Gasification, pyrolysis and combustion technologies as process alternatives for woody biomass valorization

Juan Camilo Solarte-Toro[1], Jose Andrés Gonzalez-Aguirre[1], Carlos Andrés García-Velásquez[2],
Carlos Ariel Cardona-Alzate[1*]

[1]Instituto de Biotecnología y Agroindustria, Departamento de Ingeniería Química, Universidad Nacional de Colombia, Manizales, Caldas, Zip Code: 170003, Colombia.

Department of bio-based materials, Maastricht University, Maastricht, P.O. Box 616 6200 MD, Netherlands.

*Corresponding author email: ccardonaal@unal.edu.co

Outline

1. **Introduction**
2. **Methodology**
    a) Experimental procedure
    b) Simulation approach
3. **Results**
    a) Experimental results
    b) Energy and Exergy metrics analysis
    c) Economic assessment
4. **Conclusions**
5. **References**

1. Introduction

In order to meet the global and local bioenergy needs, to address a sustainable forest management and promote environmentally friendly practices, woody biomass turns into a highly valued raw material able to be cropped sustainably in large quantities around the world.

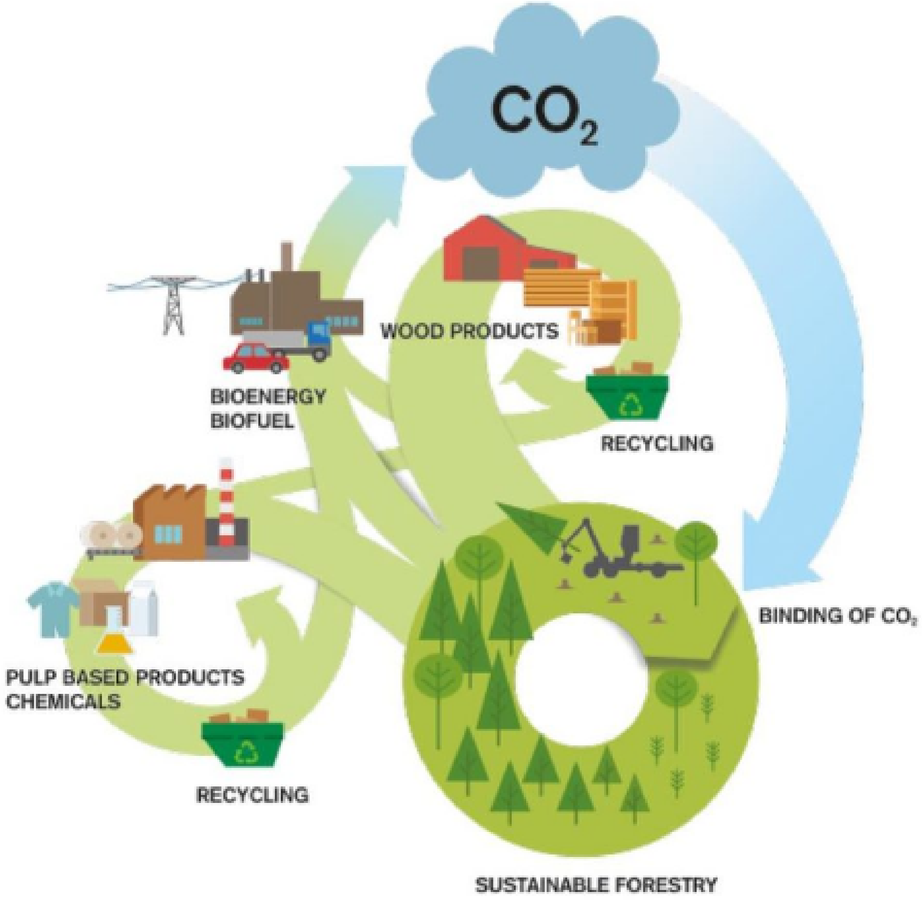


Figure 1. Woody biomass Cycle (IEA Bioenergy, 2018)

1. Introduction

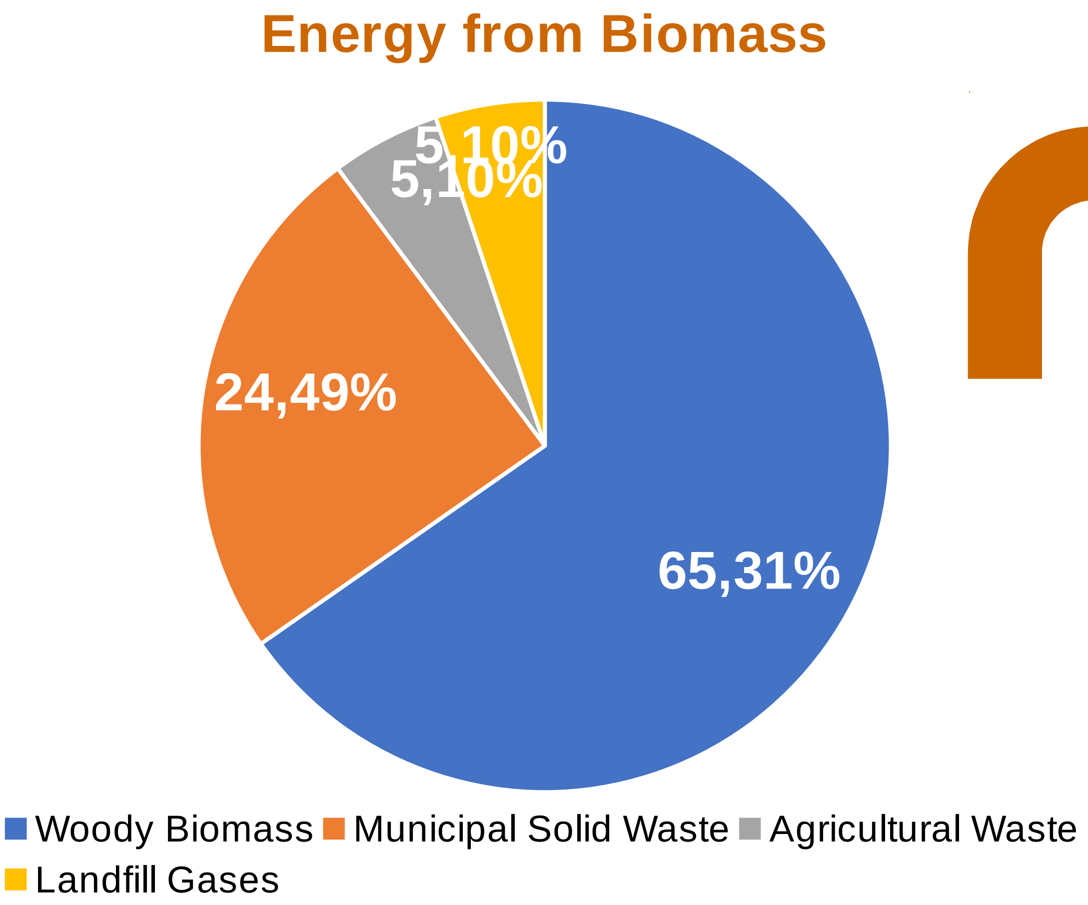
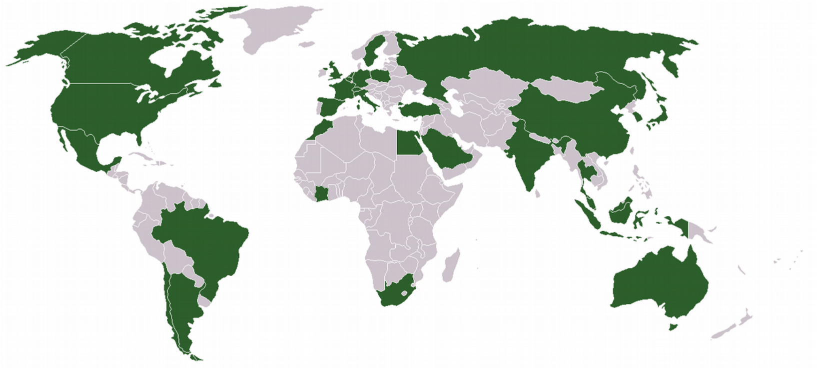


Figure 2. Energy share supplied by renewable resources



4 % of industrialized countries energy

Domestic

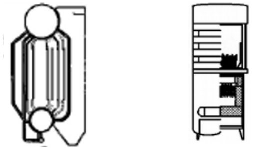
Industrial

Commercial

1. Introduction

Combustion

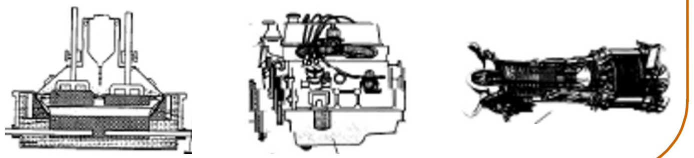
Heat
Boilers and stoves



Excess of oxygen: 5-8% vol
Temperature: <900°C
Particle size: <50mm

Pyrolysis

Bio-char / Bio-oil / Fuel Gas
Metallurgy, engines, Gas turbine



Temperature: 500 °C – Fast
400 °C – Slow
Residence time: 1 second – Fast
10 – 20 seconds - Slow

Gasification

Fuel Gas / Heat
Gas turbine, steam turbine

Temperature: 800 – 850 °C
Particle size: 0.5 – 1 cm
Oxygen content: ≈ 35 %

1. Introduction

- Economic Analysis
- Environmental Analysis
- Energy Analysis

Objective

To evaluate and compare gasification, combustion, and pyrolysis technologies as process alternatives for woody biomass valorization from energy, economic and environmental perspective using *Pinus Patula* as case of study

2. Methodology

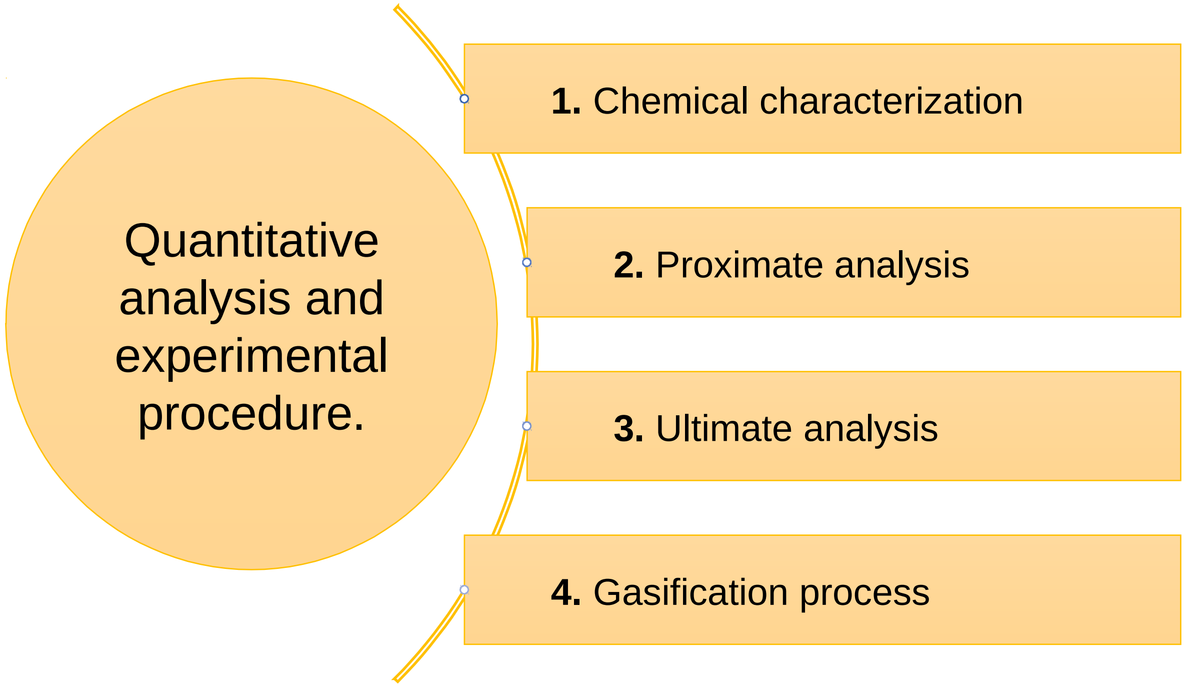


Figure 3. Steps to perform the experimental characterization of *Pinus Patula*

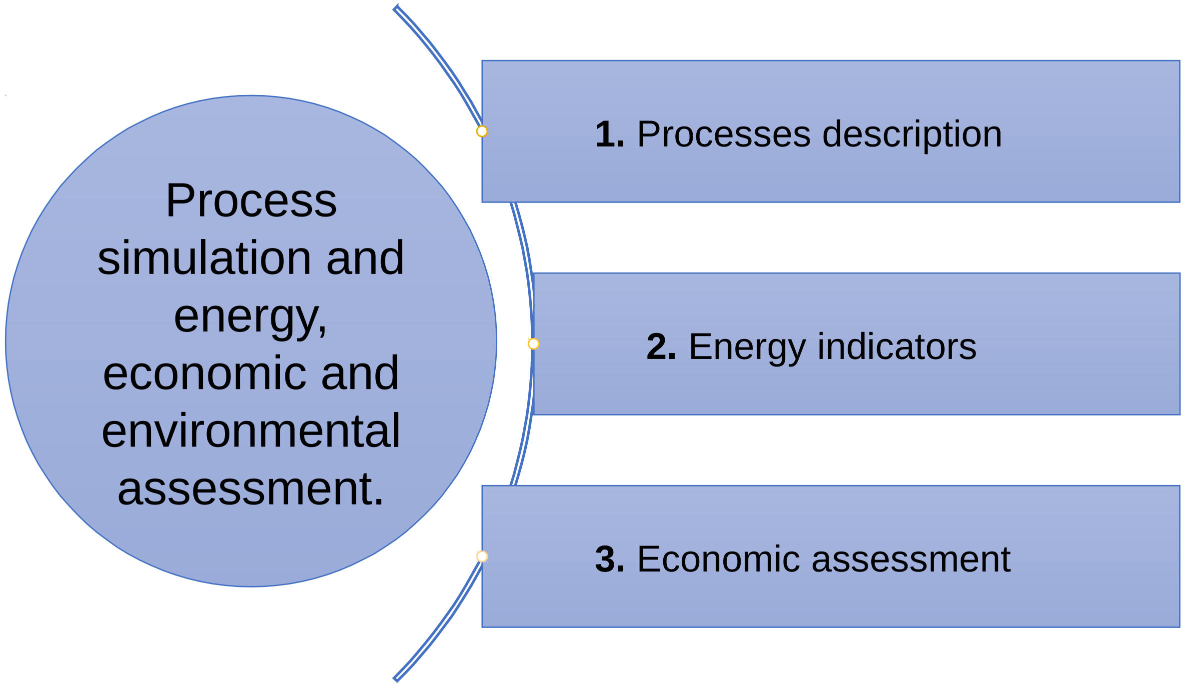


Figure 4. Steps to evaluate the thermochemical conversion of *Pinus Patula*.

2. Methodology

1. Chemical characterization

Moisture
- ASTM E1756–08(2015)

Extractives
- ASTM E1690-08(2016)

Holocellulose
- ASTM D1104-56(1978)

Acid insoluble lignin
- TAPPI 222 om-02

Ash
- ASTM E1755 - 01(2015)

2. Proximate analysis

Volatile matter
- ASTM E872-82(2013)

Fixed carbon
- ASTM E870(2013)

Ash
- ASTM E1755 - 01(2015)

2. Ultimate analysis

Carbon
- ASTM E777–17(2017)

Hydrogen
- ASTM E777-17(2017)

Nitrogen
- ASTM E778-15(2015)

Sulfur
- ASTM E775-15(2015)

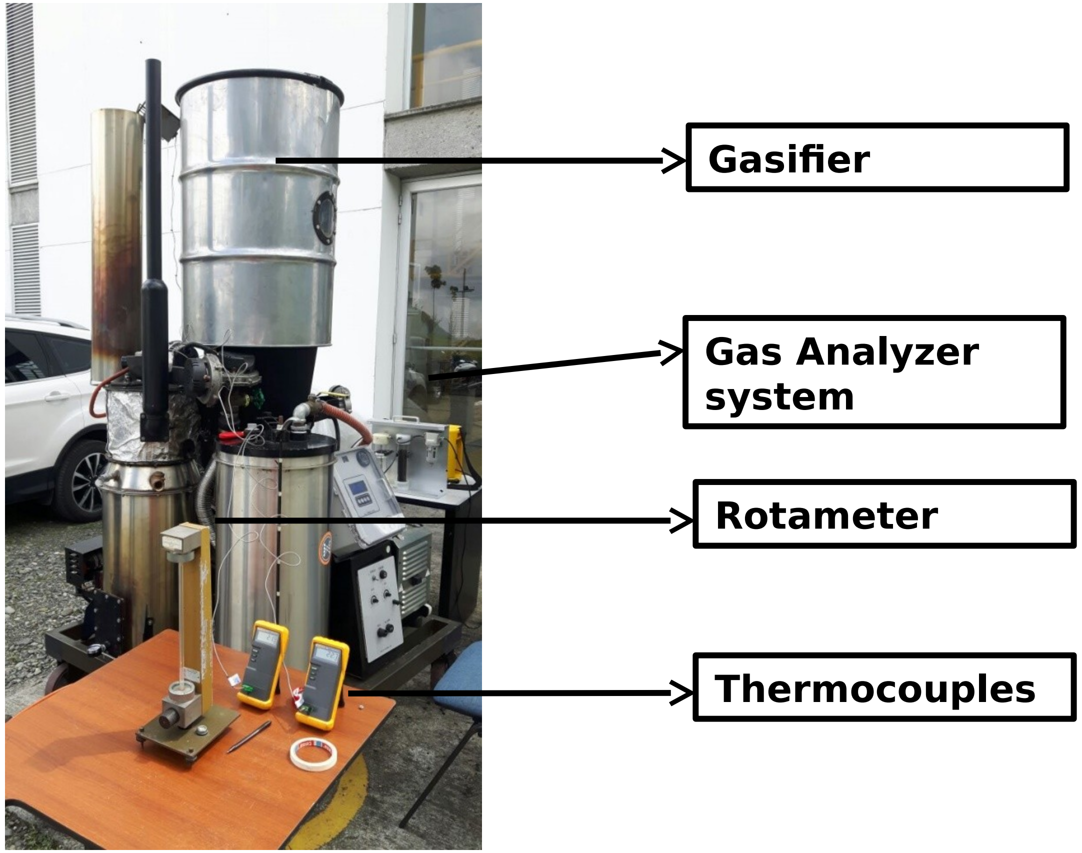
Oxygen
- ASTM E870 - 82(2013)

Figure 5. Standard methods used to characterize *Pinus Patula*

2. Methodology

4. *Pinus Patula* gasification.

- Raw material acquisition
- Raw material pretreatment
- Gasifier maintenance
- Pilot scale gasification



2. Methodology

Process flow diagrams of Gasification, Combustion and Pyrolysis processes

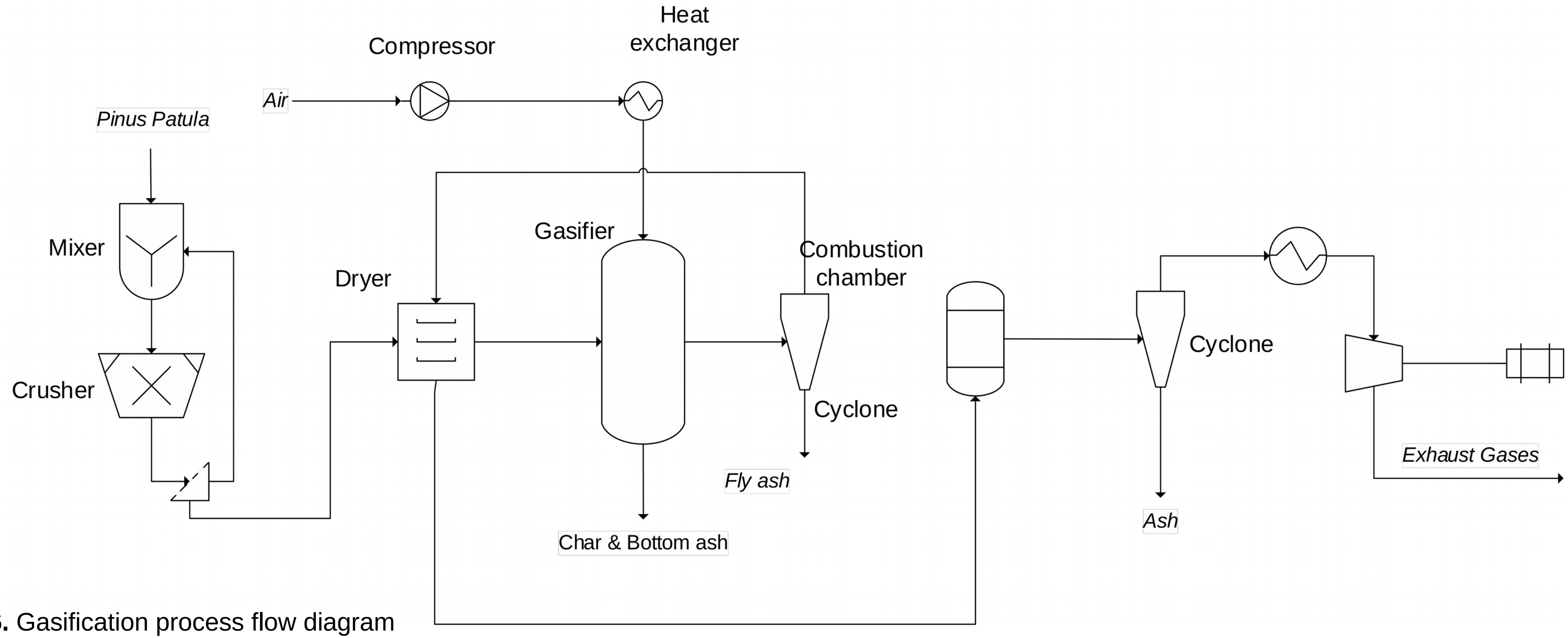


Figure 6. Gasification process flow diagram

2. Methodology

Process flow diagrams of Gasification, Combustion and Pyrolysis processes

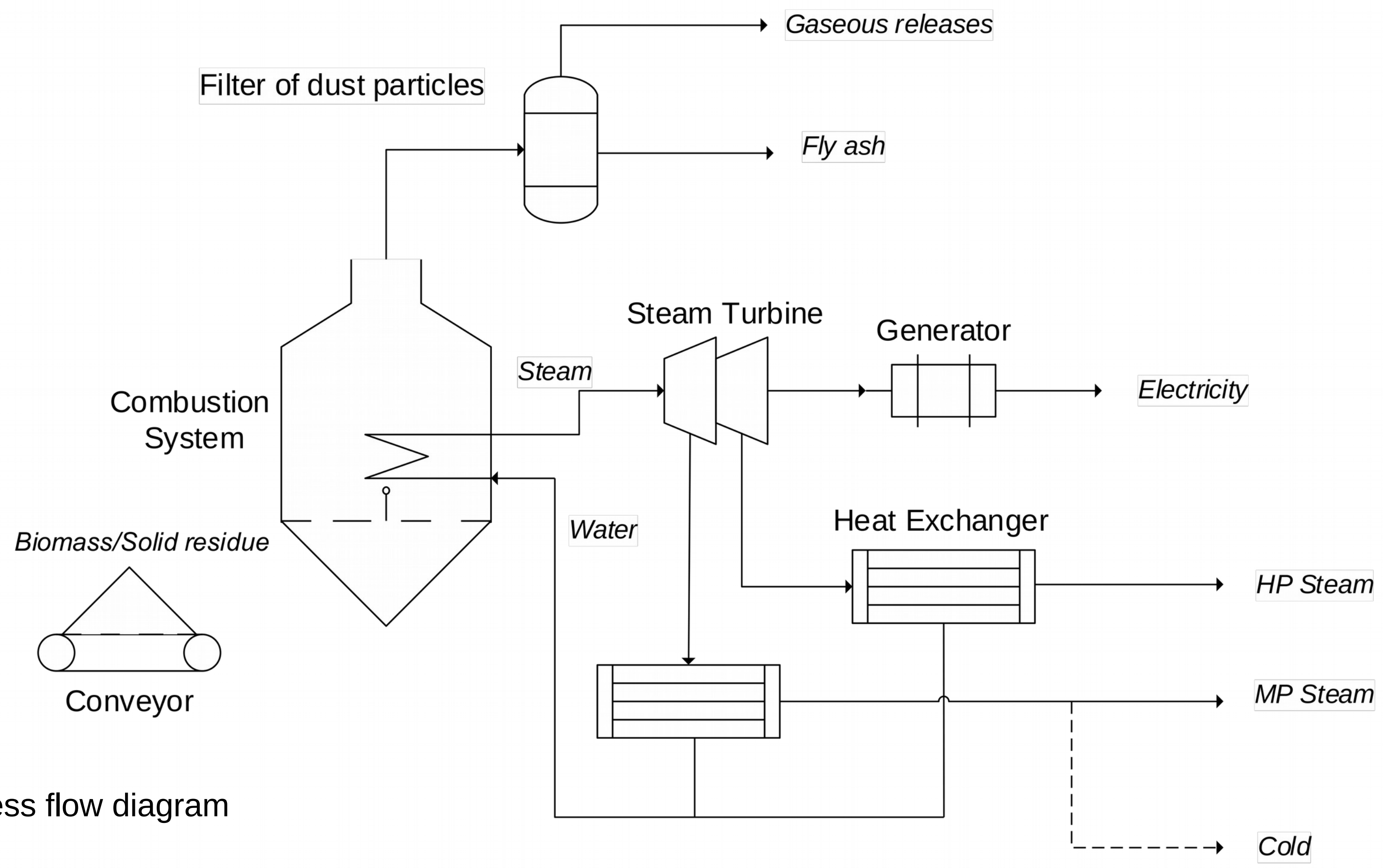


Figure 7. Combustion process flow diagram

2. Methodology

Process flow diagrams of Gasification, Combustion and Pyrolysis processes

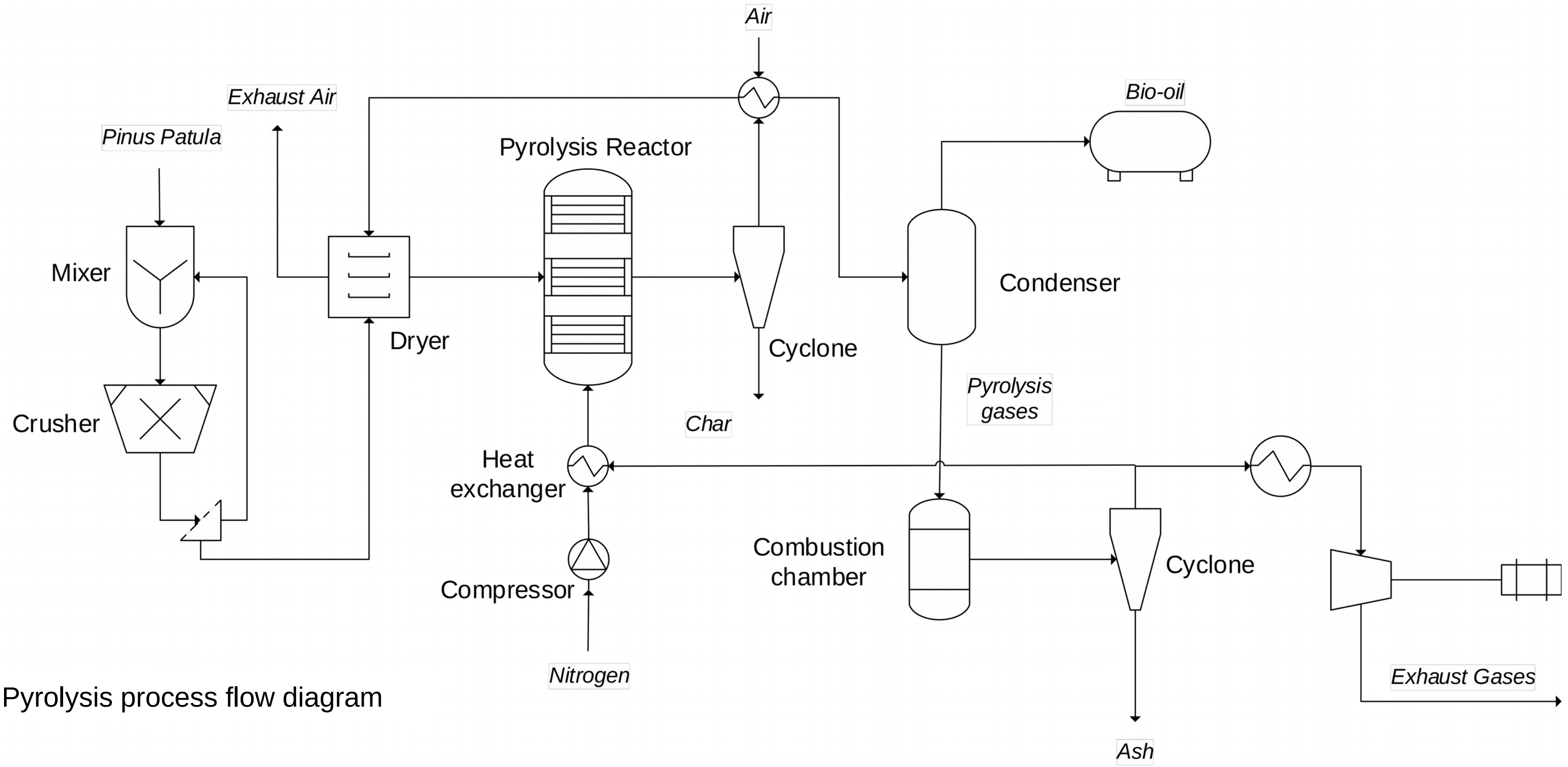


Figure 8. Pyrolysis process flow diagram

2. Methodology

Energy, Economic and environmental assessment

Aspen plus v9.0 (Aspen technologies Inc. USA).

Mass flow 250 ton/day (d.b).

Aspen Process Economic Analyzer v9.0 (Aspen technologies Inc. USA).

Economic Colombian context.
Straight line depreciation method, project plant life 10 years, Tax rate 15% y interest rate: 25%
***(Banco de la república, 2016)*.**

Process simulation and energy analysis

- Aspen blocks, process conditions and modeling of the process applying kinetic models and stoichiometric approaches.

Economic analysis

- Economic metrics calculation for each process (e.g., NPV, IRR, PO). This analysis was carried out using the software ***Aspen Process Economic Analyzer v.9.0.***

3. Results

***Pinus Patula* characterization and fuel properties**

Lignocellulosic composition

Table 1. Results of *Pinus Patula* characterization and comparison with other Woody feedstocks applied in thermochemical processes.

Analysis	Pinus Patula	Coffee Cut Stems	Wood Bark (av.)*	Oil palm fronds	Spruce Wood*
Moisture	9.21	8.7	8.8	9.68	7.6
Extractives	11.0	14.18	N.R	15.59	N.R
Cellulose	44.78	40.39	24.8	41.98	50.8
Hemicellulose	23.75	34.01	29.8	23.12	21.2
Lignin	20.22	10.13	43.8	17.32	27.5
Ash	0.25	1.27	1.6	1.99	0.5

(d.b: dry basis, av: average)
* extractive free basis

3. Results

***Pinus Patula* characterization and fuel properties**

Proximate analysis.

Table 2. Results of the proximate analysis of *Pinus Patula* and comparison with other Woody feedstocks used in thermochemical proceses

Analysis	**Content (% w/w, d.b.)**				
	Pinus Patula	**Coffee Cut Stems**	**Wood Bark (av.)***	**Oil palm fronds**	**Spruce Wood***
Volatile Matter	82.14	82.15	66.6	83.47	70.2
Fixed Carbon	17.64	16.78	31.8	14.73	28.3
Ash	0.23	1.07	1.6	1.80	1.5
High Heating Value (MJ/kg)	**19.97**	**19.32**	**20.4**	**18.56**	**19.7**

(d.b: dry basis, av: average)

3. Results

***Pinus Patula* characterization and fuel properties**

Elemental analysis

Table 3. Elemental analysis results of *Pinus Patula*

Element	**Content (% w/w, d.b.)**		
	Pinus Patula	**Coffee Cut Stems**	**Spruce Wood**
Carbon	48.96	48.35	51.9
Hydrogen	5.97	5.93	6.1
Oxygen	44.51	44.21	40.9
Nitrogen	N.R	N.R	0.3
Sulfur	N.R	N.R	N.R
Empiric formula	$C_6H_{8.83}O_{4.09}$		

(db dry basis) VM: Volatile matter FC: fixed carbon

Pinus Patula properties as **fuel material**

H/C = 1.47 (1.4 – 1.6)
O/C = 0.68 (0.6 – 1.2)
VM/FC = 4.66 (3.0 – 4.0)

3. Results

Mass and Energy indicators of the thermochemical processes

Table 4. Yields of the thermochemical conversión of *Pinus Patula*

Process	Mass yield (g/g)				
	Ashes	Biochar	Gases	Bio-oil/Tars	Carbon conversión efficiency (%)
Combustion	0.021	N.A	3.56	N.A	N.A
Gasification	0.01	5.93	2.22	0.27	94.98
Pyrolysis	0.005	0.13	0.31	0.48	75.63

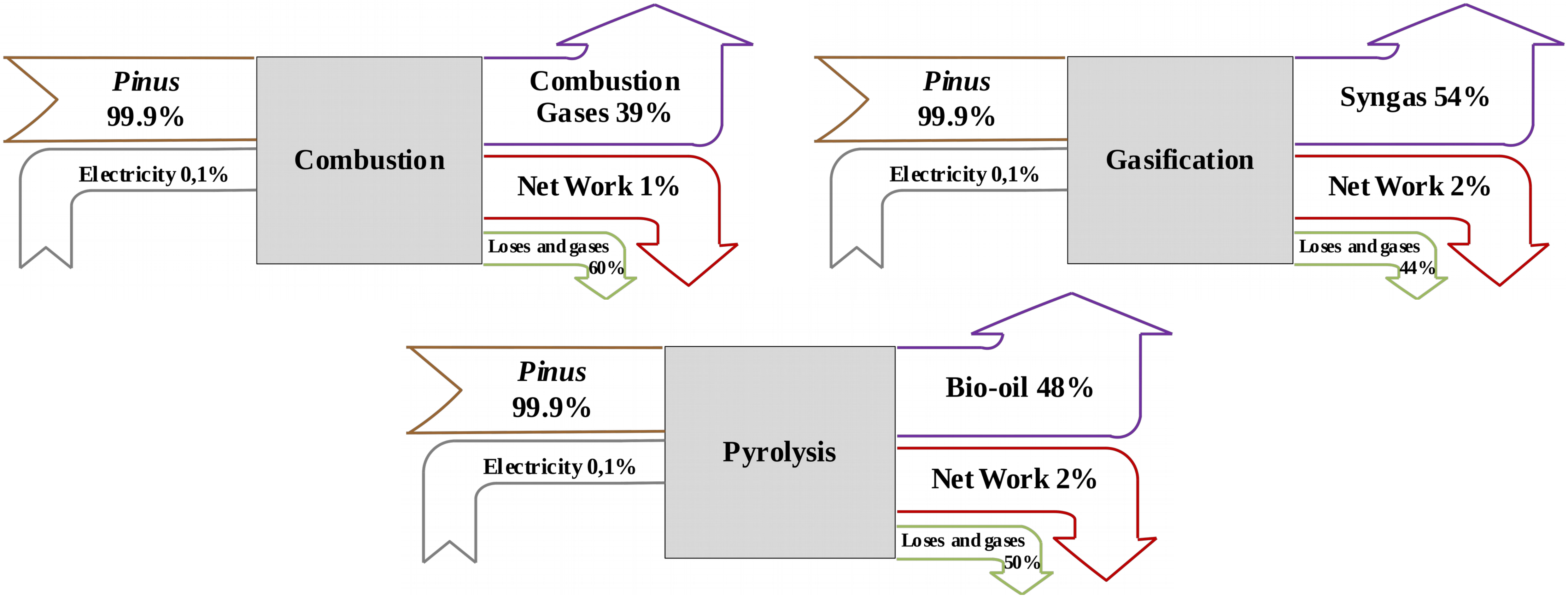
N.A: Not apply

Table 5. Energy indicators of the thermochemical conversión of *Pinus Patula*

Process	Energy efficiency (%)	Exergy losses (kW)
Combustion	39.9	194.85
Gasification	55.1	122.57
Pyrolysis	48.5	201.31

3. Results

Sankey diagrams of the thermochemical processes



3. Results

Economic evaluation of the thermochemical processes

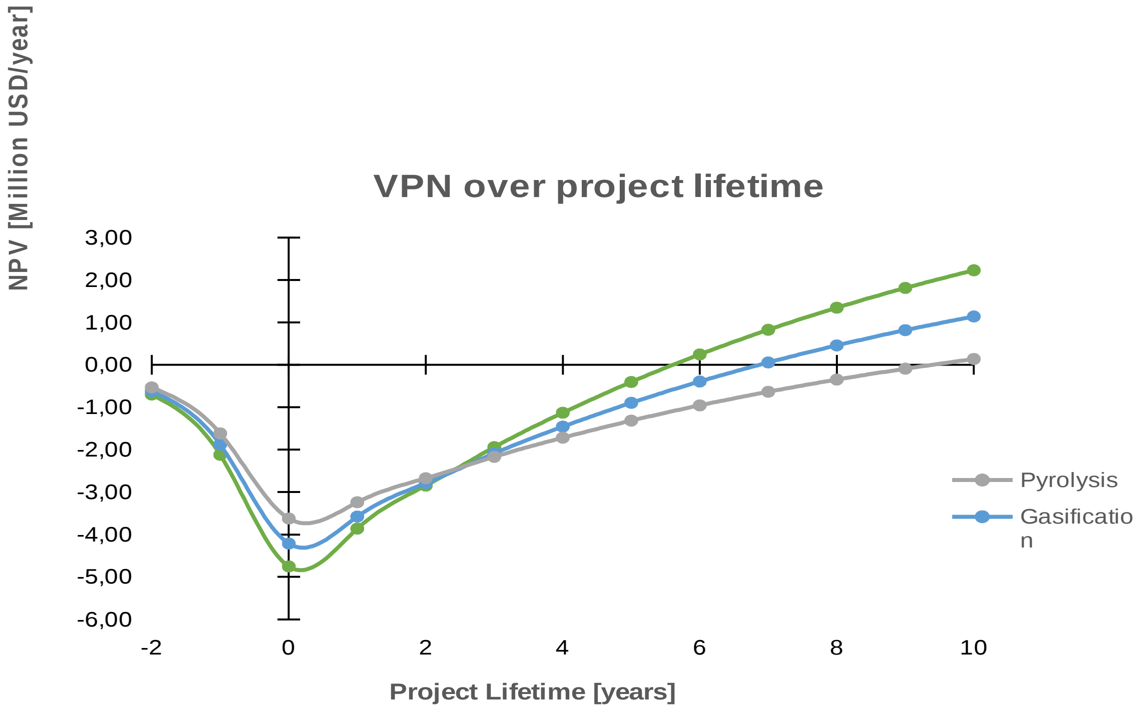


Figure 9 Net present value of the project for ten years of lifetime

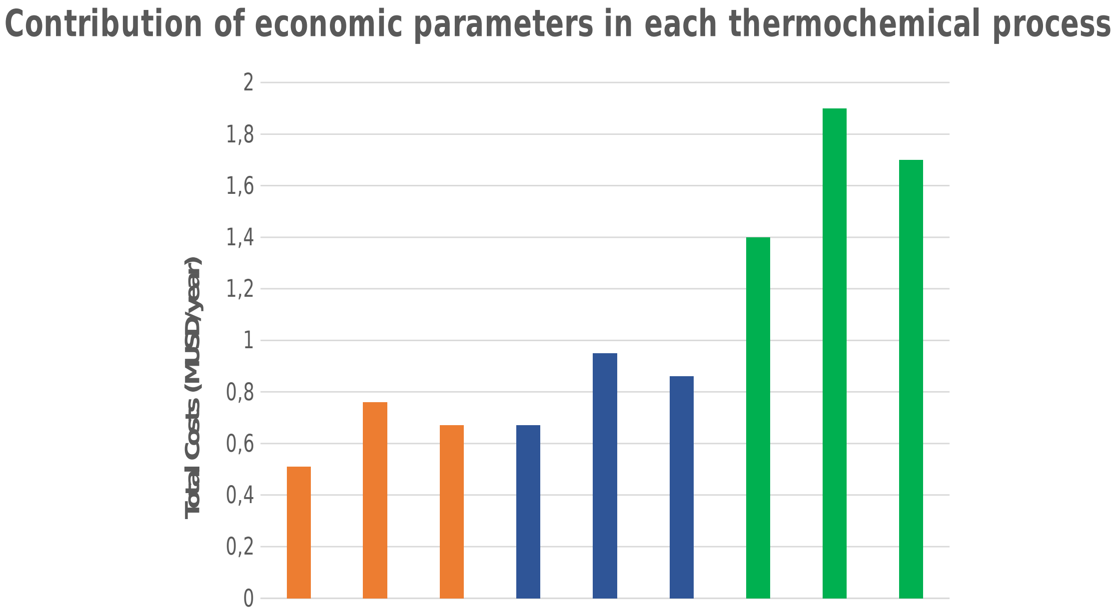


Figure 10. Share of costs for each thermochemical process

4. Conclusions

- ✓ Woody biomass present a good versatility to be upgraded into energy and value-added products through its thermochemical processing. Nevertheless, the process efficiency and the range of application of biomass gasification, combustion and pyrolysis is limited by the capacities of heat and power generation.

- ✓ Gasification presents a high potential to produce thermal energy, that can be transformed in pressurized steam. On the other hand, combustion and co-firing are strong technologies for electrical generation. Finally, pyrolysis is focused on the obtaining of added value compounds such as bio-oil.

ACKNOWLEDGEMENTS

The authors express their gratitude to the ***Reconstrucción del tejido social en zonas de pos-conflicto en Colombia del proyecto 41858***. This work has been partially financed by the **Fondo Nacional de Financiamiento para la Ciencia, la Tecnología y la Innovación, Fondo Francisco Jose de Caldas** with contract number 213-2018 and code 58960.

5. References

A. K. Sharma, M. R. Ravi, and S. Kohli, “Modelling product composition in slow pyrolysis of wood,” *Sol. Energy Soc. India*, vol. 16, no. 1, pp. 1–11, 2006.
H. Yang, R. Yan, T. Chin, D. T. Liang, H. Chen, and C. Zheng, “Thermogravimetric Analysis−Fourier Transform Infrared Analysis of Palm Oil Waste Pyrolysis,” *Energy & Fuels*, vol. 18, no. 6, pp. 1814–1821, 2004.
R. J. Wooley and V. Putsche, “Development of an Aspen Plus property database for biofuels components,” National Renewable Energy Laboratory, 1996.
V. S. Y. Soon, B. L. F. Chin, and A. C. R. Lim, “Kinetic Study on Pyrolysis of Oil Palm Frond,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 121, p. 12004, 2016.
M. Simone, F. Barontini, C. Nicolella, and L. Tognotti, “Gasification of pelletized biomass in a pilot scale downdraft gasifier,” *Bioresour. Technol.*, vol. 116, pp. 403–412, 2012.
N. V Khartchenko and V. M. Kharchenko, *Advanced energy systems*, 2nd editio. CRC Press, Taylor and Francis, 2010.
S. M. Atnaw, S. A. Sulaiman, and S. Yusup, “Influence of fuel moisture content and reactor temperature on the calorific value of Syngas resulted from gasification of oil palm fronds,” *Sci. World J.*, vol. Article ID, p. 9 pages, 2014.
I. J. Fernandes *et al.*, “Characterization of rice husk ash produced using different biomass combustion techniques for energy,” *Fuel*, vol. 165, pp. 351–359, 2016.
Z. Yao, S. You, T. Ge, and C. H. Wang, “Biomass gasification for syngas and biochar co-production: Energy application and economic evaluation,” *Appl. Energy*, vol. 209, no. July 2017, pp. 43–55, 2018.
J. Wang, T. Mao, J. Sui, and H. Jin, “Modeling and performance analysis of CCHP (combined cooling, heating and power) system based on co-firing of natural gas and biomass gasification gas,” *Energy*, vol. 93, pp. 801–815, 2015.
J. Yoder, S. Galinato, D. Granatstein, and M. Garcia-Pérez, “Economic tradeoff between biochar and bio-oil production via pyrolysis,” *Biomass and Bioenergy*, vol. 35, no. 5, pp. 1851–1862, 2011.
G. J. Ruiz-Mercado, R. L. Smith, and M. A. Gonzalez, “Sustainability indicators for chemical processes: I. Taxonomy,” *Ind. Eng. Chem. Res.*, vol. 51, no. 5, pp. 2309–2328, 2012.
G. J. Ruiz-Mercado, R. L. Smith, and M. A. Gonzalez, “Sustainability Indicators for Chemical Processes: II. Data Needs,” *Ind. Eng. Chem. Res.*, vol. 51, no. 5, pp. 2329–2353, 2012.
G. J. Ruiz-Mercado, M. A. Gonzalez, and R. L. Smith, “Sustainability indicators for chemical processes: III. biodiesel case study,” *Ind. Eng. Chem. Res.*, vol. 52, no. 20, pp. 6747–6760, 2013.
IChemE, “The Sustainability Metrics: Sustainable development progress metrics recommended for use in process industries,” 2002.
U.S .D. of Transportation, “Hazardous Materials List.” [Online]. Available: https://environmentalchemistry.com/yogi/hazmat/table/. [Accessed: 15-Jan-2017].
U. . E. P. Agency., “Toxic Releases Inventory (TRI) Program. PBT list.” [Online]. Available: www.epa.gov/toxics-release-inventory-tri-program/persistent-bioaccumulative-toxic-pbt-chemicals-covered-tri%0A. [Accessed: 15-Jan-2017].
G. Chidikofan *et al.*, “Assessment of Environmental Impacts of Tar Releases from a Biomass Gasifier Power Plant for Decentralized Electricity Generation,” *Energy Procedia*, vol. 118, pp. 158–163, 2017.
C. A. García Velásquez, “Hydrogen production through gasification and dark fermentation,” p. 181, 2016.

5. References

T. K. Patra, K. R. Nimisha, and P. N. Sheth, “A comprehensive dynamic model for downdraft gasifier using heat and mass transport coupled with reaction kinetics,” *Energy*, vol. 116, pp. 1230–1242, 2016.

N. Gao and A. Li, “Modeling and simulation of combined pyrolysis and reduction zone for a downdraft biomass gasifier,” *Energy Convers. Manag.*, vol. 49, no. 12, pp. 3483–3490, Dec. 2008.

F. M. Guangul, S. A. Sulaiman, and A. Ramli, “Study of the effects of operating factors on the resulting producer gas of oil palm fronds gasi fi cation with a single throat downdraft gasi fi er,” *Renew. Energy*, vol. 72, pp. 271–283, 2014.

F. Guo, Y. Dong, L. Dong, and C. Guo, “Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study,” *Int. J. Hydrogen Energy*, vol. 39, no. 11, pp. 5625–5633, 2014.

A. K. Sharma, “Equilibrium modeling of global reduction reactions for a downdraft (biomass) gasifier,” *Energy Convers. Manag.*, vol. 49, no. 4, pp. 832–842, 2008.

A. Esteghlalian, A. G. Hashimoto, J. J. Fenske, and M. H. Penner, “Modeling and optimization of the dilute-sulfuric-acid pretreatment of corn stover, poplar and switchgrass,” *Bioresour. Technol.*, vol. 59, no. 2–3, pp. 129–136, 1997.

J. Jensen, J. Morinelly, A. Aglan, A. Mix, and D. Shonnard, “Kinetic characterization of biomass dilute sulfuric acid hydrolysis: Mixtures of hardwoods, softwood and switchgrass,” *Environ. energy Eng.*, vol. 54, no. 6, pp. 1637–1645, 2008.

J. A. Quintero and C. A. Cardona, “Process simulation of fuel ethanol production from lignocellulosics using aspen plus,” *Ind. Eng. Chem. Res.*, vol. 50, no. 10, pp. 6205–6212, 2011.

D. Humbird *et al.*, “Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol,” *Renew. Energy*, vol. 303, no. May, p. 147, 2011.

S. Lee and Y. Koo, “Model Development for Lactic Acid Fermentation and Parameter Optimization Using Genetic Algorithm,” *Simulation*, vol. 14, pp. 1163–1169, 2004.

D.-J. Min, K. H. Choi, Y. K. Chang, and J.-H. Kim, “Effect of operating parameters on precipitation for recovery of lactic acid from calcium lactate fermentation broth,” *Korean J. Chem. Eng.*, vol. 28, no. 10, pp. 1969–1974, Oct. 2011.

C. J. S. M. Silva, S. I. Mussatto, and I. C. Roberto, “Study of xylitol production by Candida guilliermondii on a bench bioreactor,” *J. Food Eng.*, vol. 75, no. 1, pp. 115–119, 2006.

S. I. Mussatto and I. C. Roberto, “Establishment of the optimum initial xylose concentration and nutritional supplementation of brewer’s spent grain hydrolysate for xylitol production by Candida guilliermondii,” *Process Biochem.*, vol. 43, no. 5, pp. 540–546, 2008.

D. De Faveri, M. Lambri, A. Converti, P. Perego, and M. Del Borghi, “Xylitol recovery by crystallization from synthetic solutions and fermented hemicellulose hydrolyzates,” *Chem. Eng. J.*, vol. 90, no. 3, pp. 291–298, 2002.

Gasification, pyrolysis and combustion technologies as process alternatives for woody biomass valorization

Juan Camilo Solarte-Toro[1], Jose Andrés Gonzalez-Aguirre[1], Carlos Andrés García-Velásquez[2], **Carlos Ariel Cardona-Alzate**[1*]

[1]Instituto de Biotecnología y Agroindustria, Departamento de Ingeniería Química, Universidad Nacional de Colombia, Manizales, Caldas, Zip Code: 170003, Colombia.

[2]Department of bio-based materials, Maastricht University, Maastricht, P.O. Box 616 6200 MD, Netherlands.

HERAKLION2019 www.heraklion2019.uest.gr

Thanks for your attention