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Food waste biorefinery advocating circular economy: Bioethanol and distilled beverage from sweet potato

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ABSTRACT

The exponential growth rate of the global population has been causing a threat to finite resources and also increasing the amount of waste generated. The global quantitative food waste for tubers is 45% per year, which in Brazil would amount to 350,000 tons of sweet potato wasted annually. Food waste causes 10% of the emissions of greenhouse gases. In this work, food waste biorefineries are the proposed solution. Integrated processing via a combination of different technologies to produce both ethanol and distilled beverage was evaluated to valorize sweet potato waste profitably within the circular economy concept. No works concerning the integrated production of both products simulating different real market scenarios were found. Five different scenarios varying the production percentage of each product were evaluated. The higher the production of the distilled beverage, the more profitable the scenarios are. Economic results began to be positive when the production for sale of each product reaches 40%, plus 20% of ethanol for domestic consumption. The scenario with 80% of beverage production presented NPV of US$ 1,078,500.18, IRR of 51%, and discounted payback of 1.06 years. The sweet potato waste biorefinery is a sustainable model and contributes to the development of the agriculture and food sector by providing new businesses and consequent job creation. It also leads to the reduction of greenhouse emissions by producing renewable resources and marketable products, thus reaching the goals of the circular economy.

1. Introduction

An exponential growth rate of the global population has been a major challenge causing a significant threat to finite resources. At present, more than 90% of our energy needs and the majority of material demand are held by fossil-based reserves that eventually emit greenhouse gases (Mohan et al., 2016a). With the present consumption rate of fossil fuels, the available reserves may run out soon. Therefore, the requirement of alternative resources to meet our energy and material needs that are renewable and sustainable is essential (Hemalatha et al., 2019). The growth of the global population also has, as a consequence, the high amount of waste generated. It is estimated that about 1.3 billion tons of foods are lost or wasted globally, representing approximately one-third of the edible parts of food produced for human consumption (FAO, 2019). Food waste caused 10% of the emissions of greenhouse gases in the period 2010–2016 (IPCC, 2019). Brazil is one of the largest producers of agricultural and animal commodities, which produces large amounts of residues and wastes (Forster-Carneiro et al., 2013). Waste is a crucial feedstock and renewable resource with a well-defined role to play in the framework of circular bioeconomy (Mohan et al., 2019). In this context, emerge the concept of food waste biorefineries, which can be employed for the production of biofuels, targeting economic viability and sustainability within the circular economy concept (De Jong et al., 2012; Mohan et al., 2016b).

In the last few decades, there has been a trend in the production of biofuels as a need for decarbonizing our economy to mitigate climate change and to restrain the depletion of fossil resources (Papadaskalopoulou et al., 2019). Bioethanol is one of the most common commercial biofuels (Zhang et al., 2020). Sweet potato (*Ipomoea batatas*) has been considered a promising raw material for ethanol production, as it has a higher starch yield per unit land cultivated than grains (Lareo and Ferrari, 2019). The Brazilian production of sweet potatoes is the 16th in the world ranking, with a

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Nomenclature

IRR	internal rate of return
MARR	minimum acceptable rate of return
NPV	net present value
SHF	simultaneous hydrolysis and fermentation
TRS_{swp}	total reducing sugars of sweet potato, in %
x_{c_swp}	concentration of sweet potato, in kg sweet potato/ L of dilution water
$x_{et,exp}$	experimental ethanol content formed in the fermentation, in $v.v^{-1}$
$x_{et,theor}$	theoretical potential for ethanol production, in $v.v^{-1}$
x_{m_swp}	sweet potato moisture, in kg/kg
x_{swp}	amount of potato added, in kg
Y_{exp}	experimental yield of the fermentation, in %

production of 776,285 tons in 2017, obtained in an area of 54,123 ha and an average yield of 14,515 t ha^{-1} (FAO, 2017; IBGE, 2014). The global quantitative food losses and waste for roots and tubers is 45% per year (FAO, 2019), which in Brazil would amount to approximately 350,000 tons of sweet potato wasted annually. The enormous amount of this bio-waste may also contribute towards the realization of the circular economy concept.

Previous studies in our group (GIMSCOP) have improved the process of using sweet potato on ethanol production (Masiero et al., 2014; Risso, 2014; Schweinberger et al., 2016, 2019a). Schweinberger et al. (2016) showed that for ethanol production, it is better to let sweet potatoes ripen for a specified time than to process them soon after harvest, with a maximum value of ethanol production and conversion efficiency achieved at 25 days after harvest (Schweinberger et al., 2016). Thus, rotting sweet potatoes, a market residue, can be used for ethanol production. Also, there are still the sweet potato harvest residues, which are crops with imperfections considered unsuitable for sale. For this waste, Weber (2017) proposed to use the same ethanol production process with some modifications for the production of alcoholic beverages (Weber, 2017).

Conceptually, waste biorefineries produce green energy and make use of zero-waste production technologies, which motivate industries to fabricate environment-friendly products with low carbon and water footprints. Therefore, waste biorefinery should be capable of generating great marketable products and power sustainably and achieve the goals of circular economies (Dael et al., 2014). Producing both ethanol and distilled beverage, whose production uses the same factory and can be modified according to market needs, it is possible to achieve this circular economy goal. No works concerning the integrated production of both products simulating different real market scenarios were found. Also, residues generated during the manufacturing process can be turned into biochar by pyrolysis, a technique also studied in our research group (Raymundo et al., 2019). In this way, production residues transformed into biochar return to the soil in a more stable form (higher recalcitrance), thus remaining in soils for thousands of years (Oliveira et al., 2017; Sette et al., 2020; Weber and Quicker, 2018). The CO_2 captured by the plants is not released into the atmosphere as in burning or decomposition (as CH_4) but is stored in the form of carbon in the biochar. It contributes to mitigating climate change through carbon sequestration, thus closing the biorefinery circular economy cycle (Fig. 1). The characterization of the biochar produced from sweet potato waste will be presented in our future works.

In this context, the primary purpose of this study is to evaluate the technical and economic viability of a sweet potato waste biorefinery for the production of bioethanol and distilled beverage based on our group experimental results (Schweinberger et al., 2016, 2019; Weber, 2017; Weber et al., 2020), contributing in the reduction of greenhouse emissions by producing renewable and green resources and also leading to the development of new models and opportunities across the agriculture and food sector within the circular economy concept.

2. Material and methods

2.1. Sweet potato

Sweet potatoes with cream peel and cream pulp (*BRS Cuia* cultivar) were harvested in General Câmara, RS, Brazil, and the ones considered unsuitable for human consumption (harvest residue) were donated by local farmers to the distilled beverage production (Weber et al., 2020). For ethanol production, rotting sweet potatoes with cream peel and cream pulp (market residue) were collected in the local market (Schweinberger et al., 2019a).

The moisture and total reducing sugars content were determined for the sweet potato samples before their use. The moisture analysis was performed by oven drying at 105 °C to constant weight (Zenebon et al., 2008). The quantification of total reducing sugars was done through acid hydrolysis of the sweet potato, followed by HPLC analysis. Briefly, 2 g of fresh sweet potato was crushed and homogenized in a 2 mm sieve. 25 mL of distilled water and 1 mL of hydrochloric acid were added. The solution was autoclaved at 1 bar and 121 °C for 2 h. The mixture was neutralized with 10% (v/v) sodium hydroxide solution to pH 3.5–4.0, diluted, and filtered (Schweinberger, 2016).

2.2. Ethanol and distilled beverage production process

The ethanol and distilled beverage production processes are shown in Fig. 2. The main differences between both processes are indicated in Fig. 2 in different colors. Briefly, sweet potato waste was washed, diced, and steamed until it reached 76 °C. Then it was cooled and crushed in a processor. To the milled sweet potato were added the antibiotic agent, the enzymes, and the yeast. pH was adjusted to pH 4 by buffer solution addition. The mash was fermented in the shaker and after subjected to the distillation process. For the beverage, three distillate fractions were separated according to their alcohol content: head (up to 50% $v.v^{-1}$), heart (50-38% $v.v^{-1}$) and tail (38-10% $v.v^{-1}$). The heart fraction, which represents 80% of the total volume of the distillate (Oliveira et al., 2005), is diluted to 25% $v.v^{-1}$ alcohol content, bottled and taken to the expedition for future sale.

The yeast used was *Saccharomyces cerevisiae* Angel Thermal Resistance Alcohol Yeast, provided by LNF Latin America. The hydrolysis enzyme used was Stargen 002, a commercial mixture of the Genencor brand manufactured by DuPont, containing *Aspergillus kawachi* alpha-amylase expressed in *Trichoderma reesei* and *T. reesei* glucoamylase. For ethanol production, the Pectinex Ultra AFP pectinase enzyme, supplied by LNF Latin America, was used to reduce the viscosity of the medium. This viscosity reduction enzyme was not added in the distilled beverage production process because the presence of pectinases may increase the amount of methanol (Blinder, F., Voges, E., Lauge, 1988), an undesirable compound in distilled beverages that can cause headache, dizziness, nausea, and vomiting (Badolato, E. S. G., Duran, 2000). The antibiotic agent in each process was different. For ethanol, tetracycline hydrochloride (3.4 g/L) was added. By Brazilian legislation, this compound cannot be added to food products. Therefore, potassium

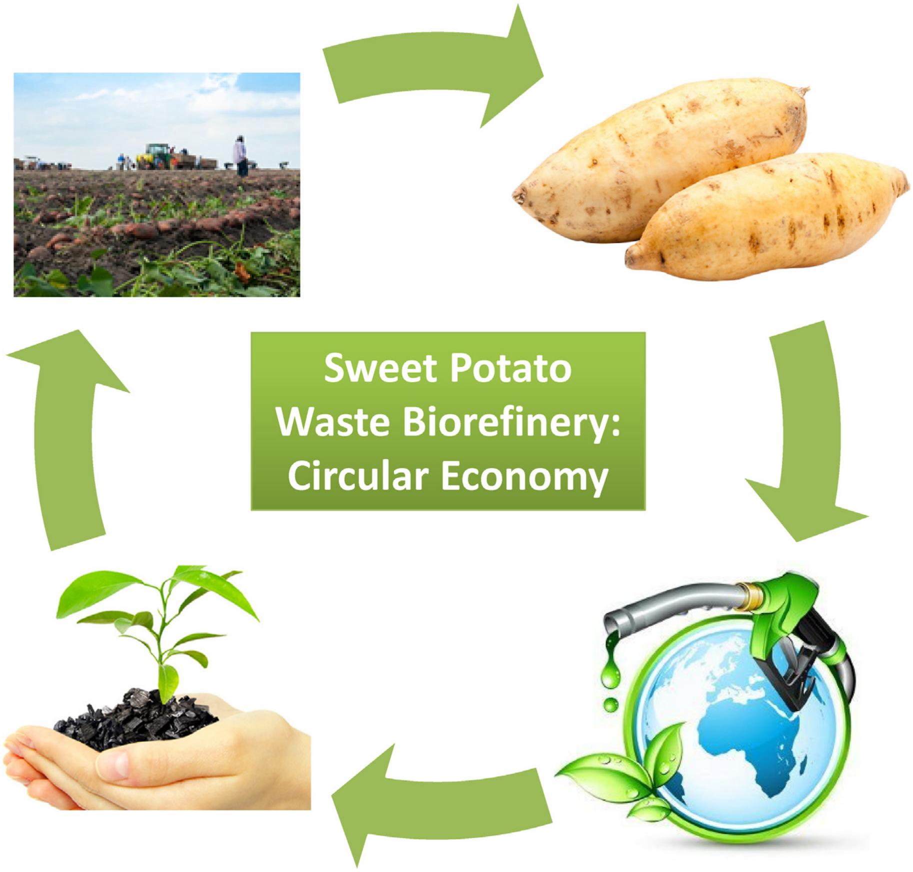

Fig. 1. Sweet potato waste biorefinery: circular economy concept.

metabisulfite (0.15 g/L), a natural antimicrobial agent permitted in foods (Food and Drug Administration, 2019), was added instead.

The simultaneous hydrolysis and fermentation (SHF) were performed at different temperatures and duration. This was set because some alcoholic beverages yeast, e.g. Lalvin EC1118, cannot be used at temperatures above 30 °C. This temperature reduction caused an increase in the process duration of 5 h, totaling 24 h.

The theoretical potential for ethanol production was calculated using Equation (1):

$$x_{et,theor}\left(\%, v.v^{-1}\right) = \frac{92.\left(TRS_{swp}.x_{c\_swp}\right)}{142.02 + 1.4202.\left(x_{m\_swp}.x_{c\_swp}\right) + 0.778.\left(TRS_{swp}.x_{swp}\right)} \tag{1}$$

This is an equation proposed by GIMSCOP in a previous study (Schweinberger et al., 2019b), where ethanol concentration ($x_{et,theor}$) is calculated as a function of sweet potato moisture (x_{m_swp}, in kg/kg) and amount of potato added (x_{swp}). The x_{c_swp} value is the proportion of sweet potato (kg) to the added volume of dilution water, so it means x_{swp} (kg)/1 L of dilution water. TRS_{swp} is the total reducing sugars of sweet potato. Equation (1) considers ideal conditions, where it is assumed that starch is completely hydrolyzed, and all sugars are converted into ethanol. Since $x_{et,exp}$ is the experimental ethanol content formed in the fermentation, the experimental yield of the fermentation (Y_{exp}) is calculated by Equation (2):

$$Y_{exp}(\%) = \frac{x_{et,exp}}{x_{et,theor}} \times 100 \tag{2}$$

2.3. Economic evaluation

2.3.1. Costs

The development of small scale production plants has high relevance in remote regions of several countries, including Brazil, adding value to regional raw materials and making processes more economically-viable, contributing to local sustainable development (Virgínio e Silva et al., 2018). The project conceived by GIMSCOP has the goal of in the future migrating to larger-scale tests. To estimate the cost involved in a 1000 L/day distilled production plant, the results obtained in our laboratory experiments have been scaled up by simulation studies. The considered costs and amount of inputs are shown in Table 1 (Weber et al., 2018), which were defined based on consultation with suppliers. The values were calculated in Brazilian real (BRL or R$), the Brazilian currency, and converted to United States Dollar (USD or US$ or $). The conversion rate adopted

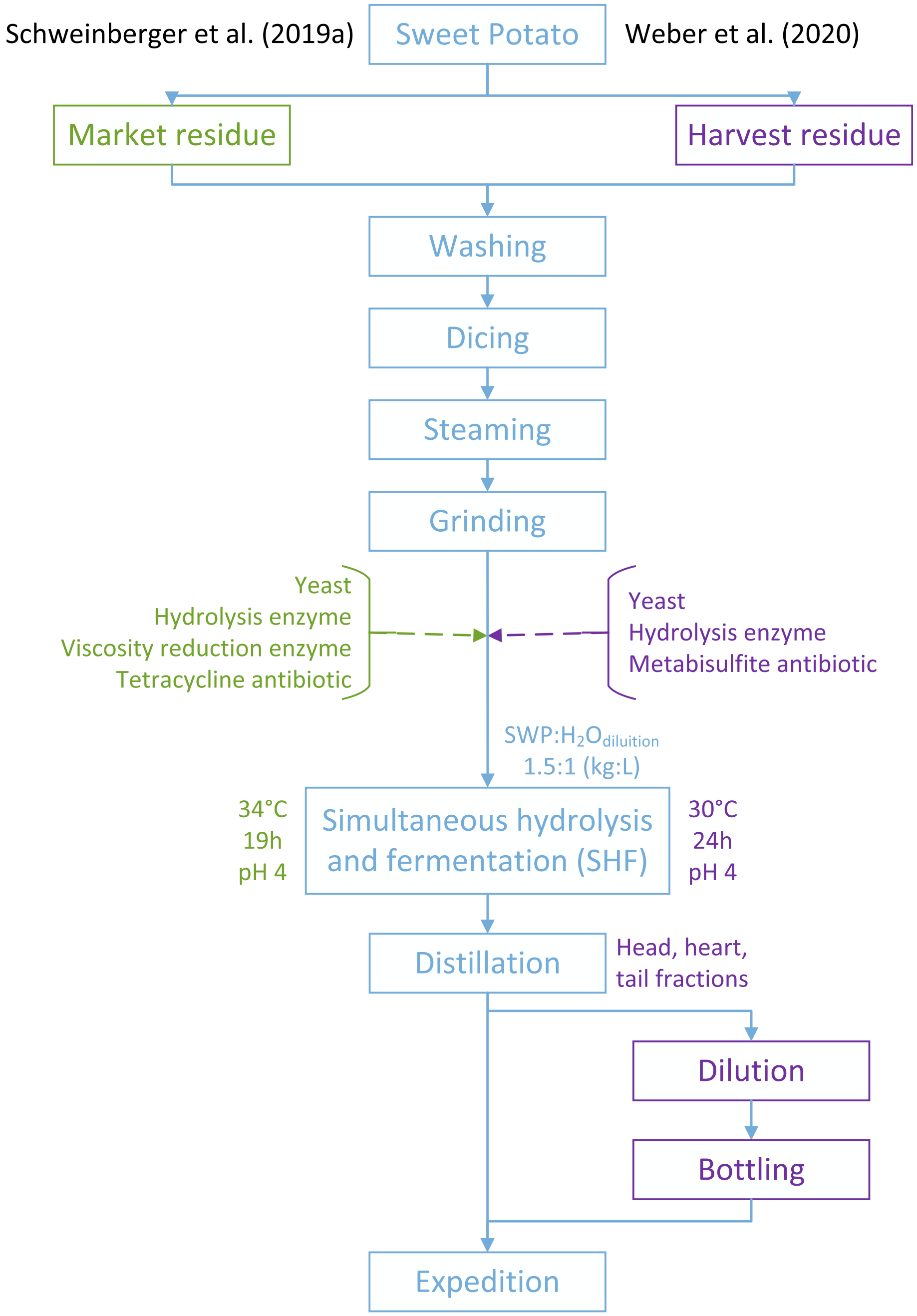

Fig. 2. Bioethanol and distilled beverage production process.

Table 1
Considered costs and amount of inputs for a 1000 L/day distilled production plant.

Input	Cost R$	US$	Ethanol	Distilled beverage
Sweet potato	0.06216 R$/kg	0.01535 US$/kg	5701.60 kg	7623.11 kg
Workers	66.75 R$/(worker.day)	16.48 US$/(worker.day)	3 workers	5 workers
Electric energy	0.5476 R$/kWh	0.1352 US$/kWh	128.3 kWh	131.98 kWh
Water	7.25 R$/m^3	1.79 US$/m^3	29.58 m^3	30.82 m^3
Hydrolysis enzyme	31.70 R$/L	7.83 US$/L	0.001 L/kg SWP	0.001 L/kg SWP
Viscosity reduction enzyme	158.30 R$/L	39.09 US$/L	0.0001 L/kg SWP	–
Yeast	64.50 R$/kg	15.93 US$/kg	0.0033 kg/kg SWP	0.0033 kg/kg SWP
Antibiotic tetracycline	349.00 R$/kg	86.17 US$/kg	0.0002833 kg/kg SWP	–
Antibiotic metabisulfite	127.80 R$/kg	31.56 US$/kg	–	0.0000125 kg/kg SWP
Firewood	42.29 R$/m^3	10.44 US$/m^3	2.2 m^3	2.2 m^3
Glass bottle (750 mL)	4.13 R$/L beverage	1.02 US$/L beverage	–	1216 L beverage

was 4.05 R$/US$ (BANCO CENTRAL DO BRASIL, 2019).

Costs for the residual sweet potatoes were calculated based on the costs of the agricultural production and biorefinery logistics. The difference in the total quantity of sweet potato needed to produce 1000 L distilled daily in both processes is related to the experimental yields of fermentation and distillation, which will be presented in the next section. A sweet potato with 30% of total sugar content was assumed as a reference. Also based in the fermentation and distillation yields and in the fermentation reaction stoichiometry, where theoretically 180 g of glucose produces 92 g of ethanol, a 1000 L/day distilled production plant can produce 800 L of heart distilled fraction, which after dilution reaches a value of 1216 L of distilled beverage per day. As each distilled beverage bottle has a volume of 0.75 L, for the production of 1216 L of distilled beverage, 1621 bottles are needed daily. Electric energy costs are related to the daily energy consumption of each equipment used in the production process. Thermal energy from eucalyptus firewood was considered for the distillation and sweet potato heating process. The difference in the energy value of the two processes is related to the energy spent on equipment related to dilution, bottling, and labeling of distilled beverages, processes that are not necessary for ethanol production. For the beverage, the heat required for distillation is lower since the distillation is up to 38% ($v.v^{-1}$) of alcohol content and not up to 96% ($v.v^{-1}$) like ethanol. However, all energy expenditure is being considered, e.g. with the beverage bottling and labeling, which ends up making the values for ethanol and beverage similar. Water costs are due to the washing of sweet potatoes, mash preparation, steam generation, and distilled beverage dilution. The variation in the water consumption value in both processes is due to the distillate dilution, being higher to the alcoholic beverage being because it is distilled up to 38% ($v.v^{-1}$) ethanol content and then diluted to 25% ($v.v^{-1}$) ethanol content. This alcoholic content was defined based on the alcohol content of shochu, a traditional Japanese distilled beverage (Pellegrini, 2014) on which the sweet potato distilled beverage was based. Enzymes are used in the process of hydrolysis and viscosity reduction of the medium; yeasts perform the fermentation process by turning sugars into alcohol, and antimicrobial agents are used to preventing contamination. The costs are in line with the values of the inputs provided by suppliers.

For the cost of workers, the national minimum salary of Brazil in 2019 was considered, i.e., the monthly amount of R$ 998, with 33.77% additional due to labor benefits, assuming 20 workdays per month. The distilled beverage process requires more workers than the ethanol production process because the separation of fractions in the distillation process requires a responsible worker and also because of the bottling and labeling processes, which require one more worker. The total tributary taxes for the distilled beverage was 21.65% added to a fixed value tribute of R$ 2.90 per bottle (MACCARI, 2013). To ethanol, the total tributary taxes in Rio Grande do Sul was R$ 1.444/L (Fecombustíveis, 2019). Income tax of 15% and the social contribution of 1.08% of the billing were set.

2.3.2. Considerations

The estimated initial investment is R$ 590,600.00. Besides, an additional expense of R$ 200,000.00 is planned with marketing and advertising of the distilled beverage. Therefore, the total initial investment is R$ 790,600.00. Cash flow was determined over 10 years, with the construction of the distillery being considered in the year prior to the first. It was considered 8 h of daily operation, totaling 40 h per week. It was considered that 100% of the initial investment would be financed and a working capital amount of R$ 160,000.00. The interest rate adopted is 8% per annum with a grace period in the first year and payment term of 5 years. Depreciation costs were determined based on the straight-line method, following the Federal Revenue Regulation RFB No. 1700 (Receita Federal, 2017). The maximum allowed depreciation rates were used: 20% per year for vehicles in general; 10% per year for machinery and equipment; and 4% per year for buildings. Also, an annual cost of maintenance of the production unit was considered. This cost was defined as a percentage of the investment value in equipment and facilities. An increasing percentage was adopted for the 10 years of operation evaluated, starting at 1% in the first year and increasing 1% each year.

The revenue is the result of the sale of ethanol and distilled beverage. It was estimated that 20% of ethanol production will be used for domestic consumption. As both products use the same factory and can be modified according to market needs, five different production scenarios were evaluated:

Scenario 1: 20% ethanol for domestic consumption; 80% ethanol production for sale;
Scenario 2: 20% ethanol for domestic consumption; 60% ethanol production for sale; 20% distilled beverage production for sale;
Scenario 3: 20% ethanol for domestic consumption; 40% ethanol production for sale; 40% distilled beverage production for sale;
Scenario 4: 20% ethanol for domestic consumption; 20% ethanol production for sale; 60% distilled beverage production for sale;
Scenario 5: 20% ethanol for domestic consumption; 80% distilled beverage production for sale.

2.4. Investment analysis

For investment analysis, discounted payback, net present value (NPV) and internal rate of return (IRR) were calculated. In the deterministic case, an NPV equation is defined by $NPV = \sum_{n=0}^{N} \frac{F_n}{(1+r)^n}$, where $F_n = b_n - c_n$ with b_n representing cash inflows and c_n representing cash outflows at period n. If NPV>0, then the project is accepted, if NPV<0, then the project is rejected. Finally, if NPV = 0, then the decision-maker stays indifferent. The calculation of IRR means the calculation of r^* in $\sum_{n=0}^{N} \frac{F_n}{(1+r)^n} = 0$. If r*>MARR, where MARR is Minimum Attractive Rate of Return, then the project is accepted, if r*<MARR, then the project is rejected. Finally, if r* = MARR, then the decision-maker stays indifferent (Bas, 2013).

3. Results and discussion

3.1. Ethanol and distilled beverage from sweet potato

Sweet potatoes from different crops show differences in composition. Kolbe et al. state that the size of sweet potatoes affects their content of organic and inorganic components, including water, starch, sugars, and organic acids (Kolbe, H., Beckmann, 1997). For the sweet potato with cream peel and cream pulp, the total sugar content evaluated by acid hydrolysis was 26.93 ± 0.86%, and the moisture content was 68.16 ± 0.38%. The theoretical ethanol content that should be formed (11.66%) was calculated using Equation (1), and then the experimental yield of the fermentation was calculated by Equation (2). The results are shown in Table 2 (Schweinberger et al., 2019a; Weber et al., 2020).

Table 2
Theoretical and experimental yield of alcoholic fermentation.

	Ethanol	Distilled beverage
$x_{et,exp}$ (% $v.v^{-1}$)	10.95	8.59
$x_{et,teórico}$ (% $v.v^{-1}$)	11.66	11.66
Y_{exp} (%)	93.91	73.65

The experimental alcoholic fermentation yield was 93.91% for ethanol and 73.65% for the distilled beverages. Even being lower than the fermentation yield for ethanol production, the distilled beverage process has also achieved a high yield of alcoholic fermentation. Similar results were achieved by Swain et al. (2013)., that reported a fermentation yield of 72% using sweet potato flour as biomass (Swain et al., 2013). Leonel et al. (1999) and Schweinberger et al. (2016) concluded that the use of pectinase as a complementary enzyme to the amylases in the hydrolysis-saccharification process provides better yields to the process (Leonel, M., Cereda, 1999; Schweinberger, 2016). These results indicate that the high viscosity of the medium and the incomplete disintegration of the sweet potato pieces, caused by the absence of pectinase in the beverage production process, impair the progress of the fermentation process, causing a decrease in the yield of the alcoholic fermentation. Therefore, the absence of pectinase in the distilled beverage process is the cause of the lower alcoholic fermentation yield.

3.2. Economic analysis

For the economic simulation process, based on the experimental results, yields of 95% and 75% were assumed for the ethanol and distilled beverage fermentation process, respectively. For the distillation process, a yield of 95% was assumed to ethanol production. Due to the distilled fractions separation of the distilled beverage, a yield a little lower, 90%, was considered for distillation. Also, a sweet potato with 30% of the total sugar content was assumed as a reference.

3.2.1. Costs

The total costs of all inputs in R$ and US$ and its percentage contribution to the total costs of producing ethanol and distilled beverage in a 1000 L/day distilled production plant are shown in Table 3.

The total daily input costs involved in the distilled beverage production process reached US$ 1999.73. This value is higher than the total daily input costs involved in the ethanol production process, which totalized US$ 735.98, mainly because of the beverage bottling process costs. Another factor in this difference is labor costs since when distillates are manufactured, two extra workers are required, which represents more labor costs. Also, as the fermentation and distillation yields in the distilled beverage production process are lower than in the ethanol process, more sweet potato is needed to achieve the same production level; more sweet potato processing leads to higher costs with enzymes, yeast, and antibiotic.

Considering the input costs contribution, it is realized that to the alcoholic beverage the highest cost is with bottles, achieving 62.06% of the total costs. This fact indicates the need to search for suppliers with lower prices or to change the type of bottle used to a cheaper model. The second higher cost for the distilled beverage, and the first to ethanol, is with yeast. This cost can be lowered by considering the recycling of yeast cells. Schweinberger considered recycling yeast 11 times, which caused a significant impact on the final cost of the process, reducing the cost by 87% on average (Schweinberger et al., 2016). Another highlight in ethanol costs is antibiotics, with 18.91% of the total costs. Potassium metabisulfite is a cheaper antimicrobial agent than tetracycline hydrochloride. Even not having the same efficiency, the metabisulfite proved to be efficient in avoiding contamination in the distilled beverage process. Therefore, to reduce ethanol costs, metabisulfite may be used in place of tetracycline.

3.2.2. Scenario analysis

The techno-economic analysis is especially important to the development of the biorefinery processes of food waste because many biorefinery technologies are more complex than those in traditional processes and require relatively high-capital investments (Jin et al., 2018). Then, in order to make the sweet potato waste biorefinery a more profitable project, an integrated processing via a combination of different technologies to produce multiple products based on the circular economy concept was performed. For the production of ethanol and distilled beverage, the same factory and the same equipment are used, which allows an adjustment of the production volume of each product, according to market needs. Therefore, five economic scenarios were simulated. The production percentage of each product in each scenario can be seen in Fig. 3.

In all cases, the domestic consumption of ethanol was kept at 20%, which is estimated to supply the entire fuel needs of the biorefinery. Scenario 1 is focused on the production and use of biofuels such as bioethanol and a non-existent market for sweet potato distilled beverages. In scenario 2, there is the beginning of the production of distilled beverage with the entry of this product in the market. The output of each product equals 40% in scenario 3. A heated economy for the production of alcoholic beverages with little focus on bioethanol can be seen in scenario 4. In scenario 5, bioethanol is produced only for internal consumption, while the entire production is destined for the spirit.

In order to evaluate the investment analysis for each scenario, the economic indicators NPV, IRR and discounted payback were calculated considering 10 years of operation. The MARR adopted was equal to SELIC rate (5%), the basic interest rate of the Brazilian

Table 3
Total daily costs of inputs and its percentage contribution to the total costs for a 1000 L/day distilled production plant.

Input	Ethanol			Distilled beverage		
	R$	US$[a]	%	R$	US$[a]	%
Sweet potato	354.41	87.51	11.89	473.85	117.00	5.85
Workers	200.25	49.44	6.72	333.75	82.41	4.12
Electric energy	70.26	17.35	2.36	72.27	17.84	0.89
Water	214.46	52.95	7.19	223.45	55.17	2.76
Hydrolysis enzyme	180.74	44.63	6.06	241.65	59.67	2.98
Viscosity reduction enzyme	90.26	22.29	3.03	–	–	–
Yeast	1213.59	299.65	40.71	1622.58	400.64	20.03
Antibiotic tetracycline	563.73	139.19	18.91	–	–	–
Antibiotic metabisulfite	–	–	–	12.18	3.01	0.15
Firewood	93.04	22.97	3.13	93.04	22.97	1.16
Glass bottle (750 mL)	–	–	–	5026.13	1241.02	62.06
Total	R$ 2980.72	US$ 735.98	100%	R$ 8098.90	US$ 1999.73	100%

[a] US$1.00 = R$4.05 (BANCO CENTRAL DO BRASIL, 2019).

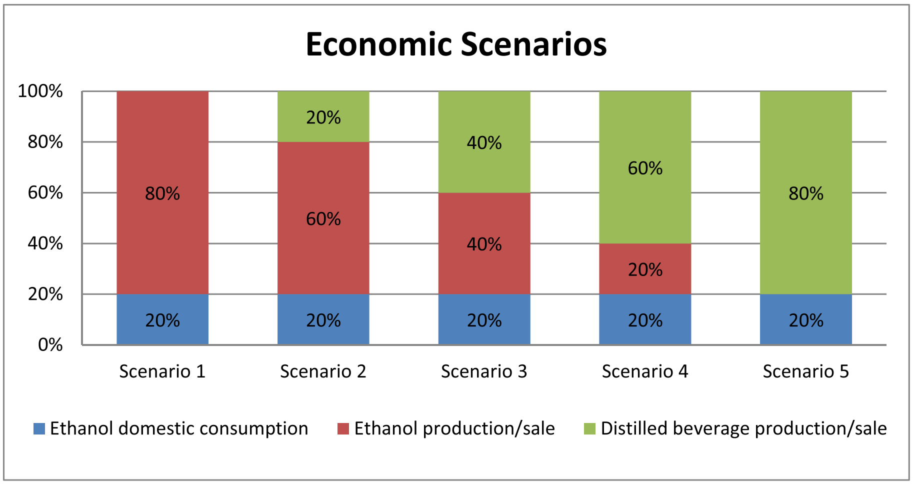

Fig. 3. Simulated economic scenarios varying the percentage volume of ethanol and distilled beverage production.

Table 4
Investment analysis indicators (NPV, IRR and discounted payback) for the five scenarios, evaluated in 10 years of operation.

Scenario	NPV (R$)	NPV(US$)[a]	IRR	Discounted payback (year)
Scenario 1	R$ −3,441,686.09	US$ −849,799.03	<0%	–
Scenario 2	R$ −1,489,283.13	US$ −367,724.23	<0%	–
Scenario 3	R$ 463,119.83	US$ 114,350.58	8%	7.11
Scenario 4	R$ 2,415,522.79	US$ 596,425.38	32%	2.00
Scenario 5	R$ 4,367,925.75	US$ 1,078,500.18	51%	1.06

[a] US$1.00 = R$4.05 (BANCO CENTRAL DO BRASIL, 2019).

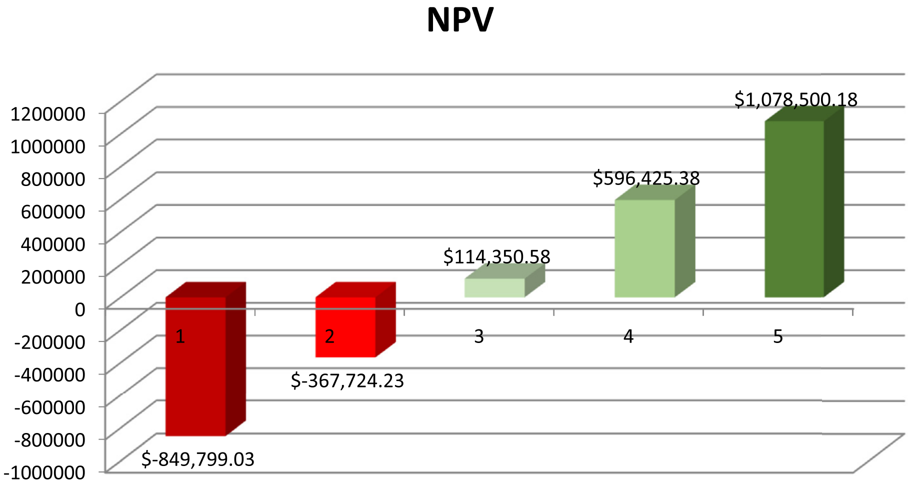

Fig. 4. NPV for the five scenarios evaluated in 10 years of operation.

economy. For the revenue calculation, medium prices of R$ 4.00 (US$ 0.99) and R$ 20.00 (US$ 4.94) were estimated for ethanol and distilled beverage, respectively. These prices were determined according to the average market prices for fuel ethanol and distilled beverages. It was considered that all production destined for sales was sold. The investment analysis indicators are shown in Table 4 and Fig. 4.

A project should be considered economically viable when NPV> 0 and IRR > MARR. Therefore, between the five economic scenarios studied, only scenarios 3, 4, and 5 are considered economically feasible. Scenarios 1 and 2 presented negative NPV and IRR values, indicating that these production scenarios would cause economic loss. Chohan et al. (2020) state that although bioethanol is produced using waste material, production costs are still high, making the process economically unfeasible at a large scale (Chohan et al., 2020). This fact happened in scenario 1, in which only ethanol was produced, showing that the expenses are higher than the revenues. In scenario 2, where the distilled beverage production is inserted, the results are a little better, but it is still an economically unfeasible scenario. From 40% of distilled beverage production, which occurs in scenario 3, the results begin to be positive, with NPV>0 and IRR > MARR. Thus, for the sweet potato waste biorefinery to be an economically viable project, the percentage production of ethanol and distilled beverage intended for sale must be at least equal. The best scenario, that presented the highest values of IRR (51%) and NPV (US$ 1,078,500.18), was the

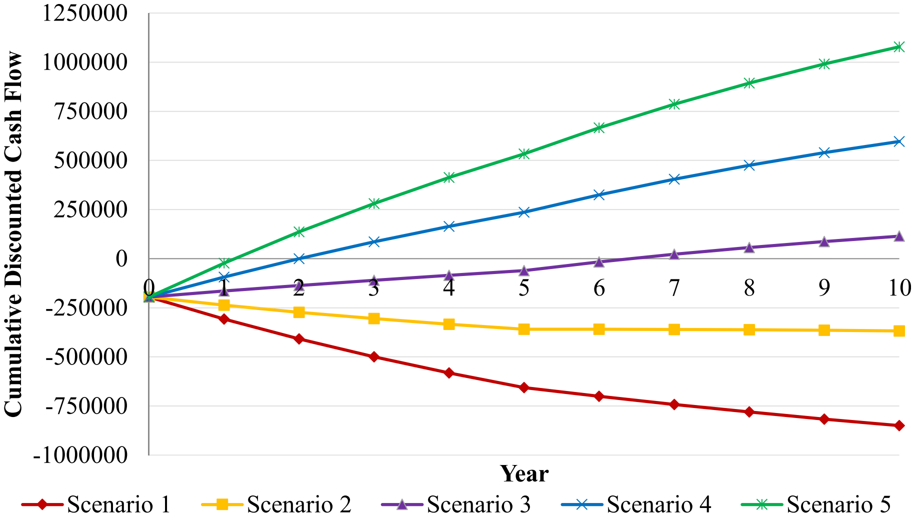

Fig. 5. Cumulative discounted cash flow for the five scenarios evaluated in 10 years of operation.

scenario 5. Therefore, the higher the production of alcoholic beverages, the greater the economic return of the project.

For a better understanding and evaluation of the economic return over the 10 years for each scenario, the cumulative discounted cash flow was calculated and plotted in Fig. 5.

From Fig. 5 it can be seen that all scenarios start with a negative cumulative discounted cash flow in the first year. Scenario 5 is the first to achieve a positive value, what happens in 1.06 year. This value is the discounted payback, i.e., the time for the investments made to be fully recovered. Scenarios 3 and 4 reach positive cumulative discounted cash flow in 2 and 7.11 years, respectively. Thus, the more alcoholic beverages are produced, the shorter the time to the return of investment. Scenario 2 shows a decreasing trend until year 5, from which it remains constant but still negative. Finally, scenario 1 shows a decreasing trend over the 10 years, being the worst economic scenario among those evaluated. Not all biorefineries are economically viable projects. The tomato pomace biorefinery proposed by Scaglia et al. showed positive economic results (Scaglia et al., 2020), while the integration of algae-based biorefinery with palm oil mill was not economically feasible (Abdul Hamid and Lim, 2019). Therefore, the results achieved by the sweet potato biorefinery show potential for a sustainable processing system through the valorization of sweet potato waste to produce higher value-added products and energy, meeting the objectives of the circular economy.

4. Conclusions

The proposal to produce bioethanol and distilled beverage using sweet potato waste as raw material was achieved, providing a better destination for the considerable amount of this available food residue. Techno-economic analysis of the sweet potato waste biorefinery was evaluated, showing promising results.

Five different scenarios varying the production percentage of each product were evaluated. The most profitable scenario was that with the highest production of the distilled beverage, while the scenarios with higher ethanol production were economically unfeasible. Economic results began to be positive when the production for sale of each product reaches 40%, plus 20% of ethanol for domestic consumption. The best scenario (80% beverage production) presented NPV of US$ 1,078,500.18, IRR of 51%, and discounted payback of 1.06 years.

The development of biorefineries plants has high relevance adding value to regional raw materials and making processes more economically-viable, contributing to local sustainable development. Therefore, the main points of a biorefinery concept, which are the sustainable processing system and the production of marketable products and energy, were successfully achieved. The sweet potato waste biorefinery provides energy generation, new businesses, and consequent job creation, savings of landfills costs, and greenhouse gas emissions reduction, also reaching the goals of the circular economy.

Concerning future perspectives, biorefineries make room for new business models, including a decentralized production model of two levels. A decentralized supply chain that integrates biomass depots as an intermediate pre-processing center may be an efficient way to transport commodities over long distances (Lemire et al., 2019). Besides, a new way of commercializing sweet potato for food purposes can be done in the format “pay what you sold and what you did not sell returns for ethanol production”. Also, although relevant research using food wastes for the biorefinery process design is increasing recently (Corona et al., 2018; Ghosh et al., 2019; Gonzalez-Garcia et al., 2018; Guo et al., 2019; Kratky and Zamazal, 2020; Zabaniotou et al., 2018; Zabaniotou and Kamaterou, 2019), there are still some issues such as feedstocks selection and supply, transportation, economic, environmental, and social evaluation that need to be considered thoroughly in the future (Jin et al., 2018). The logistics issue is fundamental for economic success and is being solved in another study in our research group.

CRediT authorship contribution statement

Caroline Trevisan Weber: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Luciane Ferreira Trierweiler:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing - review & editing. **Jorge Otávio Trierweiler:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2020.121788.

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