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Economic and Feasibility Analysis of Bioenergy Production from Sawdust via Hydrothermal Carbonisation for a Circular Economy

Fidel Vallejo[a,*], Luis Díaz-Robles[b], Ignacio Germain[b], Serguei Alejandro-Martin[c], Beatriz Ledesma[d], Silvia Román[d], Eduardo Sabio[d]

[a]Industrial Engineering, ModSim Group, National University of Chimborazo, Av. Antonio José de Sucre 060108, Riobamba, Ecuador
[b]Chemical Engineering Department, Universidad de Santiago de Chile, Santiago, Chile
[c]Wood Engineering Department, Universidad del Bío-Bío, Concepción, Chile
[d]Applied Physics Department, Industrial Engineering School, University of Extremadura, Spain
fidel.vallejo@unach.edu.ec

Hydrothermal carbonisation offers a promising solution to transform organic waste from agricultural and forestry industries into a high-calorific hydrophobic solid fuel. While still in the early development stages, HTC shows potential for large-scale implementation. Computational simulations were conducted to assess the economic viability of an industrial-scale HTC process for sawdust of radiata pine, validated against experimental data for accuracy and reliability. Results indicate that mass yield depends on temperature, residence time, and biomass-to-water ratio (B/W), while the energy yield of the hydrochar was primarily influenced by the process time and temperature. Longer times and higher temperatures generally resulted in higher energy yields. This finding highlights the importance of optimising the process parameters to achieve the desired energy output. The economic analysis demonstrated the viability of the industrial-scale HTC process. The study considered a 20 y evaluation period with a discount rate of 8 % and a weighted average cost of capital (WACC) of 5.4 %. The Return on Equity (ROE) was found to be 17.4 %. Based on these findings, utilising radiata pine sawdust, with a residual biomass flow of 200 t/day, an operating temperature of 190 °C, a reactor residence time of 1 h, a B/W ratio of 10 %, and a hydrochar pellet price of 300 CLP/kg (0.3 USD/kg) yields an economically viable scenario for stove pellet production. Sensitivity analysis showed that demand must not fall below 15 t/h for project feasibility, even when positive Net Present Value (NPV) conditions were met.

1. Introduction

In recent years, the utilisation of biomass as a renewable energy source has garnered significant attention as a means to mitigate greenhouse gas emissions and reduce dependence on fossil fuels (Saravanan et al., 2022). Biomass residues generated from industries such as forestry and pulp present both environmental challenges and opportunities for sustainable energy production. Bioenergy derived from biomass offers a promising solution to meet energy demands while minimising the environmental impacts associated with traditional energy sources (Ascher et al., 2022). Various conversion technologies have been developed and implemented to transform biomass into useful forms of energy. Among them, hydrothermal carbonisation (HTC) has emerged as an innovative approach (Lucian et al., 2020).
Hydrothermal carbonisation involves subjecting biomass to subcritical conditions in an aqueous medium, facilitating the breakdown of complex organic compounds and the reformation of carbon-rich materials. The controlled temperature and pressure conditions drive physical and chemical transformations of biomass, resulting in the production of a solid product known as hydrochar. Compared to the original biomass feedstock, hydrochar possesses improved energy density, enhanced handling and storage properties, and reduced moisture content (Benavente et al., 2015). The potential benefits of hydrothermal carbonisation are

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substantial, offering a unique opportunity to convert biomass residues into valuable energy resources while supporting waste reduction and circular economy principles. The optimization of the hydrothermal carbonisation (HTC) process and the achievement of the desired energy yield and hydrochar quality are dependent on the careful selection of appropriate biomass feedstock. Comprehensive characterization of biomass residues from industries is required to identify biomass types with optimal chemical compositions and physical properties, enabling the production of high-quality hydrochar with enhanced energy content and improved handling characteristics. Ensuring compliance with regulatory standards and environmental norms is of utmost importance in biomass utilization, as it aligns biomass treatment methods with sustainable practices and waste management goals. The valorization of biomass residues through HTC and other sustainable approaches promotes the principles of the circular economy by efficiently and responsibly managing resources throughout their life cycle (Gupta et al., 2022). However, to optimize the HTC process and achieve the desired energy yield and hydrochar quality, a comprehensive understanding of the economic aspects is essential. This study presents a comprehensive economic analysis of hydrothermal carbonisation (HTC) for biomass residues, offering valuable insights into its feasibility and profitability. Going beyond the technical aspects, the research focuses on the economic viability of implementing an industrial-scale HTC process. It encompasses the evaluation of equipment costs, auxiliary services, and operational parameters. By considering various economic factors such as discount rates, Weighted Average Cost of Capital (WACC), and Return on Equity (ROE), the analysis includes assessments of capital investment, operational costs, and revenue projections. Through this comprehensive study, a holistic view of the financial implications and potential returns associated with HTC technology for biomass utilization is provided. This analysis provides important information for stakeholders and decision-makers, supporting informed decisions regarding the implementation of HTC technology and highlighting its economic potential in biomass conversion.

2. Methodology

The mass and energy efficiencies of sawdust have been previously reported in studies conducted by Vallejo et al. (2020). The relationship between operational parameters and the characteristics of each biomass to optimise the process has also been investigated by Monedero et al. (2019). An energy efficiency analysis for a continuous pilot-scale system was conducted by Vallejo et al. (2021). These results serve to validate the values obtained through computational simulation. This section provides detailed information on the main considerations and characteristics used for this analysis.

2.1 Waste biomass characterisation

The waste biomass utilised in this study was radiata pine sawdust obtained from a cellulose production plant in southern Chile. The sawdust characterisation, including analysis of its elemental composition, macromolecular structure, moisture content, Higher Heating Value (HHV), and ash content, is presented in Table 1. These comprehensive characterisations provide essential information about the waste biomass, hydrochar, and residual liquors utilised in the study. The obtained values for the various properties serve as valuable references for understanding the composition and potential energy content of the waste biomass and its derived products.

Table 1: Characterization of Radiata Pine sawdust, hydrochar, and residual liquors

Properties	Value	Reference
Sawdust – Higher Heating Value	20.28 MJ/kg	(Lucian et al., 2018)
Sawdust – Ash Content	1.65 %	(Santoyo-Castelazo et al., 2023)
Sawdust – Density	500 – 900 kg/m^3 (20 °C)	(Vallejo et al., 2020)
Sawdust – Moisture	25.83 %	(Corvalán et al., 2021)
Sawdust – Particle Diameter	0.66 mm	(Vallejo et al., 2021)
Sawdust – Elemental Analysis	C: 48 %, H: 6.7 %, O: 37.6 %, N: 0.98 %	(Murillo et al., 2022)
Sawdust – Macromolecular Analysis	Lignin: 35.3 %, Cellulose: 32.3 % Hemicellulose: 15.4 %	(Monedero et al., 2019)
Hydrochar – Density	194 kg/m^3 (15 °C)	(Espinoza Pérez et al., 2022)
Hydrochar – Higher Heating Value	28 MJ/kg	(Vallejo et al., 2019)
Hydrochar – Elemental Analysis	C: 52.1 %, H: 6.2 %, O: 37.6 %, N: 1.8 %	(Lucian and Fiori, 2017)
Residual Liquors – Density	323 kg/m^3 (15 °C)	(Merzari et al., 2018)
Total Carbon Concentration	16 kg/m^3	(Vallejo et al., 2020)

2.2 Economic analysis

The analysis is proposed through a scaling-up approach from pilot-scale results, validated with experimental data reported by (Vallejo et al., 2020). For this reason, the equipment and expenses associated with the investment in the first plant (batch and continuous) were considered, as well as the replacement or addition of equipment necessary for the increased production of pellets and their final use in stoves. To measure the profitability of the project, the Weighted Average Cost of Capital (WACC) was used as an input variable.
This factor was necessary to quantify the effect of the debt required for the initial investment, assuming a rate of 6 % based on data available from state banks in the Latin American region. The analysis horizon was set at 20 y, a time considered sufficient for equipment depreciation and capital recovery. For the economic analysis, it was assumed that operations would be conducted in 16 h shifts per day, 20 days/month. The produced biofuel complied with ISO 17255-2 standards. The plant was designed with a total installation area of 5,000 m^2, including a storage warehouse of 100 m^2 and an office space of 500 m^2. It is important to highlight that in this economic evaluation, the assessment starts from the point where the residual biomass arrives at the collection centre until the pellet is produced. Subsequent studies should address the cost of transportation and other uses for the final product. Finally, the revenue projection was based on the expected annual sales in the Chilean market demand in the most recent year before the COVID-19 pandemic. In 2020, the cost of sawdust pellets in the market was 1.5 USD/kg, and 82 % of households in Chile used pellets for heating, especially during the winter months.

2.3 Numerical simulation

UniSim software (Honeywell, 2023) was utilised for the modelling purposes based on the following assumptions:

- Biomass and hydrochar were represented as hypothetical solid compounds since they are not available in the software.
- The biomass feedstock was considered 100 % dry.
- The effect of time was disregarded due to the continuous nature of the system (Roman et al., 2021).
- Heat losses to the surroundings were assumed to be negligible (Hoekman et al., 2014).
- Pressure losses through the valves were estimated to be in the range of 15-30 kPa.

The main equipment involved in the production process is illustrated in Figure 1 (Process Flow Diagram).

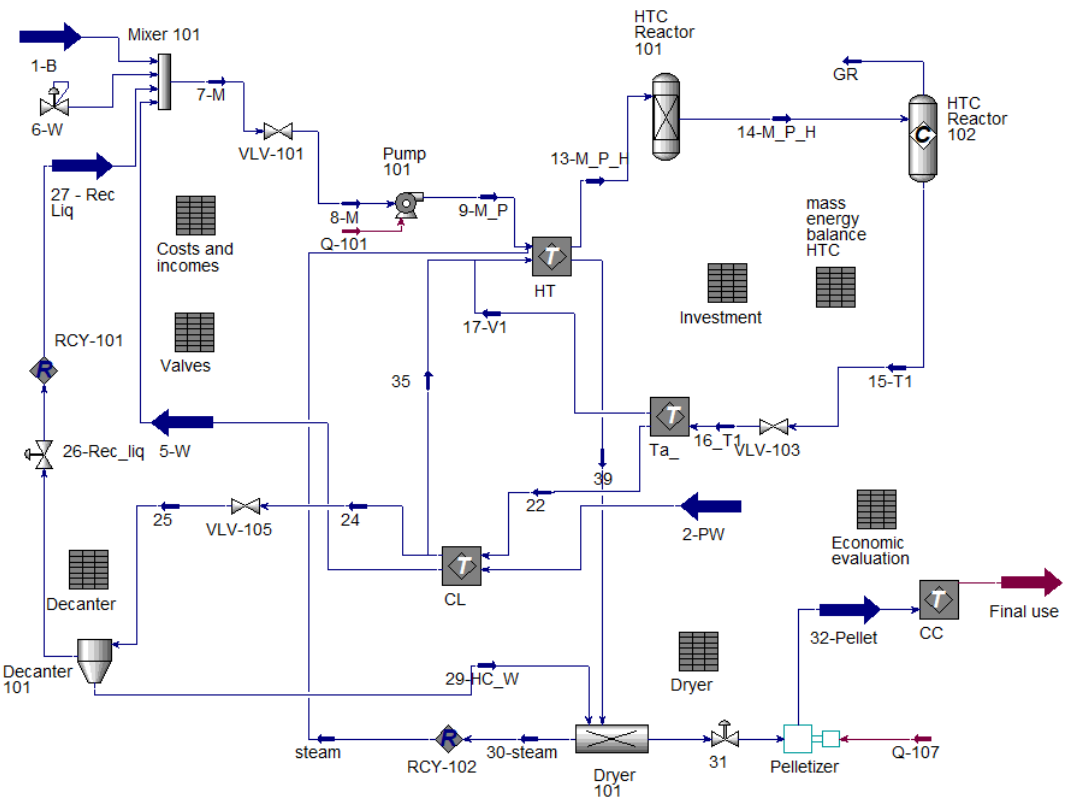

Figure 1: Process Flow Diagram for continuous bioconversion of sawdust

3. Results

3.1 Validation of computational modelling: comparing predicted and experimental results

A comprehensive phenomenological simulation was conducted to model the hydrothermal carbonisation (HTC) process, as described in the previous section. By incorporating pilot-scale and semi-industrial data, a robust and reliable modelling framework was established for accurately representing the HTC process. The pilot-scale data provided by Vallejo et al. (2021), offered valuable insights into the dynamics and parameters of the process, facilitating a detailed analysis of the fundamental phenomena and kinetics involved. In parallel, the semi-industrial data from batch operations, as described by Hoekman et al. (2014), contributed practical insights into the challenges and considerations associated with scaling up the process. This approach ensures that the simulation outcomes are based on a comprehensive analysis of the HTC process. The combination of pilot-scale and semi-industrial data provides a robust foundation for evaluating the process performance and identifying key factors for successful implementation at an industrial scale. Figure 2 illustrates the comparison of mass yields (MY) at temperatures of 190 and 250 °C for the investigated biomass samples. It was observed that biomass availability decreased as the temperature increased for each biomass. The specific composition of each biomass sample played a crucial role in determining the final yield. Factors such as cellulose, hemicellulose, and lignin content significantly influenced the mass yield of the resulting hydrochar (Vallejo et al., 2020). Notably, the hydrochar obtained at 190 °C exhibited a marked reduction in the content of extractable aqueous compounds. Additionally, the thermal degradation of hemicellulose preceded that of cellulose and lignin, with hemicellulose showing thermal instability and undergoing degradation at temperatures between 180 and 190 °C (Wang et al., 2018). The energy yield (EY), as depicted in Figure 2, demonstrated a lower value for the biomasses at 250 °C compared to 190 °C in the experimental results. However, it is important to note that the simulation results exhibited the same trend with some deviations. This can be attributed to the inherent differences between the continuous and batch operating modes employed in the experiments. Figure 2 showcases the validation results of the model using two biomass samples previously studied: pine sawdust and rapeseed straw. Each biomass was characterised by its reactivity index (IR), which was measured as 0.81 for sawdust and 0.60 for rapeseed straw. The results indicated that the mass and energy yield values did not exhibit significant variations between the different biomasses. However, for this analysis, only sawdust was further investigated due to its higher energy density and lower ash content, as reported by (Monedero et al., 2019).

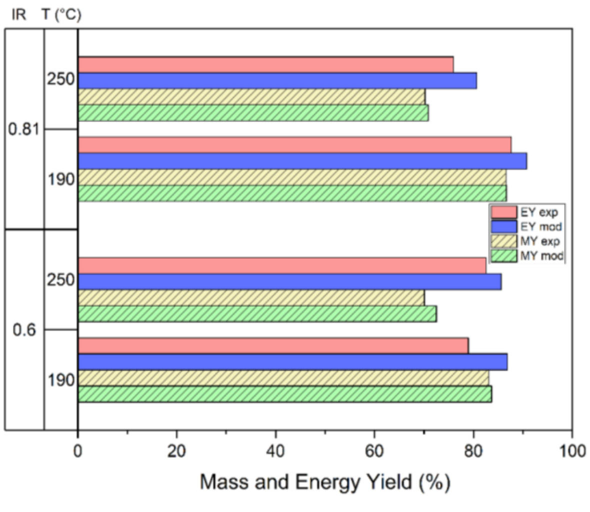

Figure 2: Mass yields (MY) and energy yields (EY) for experimental runs and numerical results

3.2 Economic evaluation results

Discount rates were considered as input variables in the project analysis. The discount rate for the pellet market ranged from 9 % to 10 %, while for renewable energy, it ranged from 7 % to 9 % (Lucian et al., 2018). These values are in line with the assumed effective discount rate of 9.3 %. For the comprehensive analysis, which included the final use of pellets in stoves, a higher discount rate was applied due to the lower demand resulting from the lack of pellet stove technology, leading to a higher opportunity cost for the pellet business. To introduce HTC pellets into the market, it is necessary to start with a small-scale batch process. It is crucial to open up the market and generate income to secure financing, grants, and subsidies that actively promote and facilitate the growth of hydrochar pellets.

Two scaling stages were considered for the transition to continuous operation in the plant. The first stage involves the transition from batch to continuous operation, while the second stage involves doubling the plant's capacity, resulting in a 10 % improvement in economic indicators. Ultimately, a gradual scaling approach is more advisable as it entails lower business risks. A Weighted Average Cost of Capital (WACC) of 5.4 % was selected for the analysis. Based on the WACC values, a debt of 2 million USD was expected with an annual interest rate of 6.24 %. Additional external funding can be sought, considering that financial costs associated with investment could account for up to 50 % of the total costs. Investment in equipment for the pilot plant was estimated using current equipment costs and Lang factors. Equipment investment represents the most significant cost for the pilot plant, especially due to the need for equipment capable of withstanding high pressures and temperatures. The lowest investment costs for the pilot plant were estimated at USD 6,391 at 190 °C, while increasing the operating temperature to 250 °C resulted in higher investment costs, reaching USD 15,500. The highest investment cost corresponds to the boiler, followed by the HTC reactor, and then the hydraulic pump when operating at 190 °C. This is because the boiler requires multiple equipment installations, and the HTC reactor is a continuous, closed, agitated, and jacketed reactor capable of withstanding pressures above 5,500 kPa.

A tornado analysis was conducted with a ±10 % variation in parameters, using a base biomass flow rate of 2,617 kg/h, an operating temperature of 200 °C, a residence time in the HTC reactor of 1 h, a B/W ratio of 10 %, and a selling price of 900 USD/t of hydrochar pellets. The Net Present Value (NPV) was negative at temperatures above 250 °C, reaching its maximum at 190 °C with 2.29 million USD. A Monte Carlo analysis was performed, varying the biomass flow rate (2,617-2,700 kg/h), operating temperature (181-220 °C), residence time in the HTC reactor (0.9-1.1 h), and selling price (800-1,000 USD/t) for hydrochar pellets from different biomass types. The results from 512 runs indicate that the most significant effect is the selling price of pellets, which was determined to be 300 CLP/kg (approximately 0.3 USD/kg). Finally, the Return on Equity (ROE) was 17.4 %.

4. Conclusions

The economic analysis of the hydrothermal carbonisation (HTC) process for radiata pine sawdust yielded positive financial indicators. The net present value (NPV) calculations showed a positive value, indicating the economic feasibility of the HTC process. The specific NPV value obtained was 2.29 million USD at the optimal operating temperature of 190 °C. Additionally, the return on equity (ROE) was determined to be 17.4 %, further demonstrating the profitability of the HTC process. The analysis of investment costs for the pilot plant indicated that the boiler represented the highest investment cost, followed by the HTC reactor and the hydraulic pump when operating at 190 °C. The investment costs for the pilot plant were estimated to be 6,391 USD at 190 °C and 15,500 USD at 250 °C. These values provide crucial insights for decision-making regarding the allocation of financial resources for the establishment and scaling of the HTC process. The Monte Carlo analysis revealed that the selling price of hydrochar pellets had the most significant impact on the economic viability of the HTC process. The optimal selling price of hydrochar pellets was determined to be 300 CLP/kg (equivalent to approximately 0.3 USD/kg). This price ensures positive financial outcomes for the project. The robustness of the economic evaluation was demonstrated through a Monte Carlo simulation, which considered variations in biomass flow rate, operating temperature, residence time in the HTC reactor, and selling price of hydrochar pellets. The results indicated that the selling price remained the most influential factor affecting the profitability of the HTC process.

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