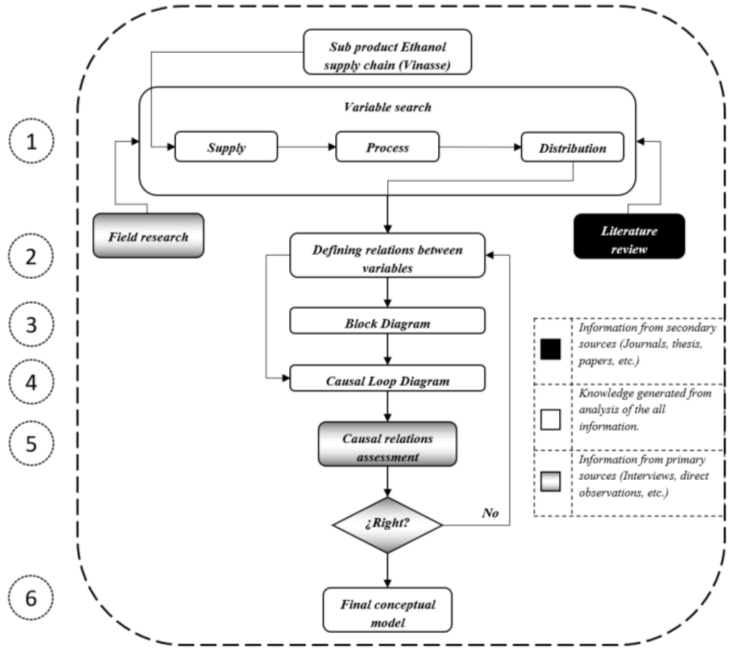

Fig. 1. A conceptual model of the vinasse based LF supply chain.

2.2 Vinasse as Soil Fertilizer

Sugarcane vinasse is typically used as the raw material of organic fertilizer. In this sense, vinasse-based fertilizers significantly reduce the negative impact that is caused by releasing excessive amounts of vinasse into the environment.

According to [12], the physicochemical and morphological properties of pectin and chitosan, when combined with sugarcane vinasse, have great potential for soil fertilization. Moreover, a study conducted in [13] combined high methoxyl pectin gel with sugarcane vinasse to produce a slow-release soil fertilizer.

Vinasse acted as the biopolymer solvent, providing greater stability to the pectin gel, and as a source of nitrogen (N), potassium (K), calcium (Ca), and magnesium (Mg). Finally, a study in [14] revealed that vinasse combined simultaneously with mineral N fertilizers increases N2O emissions 2.9-fold, if compared to N-fertilizers alone. Therefore, the authors suggested not combing both inputs, but rather applying vinasse before or after mineral N fertilization.

2.3 Vinasse for Animal Feed Production

Food waste and crop residues are commonly reused as LF. In this practice, animals act as natural bioprocessors capable of converting food residues that humans cannot eat into human edible food, such as meat, eggs, and milk [15]. The use of food waste and agro-residues as sources of animal feed often requires comprehensive analyses in terms of food safety, natural resource conservation, and climate change.

A study conducted by [16] examined whether land could be shared between food production and biofuel production. The study pointed out at sugarcane as an example of both a food crop and a biofuel crop. On the one hand, sugarcane is used for ethanol production (biofuel); on the other hand, it can produce biomass yeast, a single-cell protein used as animal feed additive. In the end, the multiple applications of sugarcane and its byproducts has an impact on the annual global yield of this crop.

Finally, researchers in [17] discussed the feasibility of replacing edible feed grains with human-inedible biomass in animal diets as a strategy to reduce food-feed competition and mitigate the environmental impact of livestock. From this discussion on state-of-the-art vinasse applications, we conclude that research on the use of vinasse for animal feed is scarce, if compared to the number of initiatives exploring vinasse potential for energy production and soil fertilization.

3 Methodology

Figure 1 depicts the methodology followed to develop the conceptual model of the vinasse based LF supply chain. The methodology comprises six main steps:

1. Identifying the model variables,
2. defining the relationships between these variables,
3. building a block diagram,
4. developing a causal diagram,
5. analyzing the causal relationships resulting from the diagram,
6. developing the final conceptual model.

All the steps are explained bellow Search for model variables. We performed a systematic review of the literature using the following keywords: vinasse, supply chain, and ethanol production.

1. Define relationships between variables. Primary relationships between variables were defined as follows: A→B.
2. Build block diagram. The block diagram was built as a graphical representation of the primary relationships identified between variables.
3. Develop causal diagram. We built a causal diagram to graphically visualize complex relationships between latent variables. The diagram also helped us find whether a given variable (the cause) had an either positive or negative impact on another variable (the effect). Causal diagrams also depict reinforcing and/or balancing feedback loops.
4. Test causal relationships. We analyzed whether the identified causal relationships, impacts, and interrelated variables were representative of the system being studied – i.e., the vinasse-based LF supply chain. Once the causal

Table 1. Variables involved in the vinasse based LF supply chain.

Variable	Descriptor	Reference
Molasses inventory (from supplier)	Amount of molasses that a sugar mill or refinery can supply to an ethanol production factory.	4, 18
Molasses procurement	The process through which an ethanol production factory procures molasses from a supplier (i.e. sugar mill or refinery).	4,7
In-factory molasses inventory	Amount of molasses (Ton) stored within the factory and necessary for ethanol production.	4,18
Master production schedule	Production program predefined by the company according to the number of customer orders received.	18
Ethanol production capacity	Amount of ethanol produced on a daily basis.	19
Ethanol production	Process of converting molasses to alcohol through distillation.	18,19
Vinasse	Residue or byproduct generated during molasses distillation.	1,5-17
Pollution	Emissions to water (local rivers or lakes) in case vinasse is not treated or contained within factory facilities.	8,9,10
Vinasse inventory	Amount of vinasse (Ton) stored and necessary for LF production.	4
LF production capacity	Amount of vinasse processed on a daily basis.	4
Production costs	Costs incurred by the factory from manufacturing LF, including steam power, electric power, and workforce, among others .	18, 19
LF production	The production process of LF.	10, 12
Finished product 5nventtory	Amount of LF ready to meet the demand.	
Waste management	Amount of vinasse daily processed to obtain LF.	13,14
Finished product demand	Amount of LF consumed by final consumers.	18, 19
Demand satisfaction	Percentage of customer orders successfully processed on time.	4, 18, 19

diagram was successfully tested, we proceeded to develop the conceptual model.

5. Develop conceptual model. The final conceptual model corresponds to the successfully tested version of the causal diagram. This model is intended to be

used in further research to simulate the vinasse based LF supply chain and consequently propose implementation policies and strategies based on the results of the simulation.

4 Implementing the Methodology

This section discusses how we implemented the methodology introduced in the previous section in order to develop the conceptual design of the vinasse based LF supply chain.

4.1 Steps 1 and 2 – Identify Model Variables and Define Relationships

It is important to accurately identify the critical variables involved in the logistic processes of the vinasse based LF supply chain. The main processes of the vinasse based LF supply chain are as follows:

- Procurement. Vinasse is procured as the raw material necessary to satisfy LF production.
- Production. Vinasse is converted to LF, an animal-edible product.
- Distribution. The feed is brought to final consumers via warehouses and retailers.

Table 1 introduces the critical variables identified in the block diagram and used to build the causal diagram of the vinasse based LF supply chain. As previously mentioned, causal diagrams are a tool for graphically visualizing and defining the multiple relationships governing a system. We also considered the causal diagram of the ethanol production process, since the vinasse used for the LF supply chain is a byproduct of said process.

4.2 Step 3 – Block Diagram

This section uses the block diagram to analyze the interactions among the multiple links of the vinasse based LF supply chain. Namely, the diagram allowed us to identify the critical variables involved in the conceptual model. As Figure 2 depicts, the vinasse based LF supply chain initiates with the harvest of sugarcane, which is then taken to sugar mills or refineries to be processed into sugar. Molasses is generated during the sugar production process as a byproduct.

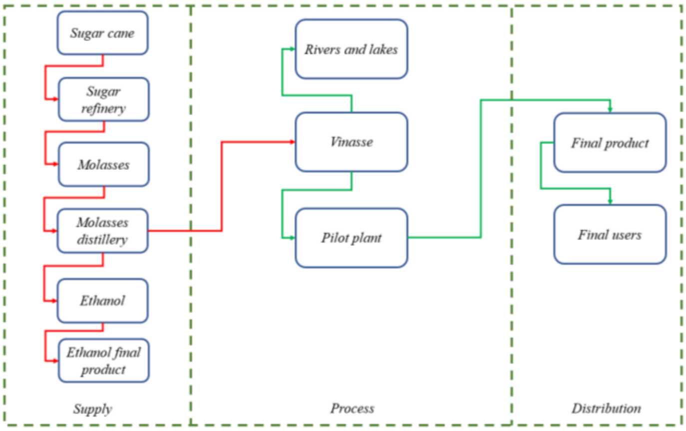

Fig. 2. Block diagram of the vinasse-based LF supply chain.

Even though it can be used to produce animal feed, in this case molasses is used to produce ethanol. Ethanol has applications in the make-up, medical, beverage, and biofuel industries. The ethanol distillation process produces around 11 L of vinasse per liter of ethanol. Vinasse is commonly disposed in water bodies such as local lakes and rivers, thus damaging local fauna and flora and reducing oxygen in aquatic ecosystems.

4.3 Steps 4 and 5 – Develop Causal Diagram and Identify Feedback Loops

Causal diagrams are graphs that help identify how the variables within a particular system interact either positively or negatively. To this end, causal diagrams rely on feedback loops connecting the system variables. Feedback loops occur as a result of the system's own complexity and can be defined as closed loops, in which a given variable has an impact on another variable, which in turns has feedback on the first variable (A⇄B). Notice that feedback loops can be either balancing (negative) loops or reinforcing (positive) loops. Figure 3 depicts our proposal of the causal diagram of the vinasse-based LF supply chain. As can be observed, the diagram comprises three balancing loops, explained as follows:

– **Balancing loop B1.** As long as Molasses Inventory (from supplier) increases, Molasses Procurement can be more efficient. Additionally, if Ethanol Production demands greater amounts of raw material, Molasses Procurement must increase, which in turn causes Molasses Inventory (from supplier) to decrease.
– **Balancing loop B2.** Ethanol Production Capacity has a direct effect on Ethanol Production, since the latter may increase or decrease as the former either increases or decreases, respectively. Likewise, larger amounts of In-Factory Molasses Inventory can increase Ethanol Production as long as the plant's infrastructure allows it. Next, as Ethanol Production soars, In-Factory Molasses Inventory decreases.

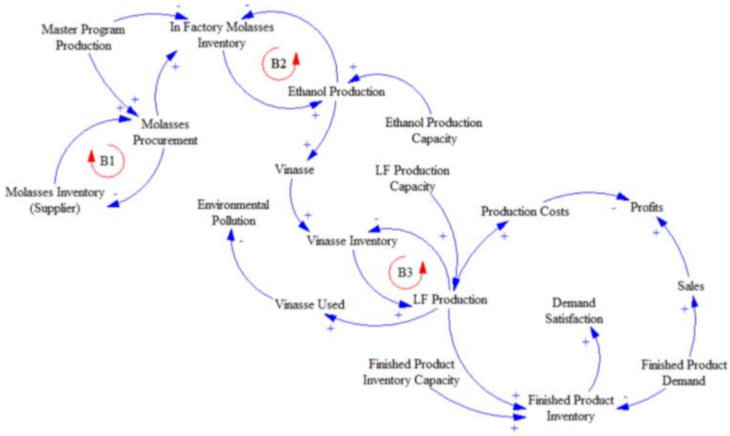

Fig. 2. Causal diagram of the vinasse-based LF supply chain.

– **Balancing loop B3.** LF Production Capacity has a positive effect on LF Production. In turn, any surge in LF Production causes Vinasse Inventory to decrease. As long as Vinasse Inventory levels suffice, LF Production is sustained; however, low Vinasse Inventory levels reduce or even completely halt LF Production. Notice that the more LF Production, the larger the amount of Vinasse Used, which consequently reduces Environmental Pollution.

LF Production has positive impacts on both Production Costs and Finished Product Inventory. Namely, more production leads to larger amounts of Finished Product. Similarly, as production levels soar, more resources are used; hence, Production Costs rise. On the other hand, Finished Product Demand has a direct and proportional influence on Sales. As Finished Product Demand either increases or decreases, Sales respectively increase or decrease.

In turn, Profits (i.e. revenue minus production costs) can be either positively or negatively altered as Sales either increase or decrease, respectively. In other words, larger Sales entail higher Profits, yet higher Production Costs lead to lower Profits. Also, Demand Satisfaction directly depends on Finished Product Inventory, as low levels of the latter may not lead to high levels of the former. Conversely, if inventory levels increase, Demand Satisfaction rates also increase.

4.4 Step 6 – Final Conceptual Model

After completing the causal diagram, we tested the causal relationships between the variables. To this end, we resorted to a panel of field experts to determine whether such relationships were representative of the system being studied – i.e. the vinasse-based LF supply chain. Next, we used the tested diagram to develop the simulation model on specialized software. The analysis of the causal diagram indicates that correct coordination among the links of the vinasse-based LF supply chain would ensure efficient vinasse utilization.

5 Conclusions and Future Work

This research adopts a system dynamics (SD) approach and designs a causal diagram to ultimately propose the conceptual model of the vinasse-based LF supply chain. The research confirms that SD can successfully model the multiple interactions governing a supply chain system. To this end, SD adopts a holistic approach to analyzing longer time and spatial scales.

Our conceptual model of the vinasse-based LF supply chain sets the grounds for much needed simulation models that can eventually help the research community design and assess LF supply chain systems to explore how industries can take better advantage of byproducts such as vinasse, while contributing to a more sustainable environment. However, the excessive amount of vinasse generated during the ethanol production process demands for new tools to properly coordinate the multiple links involved in the vinasse-based LF supply chain.

As future work, we will aim at validating our conceptual model within the industry by implementing it in a case study. The results of said validation would help us further develop the simulation model of the vinasse-based LF supply chain.

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