Techno-economic assessment of the pyrolysis of rubber wastes

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Introduction

In 2021, 3.1 billion tires were sold in Europe, where 2.8 billion were car tires (European Tyre & Rubber Manufacturers' Association, 2022). To comply with the regulations related to tires disposal and to evolve towards a circular economy, there is an urgent need for new recycling technologies. This work aims to: i) assess the feasibility of the pyrolytic conversion of rubber into value-added products, ii) perform a techno-economic evaluation of the process and assess the economic sustainability of the scale-up to 2500 kg h^{-1} of treated material.

Material and methods

The research involved common gardening rubber obtained from tires' shredding; it is made of 1-2 cm dark brown chunks and contains textiles as impurities. A horizontal batch mechanically fluidized reactor (MFR) was employed for the pyrolysis tests, fed by 1 kg of rubber under 1 L min-1 nitrogen flow, 30 rpm mixing rate, and ambient pressure. The vapors exiting the rector passed through an ice-packed single-stage condenser collecting the condensable gases, then directed into the exhaust line. The reactor was heated at 500°C for one hour, and 4 tests were performed varying the process conditions (Table 1).

Table 1. Operational conditions adopted during the pyrolysis tests

Experiment	Temperature (°C)	Heating Rate (°C min^{-1})	Holding Time (min)
1	500	25	60
2	500	25	60
	300		45
3	400	10	30
	500		50
	200		15
4	300	10	30
	400		60

The techno-economic assessment was based on the results of the third test. The approach considered capital and operational costs, equipment depreciation, taxes, and the net present value (NPV) (Figure 1). 5 different scenarios were evaluated: i) Base scenario, based on the lab-scale plant results; ii) Scenario 1, simple scale-up of base scenario; iii) Scenario 2, scale-up using Québec electric energy cost (0.043 USD kWh-1); iv) Scenario 3, scale-up using natural gas as heat source instead of electricity; v) Scenario 4, scale-up using the produced methane as heat source; vi) Scenario 5, theoretical case producing a gas fraction containing 80% hydrogen and 20% methane; vii) Scenario 6, theoretical case producing a gas fraction containing 80% ethylene and 20% methane.

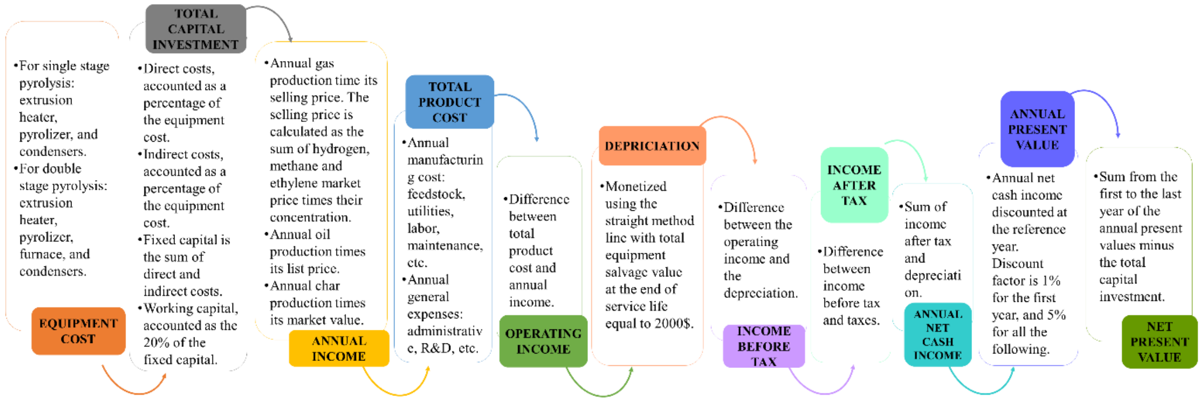

Figure 1. Outline of the approach of the techno-economic analysis

Results and discussion

The main products obtained from rubber pyrolysis were gas, oil, and char. The gas product had an intense odor, the oil showed low viscosity and dark brown color. The char was brittle and black. In accordance with the literature (Martínez et al., 2013; Singh et al., 2019), around 50% of the products were solid. Moreover, gas yields ranged 24.5-31 % and oil 17-22.5%. The third run was the one showing the highest amount of liquid product, the highest oil yields were reached at 400°C.

The char's characteristics were: higher heating value was 30.829 MJ/kg (comparable with bituminous coke 30.2 MJ/kg), carbon content 84.42% (making it interesting for carbon black production). The quality of non-condensable products depended on temperature: at 300°C ethylene 21.3%v, propane 46.1%v, and butane 10.6%v); at 400°C hydrogen and methane exceeded 20%v; at 500°C hydrogen ranged 46-69%v and methane 21-36%v. The oil characterization returned over 100 compounds, mostly with less than 14 C atoms, making the oil comparable to unrefined gasoline. At 300°C the oil was mainly composed of C10 compounds (benzene, D-limonene, cyclo-hexadiene, and cyclo-heptane); at 400°C was a mix of C7 to C10 hydrocarbons and benzene compounds had the highest concentration; at 500°C was observed a decrease in C10 compounds' concentration and an increase of C7 compounds. The oil's higher heating value was 40.933 MJ/kg which is comparable with the values found in the literature (Campuzano et al., 2021; Rofiqul Islam et al., 2008).

The economic analysis showed a negative net cash income for the base scenario (1 kg/h), and the resulting NPV was adverse throughout the operating life of the plant (20 years). The difference among the scenarios was focused on manufacturing cost's quantification. A decrease in the manufacturing cost was identified as the price of electricity lowered (Scenario 2), as electrical power was replaced by natural gas (Scenario 3), and when methane was recycled into the system (Scenario 4). Scenario 4 had the highest annual net cash income (3.55 M$/y). Scenario 5, based on methane recycling and hydrogen production, was the most remunerative (3.95 M$/y), while Scenario 6 was the least profitable (1.54 M$/y). Scenario 1 presented a net profit at the end of the lifetime equal to11 million dollars and the break-even point was reached after about 11 years; it was not advantageous from an industrial point of view, having too high initial investment risk. In Scenario 2 the reduction of the energy cost improved the final net profit, and the payback period lowered to 8.5 years, but it was still not interesting for industrial implementation. Scenarios 3 and 4 showed the same payback period (7.5 years), but the final remuneration of scenario 4 was greater because its manufacturing cost was lower. Scenario 5 was the most favorable from an economic point of view, with a payback period between 6 and 7 years, and net profit at plant end life of 28 M$. Scenario 6 was the only scale-up case where the plant was not economically feasible and the NPV at the end of the operating life was negative, so the plant had not recovered the initial investment.

Conclusion

Increasing rubber's pyrolysis temperatures created a double effect: the oil composition shifted to lightweight compounds "gasoline-like", and the gas showed higher concentrations of methane due to enhanced cracking. Nonetheless, further experiments and research are needed to customize the pyrolysis' operational parameters. The results obtained in the economic analysis were in some cases quite promising. The economical sustainability of the processes was mainly given by hydrogen in the gas product, due to green hydrogen's high market value (2 USD kg^{-1}). Rubber pyrolysis in any scenario required 7-8 years to become profitable. When ethylene production was involved, the plant was not profitable over a work-life of 20 years. Hydrogen valorization was related to the most advantageous scenario, having payback period equal to 6-7 years.

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