# Bioenergy and Biorefinery potential of residues: A representative case of the Sucre region in Colombia

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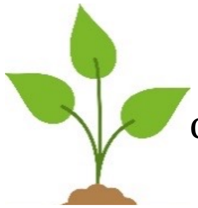
# 1. Introduction

## Bioeconomy & Biorefineries



**Bioeconomy** should be defined as the sustainable **use** of different renewable **biological resources** and/or its **conversion** to several high-value bio-based products or services. The common definition of Bioeconomy requires changes as the sustainability includes the social and environmental restrictions. May be **Biosustainability** could be a better reference.

**Advantages.**

- ✓ New green industries
- ✓ Less oil-based products
- ✓ Climate change mitigation
- ✓ New business opportunities (especially in rural areas)

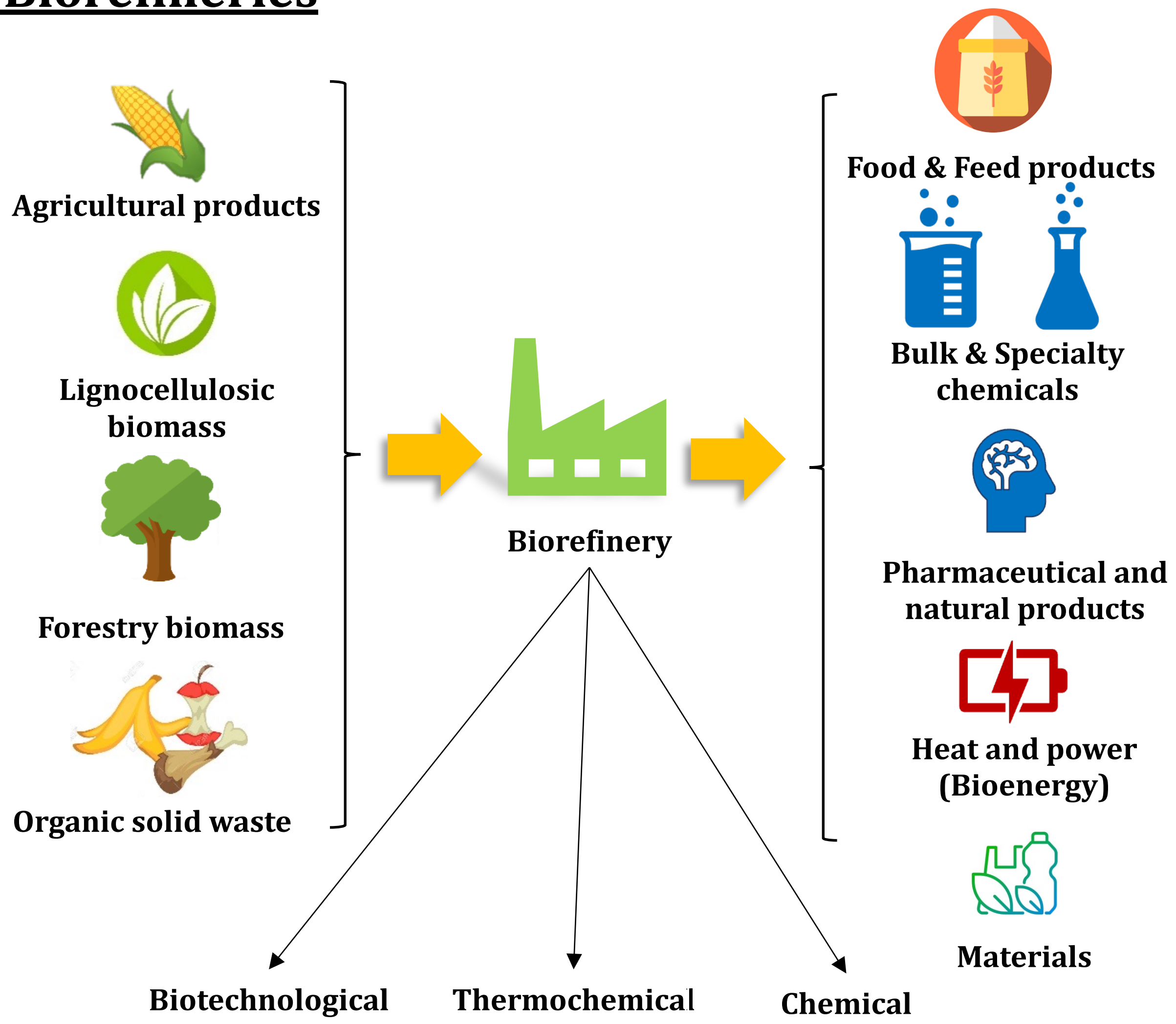



**Figure 3.** A biorefinery scheme

# 1. Introduction

## The biorefinery concept

A biorefinery is a **complex system**, where biomass is integrally processed to obtain in a sustainable way more than one product including **food, feed**, **bioenergy, biofuels, chemicals and high value-added compounds** that only can be extracted from bio-based sources (Moncada, Aristizábal-Marulanda, Cardona Alzate, 2016)

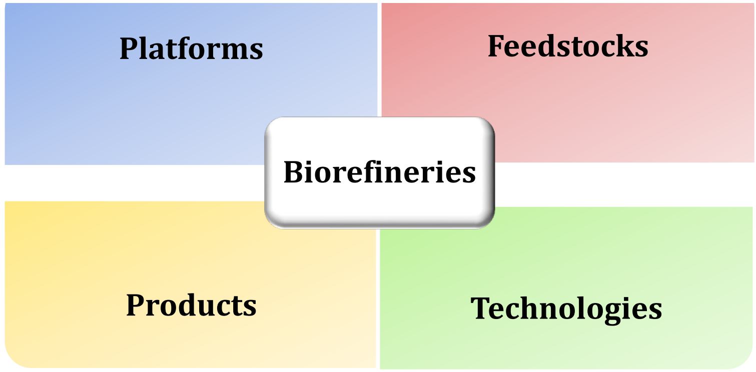



**Figure 4.** Main components of a biorefinery system

Two main types of biorefineries:

**Energy-driven** and **Product-driven biorefineries**


Moncada, Aristizábal-Marulanda, Cardona Alzate, Biochemical Engineering Journal, 116, 15, 122 - 134 ,2016


## Design methodologies

**Conceptual design** — This design approach is based on the hierarchy, sequencing and integration concepts.

**Optimization** — This design approach uses superstructure schemes and mathematical modeling as tools for designing.

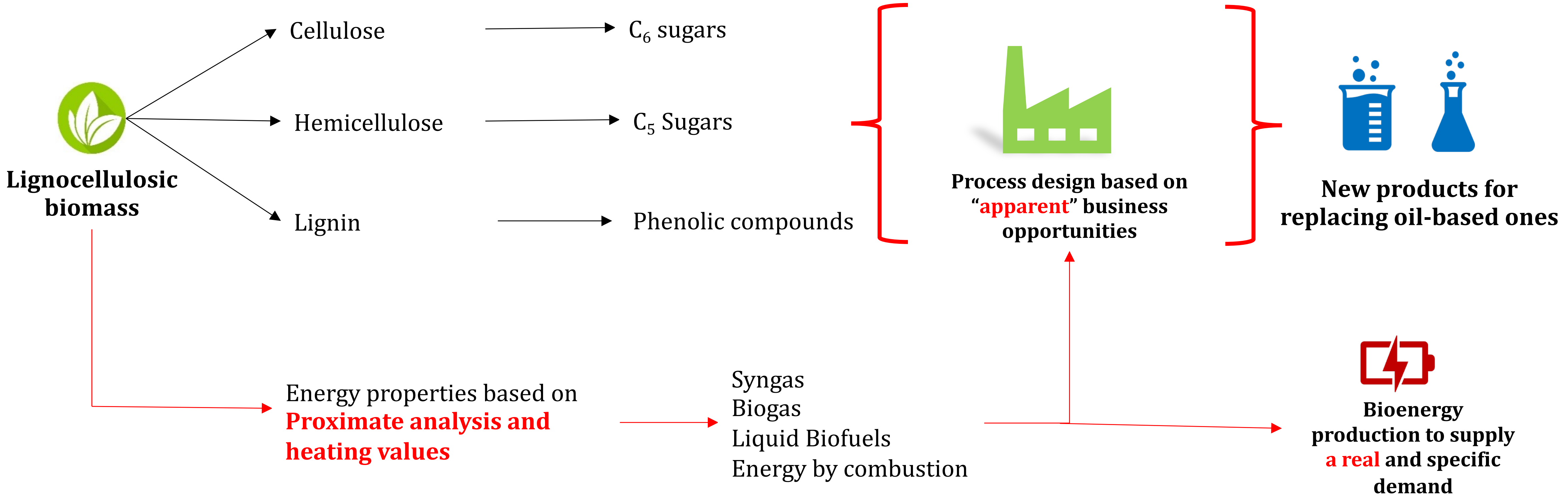
## Factors to be considered in Biorefineries Design

- ✓ Theoretical basis. Biotechnology, Chemical Engineering
- ✓ ***Raw materials characterization and potential energy uses***,
- ✓ Experimental Setup For Stand-alone Processing Lines,
- ✓ Modelling And Simulation,
- ✓ Integration Possibilities,
- ✓ Supply Chain
- ✓ Scale Analysis
- ✓ Practical (Real) Proposal To Be Installed

# 2. Problem statement.

**Most biomass applications have been proposed** based on innovative processes for high-value-added products obtaining, **leaving aside fundamental applications related to bioenergy production. The availability of raw materials in tropical countries is too much and the products possibilities are also high.**

**<u>Basic idea when searching for biomass valorization routes</u>**



# 3. Research objective

The research work aims **to analyze the potential** of different **biomass residues for energy and product driven biorefineries generation** purposes based on **the energy content** and **the upgrading opportunities** to a products portfolio using a design strategy based on chemical characterization and bioprocesses selection.

**The Sucre province in the north of Colombia is considered as a case study since several crops and biomass residues are produced.**


**Figure 5.** Colombia map – Sucre department. Taken from https://shorturl.at/xQRST

**This region has several crops:**

- Maize/Corn
- Cassava
- Plantain
- Avocado
- Rice
- Palm oil

**This region has several crops (examples):**

**Cassava stems**

**Corn cobs**

**Rice Husk**

**Plantain residues**

# 4. Design Strategy for biorefineries.

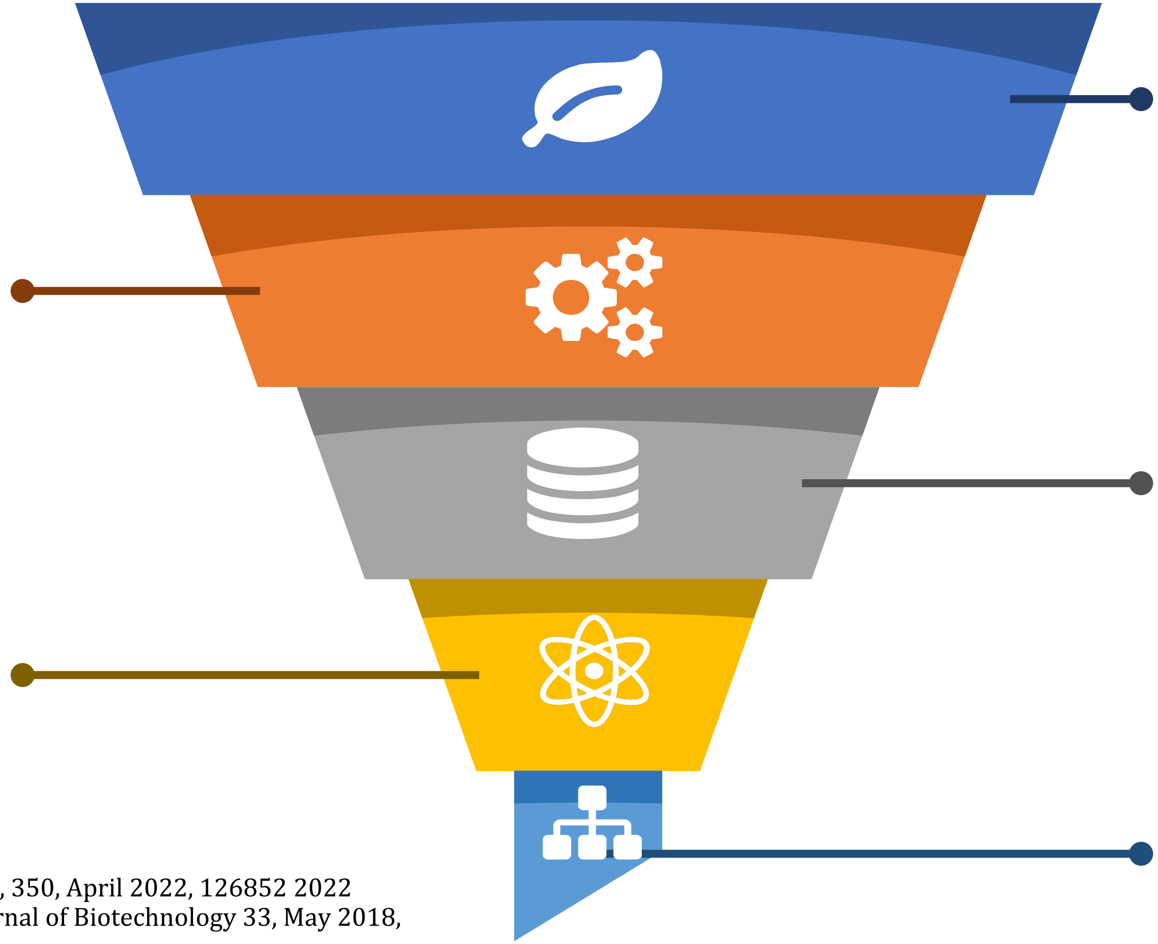
**Processing Routes Selection** (Ortiz-Sanchez and Cardona Alzate, 2022) + **Energy Potential Analysis** (Solarte-Toro…Cardona Alzate, 2018)

**Technological and Industrialized context**

Technological Readiness Level of the context to analyze the valorization of biomass

**Portfolio of BioProcesses**

Technological readiness level and technical, energy, economic and environmental indicators to define different routes of biomass transformation that are feasible



**Biomass factors and limitations**

Productive chain, Scale,

**ANALYSIS OF ENERGY APPLICATIONS PRIOR TO PROPOSE COMPLEX VALORIZATION SCHEMES**

**Biomass composition**

Chemical composition of the raw material: Fraction of raw material

Extractives, Fats, Cellulose, Hemicellulose, Lignin, Protein, Pectin, Ash

**Scenarios or Superstructure**

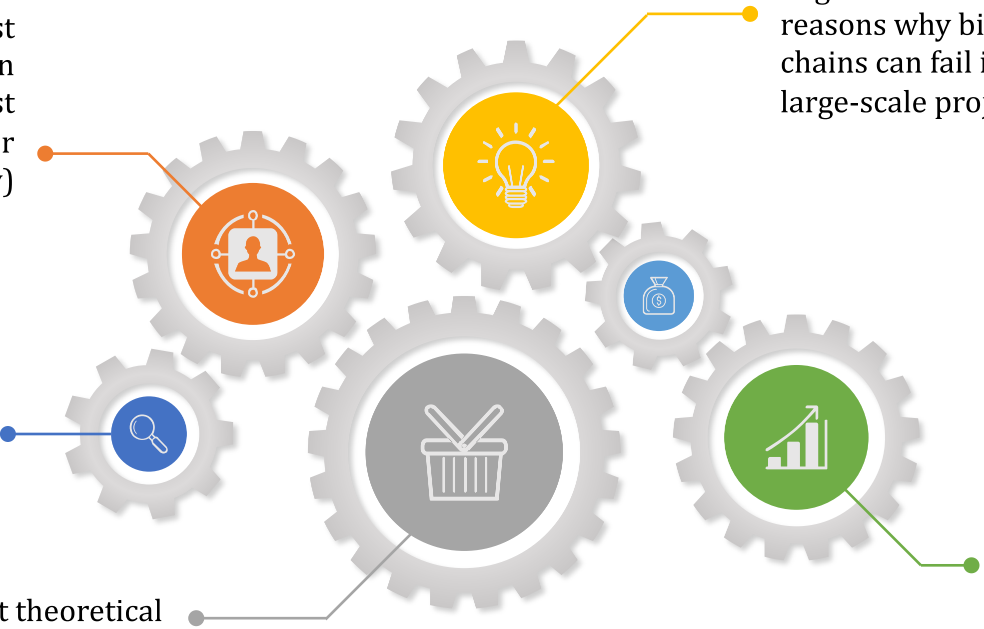
Scenarios or superstructure according to the problem raised, the chemical composition of the biomass, and the technological context

**Figure 6.** Biorefineries design strategy involving several aspects

Ortiz-Sanchez and Cardona Alzate, Bioresource Technology, 350, April 2022, 126852 2022
Solarte-Toro, Chacón-Pérez, Cardona Alzate, Electronic Journal of Biotechnology 33, May 2018,

# 4. Design Strategy for biorefineries.

## Biorefineries barriers




## Biorefineries barriers


**Figure 7.** Barriers for biorefineries implementation in different world regions

# 4. Design Strategy for biorefineries.

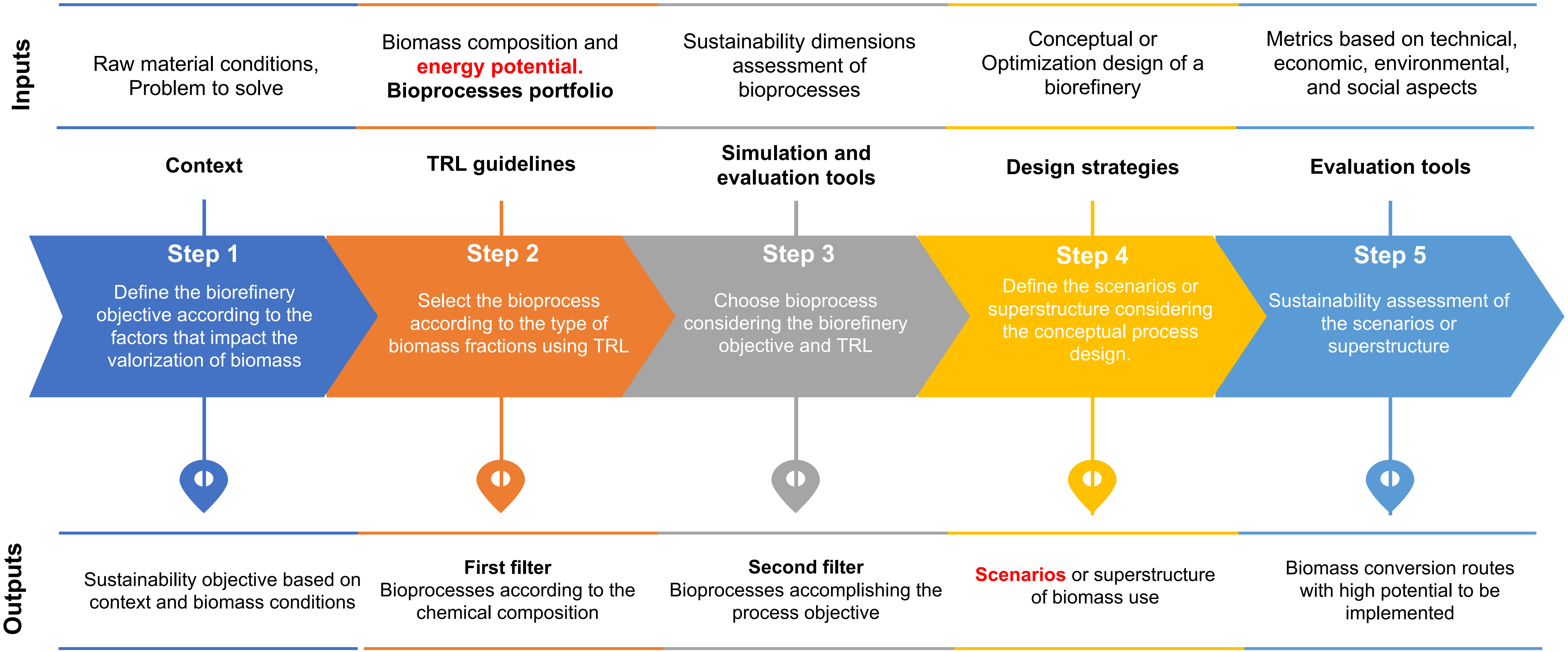



**Figure 8.** Step-by-step for designing biorefineries based on energy potential and chemical composition

# 4. Design Strategy for biorefineries.

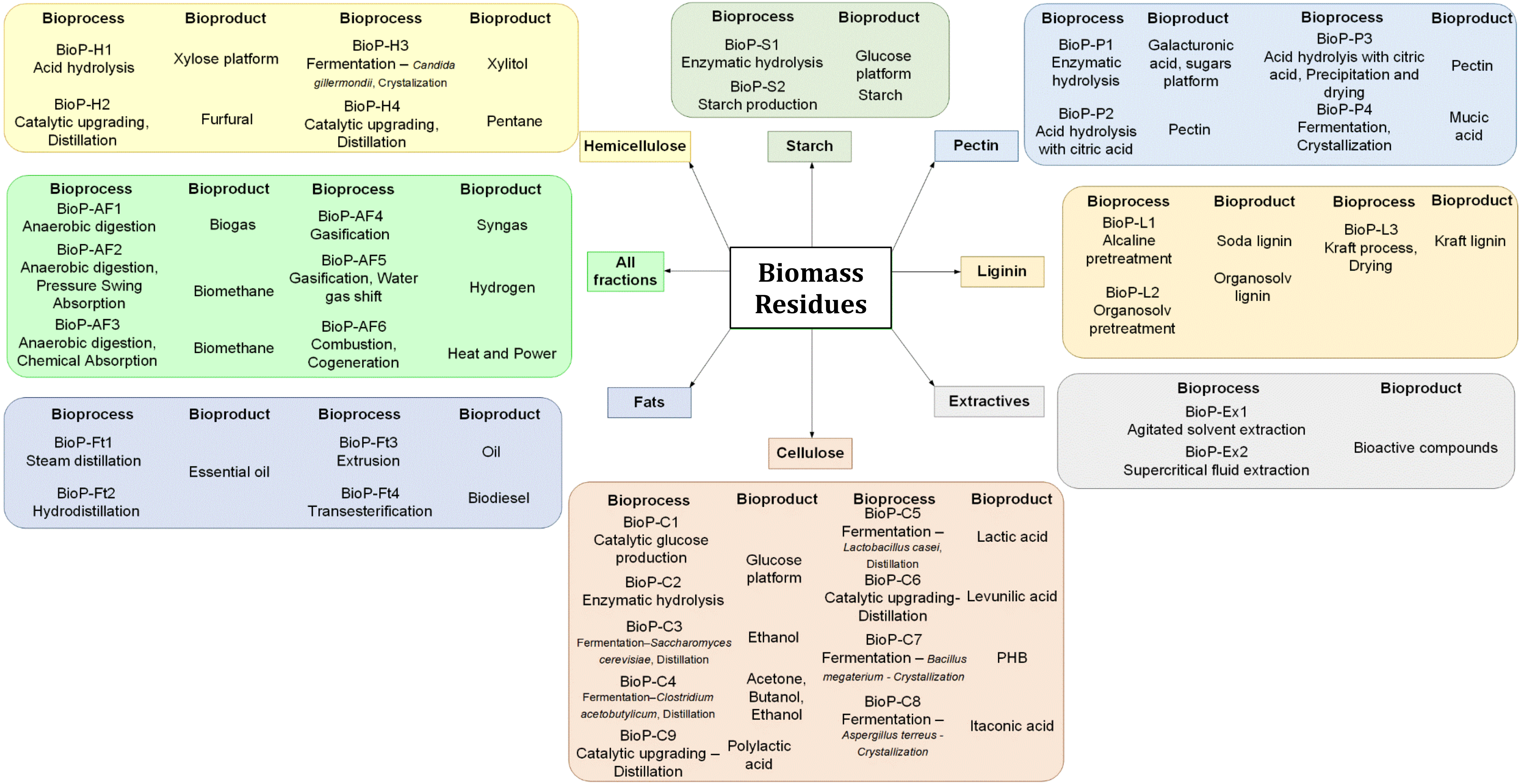



**Figure 9.** Compendium of bioprocesses addressed to upgrade different biomass fractions.

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

### Step 1. Defining residual biomass and biorefineries purpose

**Biorefinery purpose:** to upgrade residual biomass considering energy applications and several bioprocesses from the Sucre region in a sustainable way

**Ten (10) residual biomass** from different crops/sources where analyzed based on chemical composition and energy potential

**Table 1.** Residual biomass selected for applying the strategy in the Sucre region

| Crop/Source | Residual biomass | Symbol |
|---|---|---|
| Avocado | Avocado seed | AS |
| | Avocado peel | AP |
| Plantain | Plantain pseudostem | PPS |
| | Plantain rachis | PR |
| Corn/Maize | Corn cobs | CC |
| Rice | Rice husk | RH |
| Cassava | Higher cassava stem | HCS |
| | Lower cassava stem | LCS |
| | Cassava leaves | CL |
| Food residues | Food waste | RFW |

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

### Step 2. Biomass composition and energy potential – Bioprocesses elucidation

### 2.1. Raw materials for energy driven-applications
based on thermochemical processing

**Table 2.** Variables for considering residual biomass for thermochemical processing

| Sample | Raw moisture content (%) | VM/FC | LHV [MJ/kg RM]* | Biomass for 1 MW [kg RM/h]** |
|---|---|---|---|---|
| CC | 40 - 50 | 7,71 | 18,07 | 199,23 |
| RH | 20 - 30 | 5,78 | 17,08 | 210,77 |
| CL | 75 - 85 | 6,58 | 17,59 | 204,66 |
| LCS | 40 - 60 | 9,53 | 16,55 | 217,52 |
| HCS | 40 - 60 | 5,88 | 17,60 | 204,43 |
| PR | 60 - 75 | 6,03 | 16,98 | 212,01 |
| PPS | 70 - 90 | 6,75 | 17,29 | 208,21 |
| RFW | 70 - 90 | 6,21 | 18,04 | 199,56 |
| AS | 60 - 75 | 4,64 | 18,37 | 195,97 |
| AP | 60 - 75 | 4,87 | 18,05 | 195,97 |

*__RM:__ Raw material, **LHV**: Low Heating Value. **VM:** Volatile matter. **FC:** Fixed Carbon

**Estimated flow to produce **1 MW of energy** using combustion

**Thermochemical processing**

- ✓ Corn cobs
- ✓ Rice husk
- ✓ Lower cassava stems
- ✓ Higher cassava stems

**Energy-driven biorefineries based on thermochemical processing** (combustion, gasification, and pyrolysis)

**Bioproducts formulation or biogas production**

- ✓ Cassava leaves
- ✓ Plantain Rachis
- ✓ Plantain pseudostem
- ✓ Food waste
- ✓ Avocado seeds
- ✓ Avocado peels

**Product-driven biorefineries or energy-driven processes based on anaerobic digestion**

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

### Step 2. Biomass composition and energy potential – Bioprocesses elucidation

### 2.2. Raw materials for energy driven-applications based on anaerobic digestion

**Table 3.** Residual biomass selection for anaerobic digestion and bioprocessing

| Sample | %Cellulose | Biogas potential [$m^3$/kg RM*] | Anaerobic digestion [kg/h]** |
|---|---|---|---|
| CL | 46,49 | 1,01 | 518,81 |
| PR | 31,48 | 0,32 | 1637,50 |
| PPS | 45,45 | 0,81 | 646,91 |
| FW | 50,97 | 0,77 | 680,52 |
| AS | 37,96 | 0,92 | 569,57 |
| AP | 23,24 | 0,90 | 582,22 |

***RM:** Raw material, **Biogas potential**: Estimated based on the Buswell's equation

**Estimated mass flow to produce **1 MW of energy** with an internal combustion engine using biogas as biofuel (50% $CH_4$)

**Anaerobic digestion**

- ✓ Cassava leaves
- ✓ Avocado seeds
- ✓ Avocado peels

**Energy-driven biorefineries based on anaerobic digestion**

**Bioproducts formulation**

- ✓ Plantain Rachis
- ✓ Plantain pseudostem
- ✓ **Food waste**

**Product-driven biorefineries for $C_6$ and $C_5$ sugars upgrading**

**Food Waste** has the highest cellulose content. Thus, a high potential for producing $C_6$-derived products

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

### Step 3. Select bioprocesses based on the context, TRL, and sustainability metrics

**Choose the best bioprocesses for each raw material fraction** based on the Bioprocesses portfolio described by Ortiz-Sanchez and Cardona Alzate, 2022

**BioP-C1:** Catalytic glucose,
**BioP-C2:** Enzymatic hydrolysis
**BioP-C3:** Ethanol,
**BioP-C4:** Butanol,
**BioP-C5:** Lactic acid,
**BioP-C6**: Levulinic acid,
**BioP-C7**: PHB,
**BioP-C8:** Itaconic acid,
**BioP-C9**: Polylactic acid.,

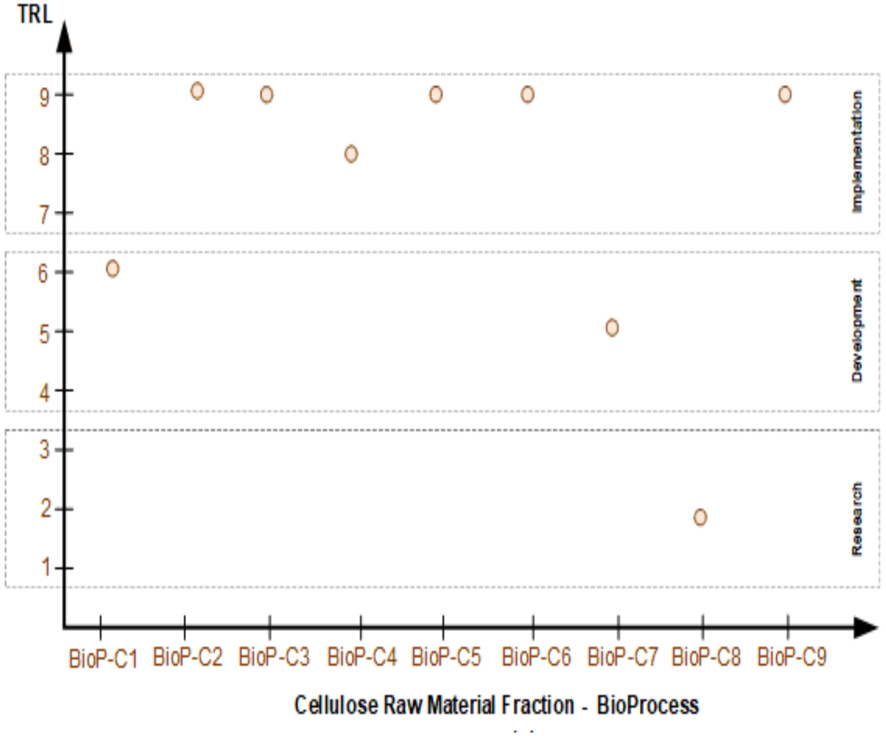



**Figure 10.** Bioprocesses for upgrading cellulose. Taken from Ortiz-Sanchez and Cardona, 2022.

Processes with a high **TRL (>7)** are selected

### Bioprocesses for upgrading Cellulose platform in Food Waste

- **BioP-C2:** Enzymatic hydrolysis
- **BioP-C3:** Ethanol fermentation
- **BioP-C9:** Polylactic acid

Bioprocesses selected for upgrading **Food Waste** since **large amounts are produced** in Sucre – Region



Ortiz-Sanchez and Cardona Alzate, Bioresource Technology, 350, April 2022, 126852 2022

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

**Step 4. Define biorefinery scenarios or a superstructure**

**Define several biorefineries** based on the selected bioprocesses applying the conceptual design approach

**Scenario 1.**
Ethanol production using food waste

**Mass flow:** 44.5 ton/day

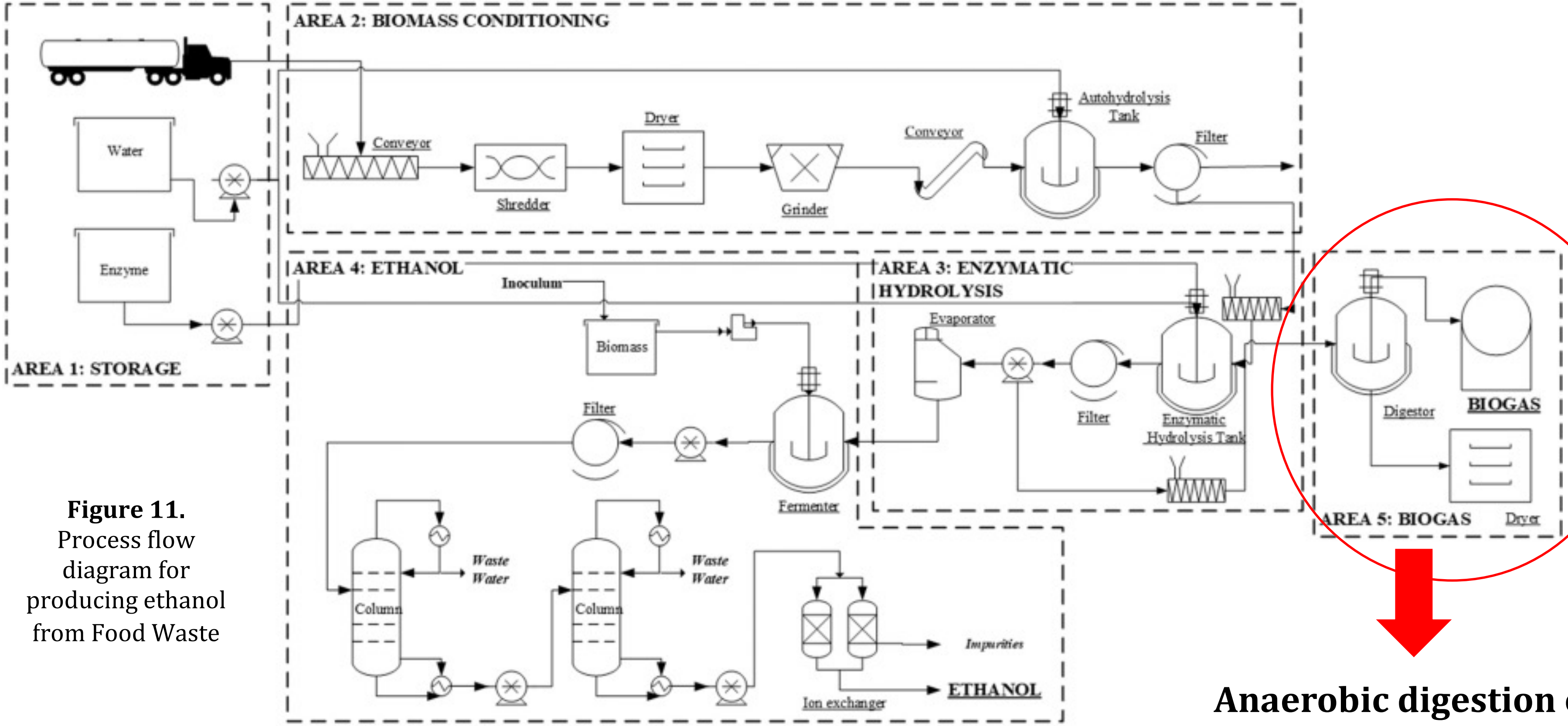



**Figure 11.** Process flow diagram for producing ethanol from Food Waste

**Anaerobic digestion of exhausted residues**

# 5. Applying the design strategy

**Scenario 2.**
Polylactic acid production using food waste

**Mass flow:** 44.5 ton/day

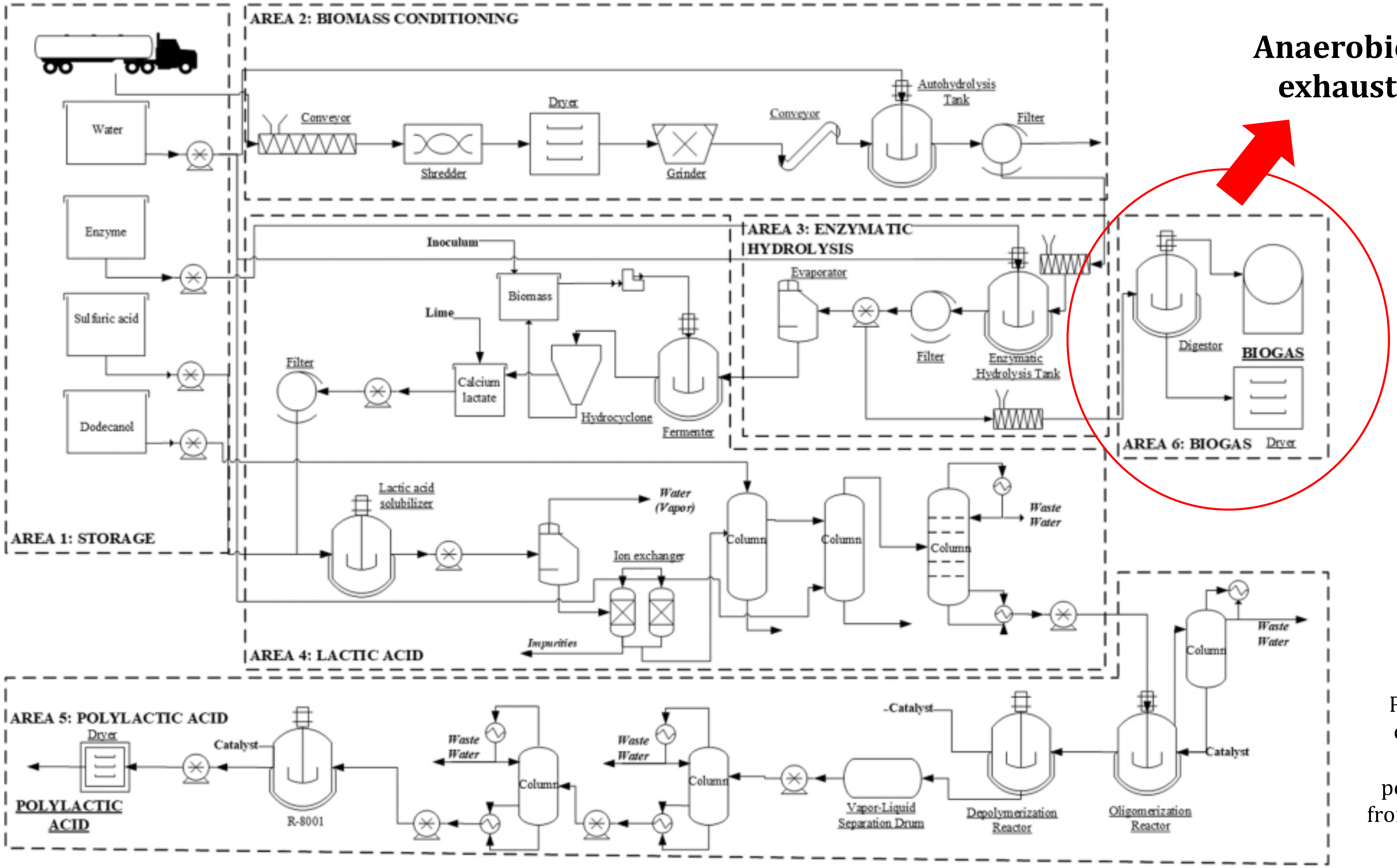



**Figure 12.** Process flow diagram for producing polylactic acid from Food Waste

# 5. Applying the design strategy

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## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

### Step 5. Sustainability assessment of the defined scenarios

To estimate the **sustainability index** of the proposed scenarios following the methodology proposed by Solarte-Toro and Cardona Alzate, 2023

**Table 4.** Residual biomass selection for anaerobic digestion and bioprocessing

| Indicator | Units | Sc. 1 | Sc. 2 |
|---|---|---|---|
| Global yield | kg Prod/kg RM* | 0,52 | 0,50 |
| Process Mass Intensity | kg RM/kg Prod | 7,14 | 8,33 |
| Energy consumption | GJ/ton | 131,16 | 411,76 |
| Sel-generation index | % | 13,51 | 4,29 |
| Payback period | Years | 16,00 | 9,00 |
| MPSEF** | Ton/day | 30,50 | 10,50 |

***RM:** Raw material

****MPSEF:** Minimum Processing Scale for Economic Feasibility

**Table 5.** Sustainability index for comparing food waste upgrading scenarios (Equal weighting applied)

| Indicator | Units | Sc. 1 | Sc. 2 |
|---|---|---|---|
| Sustainability Index* | % | 63 | 68 |

***RM:** Sustainability index estimated based on the techno-economic performance

**Polylactic acid production is more sustainable than etanol production using food waste**





Solarte-Toro, Ortiz-Sanchez, and Cardona Alzate. Renewable Energy. 206, Pages 1147-1157, 2023

# 5. Applying the design strategy

## Sucre region case study:
## Biorefineries based on residues energy potential and chemical composition.

## Results summary

**Table 6.** Summary of processing alternatives for upgrading biomass residues in Sucre Region

| Sample | | | Raw material properties | Possible upgrading processes according to the methodology | Products | Validating with literature |
|---|---|---|---|---|---|---|
| Energy-Driven biorefineries | Corn cobs | CC | Low initial moisture content, high calorific value | Fast pyrolysis (VM/FC > 6) and combustion (VM/FC < 6)* | Bio-oil, biochar, and electricity | Santos Andrade et al, 2022<br>Wang et al., 2020<br>Andrade and Ambye-Jensen., 2022 |
| | Rice husk | RH | | | | |
| | Lower cassava stem | LCS | | | | |
| | Higher cassava stems | HCS | | | | |
| | Plantain rachis | PR | High initial moisture content, high biogas producton potential | Anaerobic digestion | Biogas and Digestate (as fertilizer) | |
| | Avocado seeds | AS | | | | |
| | Avocado peels | AP | | | | |
| Product-driven biorefineries | Cassava leaves | CL | High cellulose content, high initial moisture content, low calorific value | $C_6$, $C_5$ and lignin upgrading through fermentation and catalytic processes | Phenolic compounds, protein, and biogas | |
| | Plantain pseudostem | PPS | | | Liquid biofuels and Cellulose fiber | |
| | Food waste | FW | | | Liquid biofuels or Polylactic acid | |

***VM/FC:** Volatile matter to fixed carbon ratio

Santos Andrade et al, Plants 2022, 11(24), 3577
Wang et al., Bioresource Technology, 303, ,2020, 122852
Andrade and Ambye-Jensen, Computer Aided Chemical Engineering, 51, 2022, Pages 877-882

# 6. Conclusions

- The proposed methodology allows to identify real and feasible ways to upgrade residual biomass based on the chemical composition and energy potential. Indeed, thermochemical processing is the first option to upgrade a biomass source as in the case of corn cobs, rice husk, and cassava stems.

- Raw materials with a high raw moisture content have been elucidated as potential biogas sources since low digestor volumes are required. This statement was corroborated after analyzing the potential biogas production of avocado and plantain residues.

- High cellulose, hemicellulose, and lignin content, and low calorific values are suitable raw materials properties for elucidating a bioproducts portfolio based on the proposed methodology.

- A food waste biorefinery for producing polylactic acid is more sustainable than ethanol production following the proposed methodology.

- The Sucre region has a high potential to develop energy-driven processes since large amount of residues are produced. Moreover, most residues have a high calorific value and biogas production potential.

# 7. Acknowledgements

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