HYDROTHERMAL TECHNOLOGIES FOR THE PRODUCTION OF RENEWABLE BIOFUELS: A TECHNO-ECONOMIC REVIEW

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ABSTRACT

The rapid increase in waste generation from industrial, municipal, and domestic sources, coupled with stricter environmental regulations, highlights the need for innovative residues valorization routes. Concurrently, global decarbonization goals and climate neutrality commitments have driven the search for technologies that reduce fossil fuel emissions. In this context, hydrothermal processes are gaining attention for their role in converting biomass into valuable products such as biofuels. Hydrothermal processes, including hydrothermal carbonization, liquefaction, and gasification, operate under distinct conditions to produce solid, liquid, or gaseous products. This review evaluates the scale and economic aspects of HTC and HTL processes, highlighting their potential in waste valorization and biofuel production.

Keywords: biomass valorization; biofuels; energy transition; hydrothermal process.

INTRODUCTION

The generation of solid and liquid waste from industrial, municipal (MSW) and domestic sources is rapidly increasing, while environmental laws of discharge are becoming stricter. Simultaneously, global ambitions for decarbonization, aligned with the climate neutrality commitments made under the Paris Agreement, are driving the search for new technologies and processes capable of reducing emissions resultant from the widespread use of fossil fuels. In this context of global redefinition, various technologies are being evaluated with distinct but intrinsically connected objectives [1,2].

Firstly, processes that could minimize the generation of waste and undesirable byproducts, or valorize them, promoting the efficient use of natural resources and maintaining them in a closed-loop cycle are being investigated. Secondly, researchers are also focused on routes to produce alternative fuel and/or energy carriers that could mitigate the indiscriminate use of petroleum and its associated climatic effects. In this context, thermochemical processes are gaining extensive interest as facilitators of the critical transition from fossil fuels to renewable ones. Thermochemical processes are divided into four types: direct combustion, pyrolysis, gasification, and hydrothermal process, the focus of the current work [3,4].

Hydrothermal processes (HTPs) take place at moderate to elevated temperatures, under above-saturated pressure, which deeply alters several physicochemical properties of water (i.e., its density, dielectric constant and ionic product), allowing its use both as solvent and reactant to convert biomass into biofuels, valuable chemicals and even energy vectors. The HTPs can be further classified into three subcategories based on their operating pressure and temperature, and desired products: the hydrothermal carbonization, hydrothermal liquefaction, and hydrothermal gasification [5,6].

In the hydrothermal carbonization (HTC), biomass is processed alongside water at temperatures between 180 and 250 °C, under autogenous pressure of 1 to 4 MPa. During the process, polysaccharides such as cellulose and hemicellulose are hydrolyzed into monosaccharides, which are further dehydrated and condensed into the main product of the HTC process, a solid carbonaceous product named hydrochar, which has applications as solid fuel, partially or totally replacing mineral coal [7].

On the other hand, hydrothermal liquefaction (HTL) operates at higher temperatures and pressures. The HTL process is typically carried out between 250 and 350 °C, often exceeding 5 MPa and reaching up to 20 MPa. In comparison to HTC, the HTL process is fast, ranging from minutes to a few hours. Reactions such as depolymerization, bond breaking, rearrangement, and decarboxylation take place during the HTL process and result in a liquid product called biocrude or bio-oil, which can be further refined into transportation fuels and other valuable chemicals [8].

Finally, at temperatures and pressures near and above the critical point of water (374 °C and 22.1 MPa), the process is called hydrothermal gasification (HTG) or sub/supercritical water gasification (SCWG), and the free radical reactions dominate the mechanism. The HTG process is the most preferred method for degradation of biomass with higher moisture content, being especially suited for the continuous conversion of liquid organic effluents into H_2-rich syngas with minor contents of CH_4, CO_2 and CO [9].

In this context, various experimental studies have been dedicated to the investigation of the use of hydrothermal processes for the valorization of biomasses and residues such as plastics [10], food waste [11], sludge [12] and agro-industrial by-products [13] into high value-added chemicals, biofuels and energy vectors. On the other hand, the availability of scale-economic evaluations of such processes remains limited. Generally, computational simulations of industrial scale operational are proposed based on the data resultant from experiments conducted at bench scale. Lastly, studies reporting large-scale operations based on HTG processes for the production are even scarcer. In this sense, the current work reviewed, compared and discussed a total of five articles regarding both scale and economic aspects of HTC and HTL processes.

MATERIALS AND METHODS

A bibliographic review was conducted to select articles from the database of the Science Direct and Springer website. For this, the search was limited to the last 20 years, ranging from 2004 to 2024, and the following keywords (or association of keywords) were used: economic, hydrothermal, carbonization, liquefaction, HTC, and HTL. From the combined search process, a total of five research articles, comprising different processing capacities, were selected and used as a database source for the analysis and review. The articles were chosen to ensure comprehensive and diverse coverage of topics related to the current scale and economic aspects of HTPs, providing a broad and up-to-date view on the subject.

RESULTS AND DISCUSSION

The summarized data of the selected articles is presented on **Table 1**.

Table 1. Summarized data of the selected articles.

Reference	[14]	[15]	[16]	[17]	[18]
Technology	HTC	HTC	HTL	HTL	HTL
Biomass (feedstock)	Food waste	Pruning + MSW	Sugarcane bagasse	Microalgae waste	Sugarcane bagasse
Reactor	Batch	Batch	Continuous	Continuous	Batch
Temperature (°C)	180	230	300	348	280
Pressure (MPa)	1	3	16.5	20.8	13.5
Processing capacity $\left(\frac{dry\ ton}{day}\right)$	9	157.5	125	608	1637
Total Capital Investment - TCI (US$)	298,200.00	13,679,500.00	73,900,000.00	262,000,000.00	361,000,000.00
Operational Expenditures (OPEX)	355,600.00	1,907,500.00	14,710,000.00	48,800,000.00	48,900,000.00
Production $\left(\frac{kg\ product}{dry\ ton}\right)$	400	389	470	478	342
Product Selling Price $\left(\frac{US\$}{kg}\right)$	0.14	0.43	0.42	0.75	0.49
Gross Income (US$)	428,400.00	8,545,327.45	10,980,000.00	70,839,600.00	115,100,000.00
Net profit/year (US$)	72,800.00	6,637,827.45	- 3,730,000.00	22,039,600.00	66,200,000.00
Return on Investment (US$)	24.41%	48.52%	-5.05%	8.41%	18.34%
Payback period (years)	4.1	2.1	x	11.9	5.5
Base year	2020-2022	2012	2017	2007	2019

From the data presented on **Table 1**, a graphical analysis was conducted to illustrate the comparison between the processing capacity, payback period and total capital investment of the HTC and HTL processes. The obtained results are presented in **Figure 1.**

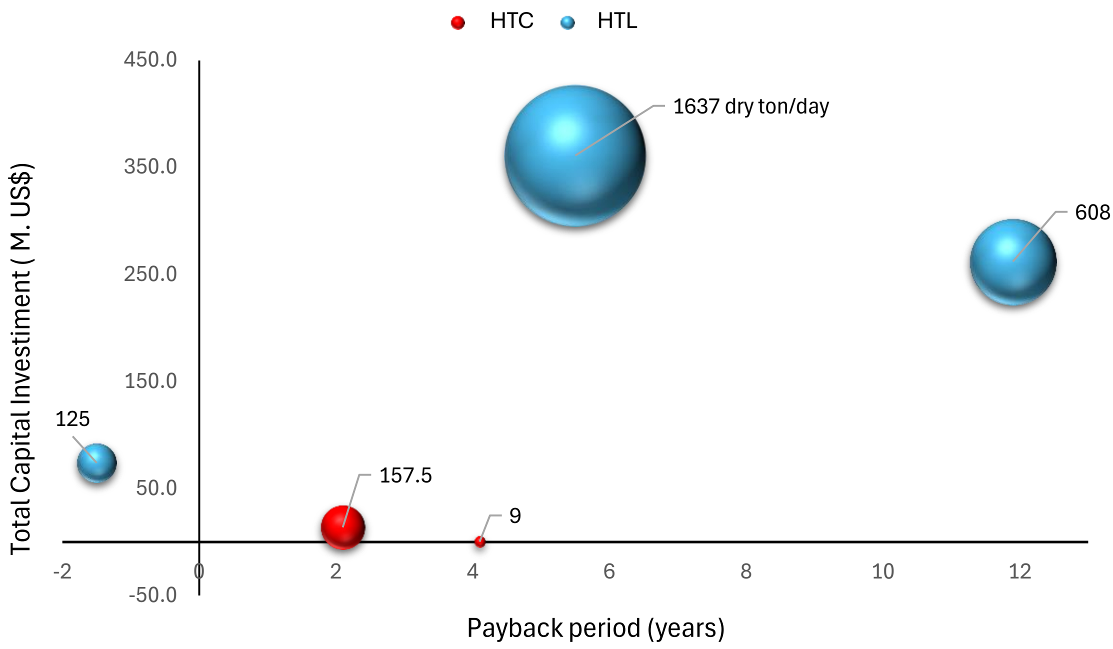

Figure 1. Viability analysis of HTC and HTL processes.

Despite the large difference factor in scale, both selected HTC process showed economic viability, meaning that the product revenue would pay the initial investment within the lifetime of the industrial plant and generate profit. Therefore, the HTC process stands out as a potential technology for the decentralized valorization of biomasses, without the necessity or large quantities of feedstock availability.

On the other hand, the smallest processing capacity HTL operation did not show economic viability (presented with a “negative payback period” for illustration). Those results indicate that the economic feasibility of the HTL processes is more “scale-dependent” than the HTC ones, that is, the break-even point for the HTL processes is strictly related to the processing capacity parameter. This observation can be partially explained due to the higher TCI and OPEX requirements for the HTL processes in comparison to the HTC operation, even at similar processing capacities. The necessity of hydrodeoxygenation and distillation facilities for the treatment, upgrade, purification and separation of the HTL products increase the overall investment expenditure, making HTL process more suitable for widely available biomasses or residues, such as municipal and agro-industrial wastes.

CONCLUSION

A total of five research articles investigating the application of both HTC and HTL for the production of biofuel were reviewed. The analysis revealed that HTC processes offer robust economic viability across smaller scales, making them suitable for decentralized biomass valorization. In contrast, HTL processes exhibit scale-dependent economic feasibility, with smaller operations struggling due to higher total capital investment and operational expenditures. Thus, HTC processes emerge as a more economically favorable option for diverse applications, while HTL's should be implemented for larger-scale operations.

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