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The Important Role of Pyrolysis and Hydrothermal Carbonization in a Sustainable Circular Bioeconomy: A Brief Literature Review

Istotna rola pirolizy i karbonizacji hydrotermalnej w zrównoważonej biogospodarce o obiegu zamkniętym: krótki przegląd literatury

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Abstract: This is a brief but focused literature review of articles centered around pyrolysis and hydrothermal carbonization (HTC) using various feedstocks, including residues from industries, agriculture, and landfill waste. The deployment of bio-wastes will be the cornerstone of circular bio-economies in the future. The main emphasis is on gleaning how these two technologies can contribute to a sustainable circular (bio) economy, by understanding the process parameters influencing the quality, type and quantity of the final output. HTC and pyrolysis, it may be undeniably stated, can support the progress towards a clutch of sustainable development goals (SDGs), as they operate right at the confluence of solid waste management and renewable energy production. As mentioned in many of the articles reviewed in this paper, a high process temperature usually results in higher yields of bio-oil and biogas/pyrogas (and thereby less biochar), implying a higher energy recovery. HTC trumps pyrolysis on many counts – economy, energy-efficiency and product (hydrochar) quality. However, pyrolysis is a simpler method to regulate, and pyrochar, has a higher market value vis-à-vis hydrochar. While both these technologies generate valuable end-products regardless of the type of feedstock used; the articles reviewed clearly show that the feedstock does influence the quality of the output and thereby the application to which it can be directed. The review leads to recommendations for future research in collecting data and creating a model to investigate various process parameters. Some of these recommendations are detailed comparative life cycle assessments (LCAs) to study the environmental impacts of technology-choices, , research into tailoring the optimal method and temperature to the feedstock deployed, and comprehensive forecast-based economic analysis of commercial-scale pyrolysis and HTC projects, are called for. As stated at the beginning, this is a brief review, which can also be expanded to take more published articles into its fold.

Keywords: Bio-economy, Energy, Feedstock, Hydrochar, Hydrothermal carbonization, Pyrochar, Pyrolysis

Streszczenie: Artykuł zawiera zwięzły przegląd publikacji naukowych dotyczących pirolizy i karbonizacji hydrotermalnej (HTC) zachodzących przy użyciu różnych surowców, w tym pozostałości przemysłowych, rolniczych i odpadów składowanych na wysypiskach. Wykorzystanie bioodpadów stanie się w przyszłości podstawą biogospodarki o obiegu zamkniętym. Artykuł kładzie nacisk na pytanie, w jaki sposób te dwie technologie mogą przyczynić się do prowadzenia zrównoważonej (bio) gospodarki o obiegu zamkniętym, poprzez zrozumienie parametrów procesu wpływających na jakość, rodzaj i ilość produktu końcowego. Można z całą pewnością stwierdzić, że karbonizacja hydrotermalna i piroliza mogą stanowić krok w kierunku realizacji szeregu celów zrównoważonego rozwoju (SDG), ponieważ stanowią punkt zbieżny pomiędzy gospodarowaniem odpadami stałymi i produkcją energii odnawialnej. Jak wspomniano w wielu omawianych poniżej artykułach, wysoka temperatura procesu zwykle skutkuje wyższą wydajnością biooleju i biogazu/pirogazu (a tym samym mniejszą ilością biowęgla), co przekłada się na większy odzysk energii. Karbonizacja hydrotermalna pod wieloma względami przewyższa pirolizę w zakresie rachunku ekonomicznego, efektywności energetycznej i jakości produktu (hydrowęgla). Z drugiej strony, piroliza jest łatwiejsza do uregulowania, a pirowęgiel, w porównaniu z hydrowęglem, ma wyższą wartość rynkową. Obie te technologie pozwalają na uzyskanie wartościowych produktów końcowych niezależnie od rodzaju użytego surowca. Omawiane artykuły wyraźnie wskazują na fakt, że surowiec rzeczywiście wpływa na jakość produktu wyjściowego, i w ten sposób definiuje sposoby jego zastosowania. Przegląd artkułów pozwala na sformułowanie zaleceń dotyczących przyszłych badań w zakresie gromadzenia danych i tworzenia modelu służącego badaniu różnych parametrów procesu. Część z tych zaleceń obejmuje szczegółowe, porównawcze oceny cyklu życia (LCA) przedstawione w celu zbadania wpływu wybranych technologii na środowisko, badania nad dostosowaniem optymalnej metody i temperatury do stosowanych surowców oraz kompleksową, opartą na prognozach, analizę projektów pirolizy oraz HTC prowadzonych na skalę przemysłową. Jak wspomniano na wstępie, artykuł stanowi krótki przegląd, który można poszerzyć uwzględniając kolejne publikacje.

Słowa kluczowe: biogospodarka, energia, surowiec, hydrowęgiel, karbonizacja hydrotermalna, pirowęgiel, piroliza

Introduction and Background

It is now a cliché that population growth and relentlessly leapfrogging technological development have led, over the years, to a spike in consumption of goods and services. The upshot of all this uninhibited consumerism has been the generation of humungous amounts of wastes, and deterioration in the quality of the environmental media (lithosphere, pedosphere, hydrosphere, atmosphere) around us. Concomitant to the increase in waste generation, the amounts consigned to landfills or incinerated (either with or without recovery of energy) have also risen. In this backdrop, the need for innovative methods to manage wastes (which are veritably resources in a circular economy), becomes at once indisputably clear (Bergstrand and Bonnier 2015). Carbonization technologies have been around for a long time and have attracted the attention of researchers. The broad range of applications allows for the utilization of a wide variety of residues and solid wastes for clean energy production. Incineration results only in the generation of heat as output and poses the risk of damage to the combustion furnaces, especially when raw feed containing high concentrations of alkali metals (sodium, potassium) are used. Pyrolysis on the other hand, heats the feedstock in an oxygen-free environment, resulting in the production of pyrochar. Hydrothermal carbonization (HTC) carbonizes raw materials in an aqueous medium, and the heating occurs at the end of the process in a closed system under pressure, leading to the production of hydrochar and bio-oil in the process. There is a trade-off between time and temperature, with HTC being performed under lower temperatures for a longer time than pyrolysis. Pyrochar binds carbon and prevents it from being released into the atmosphere as a greenhouse gas (GHG). The bound carbon in the pyrochar can, in turn, facilitate outputs suitable for soil remediation and water purification; and also, be looked upon as an alternative to fossil fuels. Pyrolysis oil can be refined further into biofuels (Naturvårdsverket 2023). As gathered from Correa et al (2019), while pyrolysis techniques predate HTC by a few centuries, the latter is poised on the threshold of rapid development and subsequent adoption into a circular bio-economy in the years to come

Be it the younger HTC or the better-entrenched, older pyrolysis technologies, carbonization of organic wastes can play a key role in decreasing the GHG footprint of the anthroposphere and contribute immensely to socio-economic development and environmental upkeep (Clifford n.d.). Carbonization methods can be linked to several of the UN's 17 SDGs, an agenda for sustainable development aiming for ecological, economic, and social sustainability worldwide by 2030 (UNDP 2015). The prominent ones (which in turn interact synergistically with some other secondary SDGs), can be listed below:

- #7 – Affordable and Clean Energy
- #11 – Sustainable Cities and Communities
- #13 – Climate Action.

1. Goal and Scope

The overarching goals of this exercise are:

- To read and carefully review peer-reviewed journal publications
- To glean similarities and differences, in terms of methods, driving factors and results arrived at

The scope or specific objectives, in other words, is under:

- To develop a sufficiently in-depth understanding of pyrolysis and HTC by narrowing the scope to a few articles – the methodology adopted for identifying and selecting them from databases, has been outlined in the next section of the paper.
- To investigate how pyrolysis and HTC contribute to sustainable development at the time of writing.
- To provide recommendations for further research in this field of the circular bio-economy.

2. Search Methodology

The authors decided to zero in on 15 articles for this review, which were selected by taking recourse to the Web of Science search engine, through the library of Karlstad University. The streamlining and narrowing-down entailed limiting the search to a time interval of the last 5 years, in order to ensure the relevance of the peer-reviewed articles from academic journals, and inclusion of the state-of-the-art in pyrolysis and HTC. While the compound search-phrase *"pyrolysis"* and/or *"HTC"*, quite obviously yielded many matches, more specific supplementary keywords were added, as shown in Table 1, as the second step in the streamlining/narrowing-down. While this served to whittle down the number of articles, the matches were still quite many, when one additional word was added to the search-phrase (or a part of it). As a third step, the authors did a preliminary review of the abstracts of the articles, to end up with the final clutch of 15 articles for detailed reviewing. The supplementary keywords chosen accounted for the parameters of feedstock, process, scale, different pyrolysis/HTC methods, economic analysis, and sustainable development to achieve global goals. Some searches were based on finding methods recommended by another article for further study/research.

The abstract, introduction, parts of the methodology and the conclusion of the articles were carefully read to briefly answer the questions – When, Who, Where, Why, How, What and What not/What else – enabling a thorough understanding of the contents of the articles. This also helped the authors to ascertain and confirm the suitability of the articles to provide answers to the research questions outlined in the scope earlier.

3. Results of the Literature Review

3.1. Place of Origin, Purpose, Scope, Modus Operandi

What all the articles have in common is the fact that they focus on potential feedstocks for pyrolysis and/or HTC treatment, the parameters influencing the carbonization process, and the influential factors for the composition and quality (and thereby, applicability) of the final product. The year-of-publication is within the 5-year period 2019–2023 (Figure 1), and that guarantees relevance and currency, as referred to in the previous section, while enabling the authors to sketch a more precise account of the "what-is" and "whereto-in-the future". As seen in Figure 1, a majority

Table 1. The search methodology summarized

Keywords	Number of hits	In selection	Chosen article
Pyrolysis, HTC, LCA	5	4	Cavali et al. (2015)
Biochar, Pyrolysis, Environmental, Feedstocks	199	1	Das et al. (2021)
Vacuum pyrolysis, Economic, Environmental, Social	3	1	de Oliveira Neto et al. (2019)
Pyrolysis, HTC, Sawdust	16	3	Li, J. et al. (2020)
Pyrolysis temperature, Feedstock type, Predicting	3	1	Li, S. et al. (2019)
Catalytic pyrolysis, Economic analysis, Pyrolysis product	3	1	Lin et al. (2022)
Pyrolysis, HTC, Gasification	66	2	Lv et al. (2022)
Slow pyrolysis, Biochar, Pyrolysis liquid	7	1	Manmeen et al. (2023)
Pyrolysis, HTC, LCA	5	1	Miesel et al. (2019)
Pyrolysis, Biochar, HTC	115	6	Miliotti et al. (2020)
HTC, Pyrolysis	380	20	Olszewski et al. (2020)
Biochar, Pyrolysis, Environmental, self-sustainable	6	1	Osman et al. (2023)
Pyrolysis, Biofuel, Economic	279	1	Pourkarimi et al. (2019)
HTC, Char product	2	1	Yang et al. (2023)
HTC, Feedstock	182	10	Zhou et al. (2019)

of the publications are from the start of the time-period considered, with a rather even distribution among the other years, with 2021 being an exception. However, it must be clearly stated here that the sole article selected from year-2021 is very comprehensive in its scope, covering a diverse range of compositions of feedstocks and pyrolysis temperatures. Additionally, there were relatively fewer publications in 2021 (perhaps owing to the pandemic).

The pie-chart in Figure 2 shows the geographical distribution of the articles. The selection [as described in the Methodology section – (2)] was carefully and intentionally done in order to "represent" the world. While a more extensive review will automatically take articles published around the world into consideration, a streamlined review focusing on relevance, currency and geographical diversity (to make the review interesting enough to readers from around the world, despite or rather because of its brevity) makes the selection process crucial and time-consuming. North America, South America, Europe, and Asia figure in the mix, with China leading the pack of nine countries, with 33% of the articles. Selection of multiple articles from China was done primarily with the intention of testing how the carbonization methods varied over the short 5-year period, while holding the origin constant. Although not all articles are case-studies, the authors are of the view that articles which are reviews provide valuable insights into how researchers approach the topic – influenced by the economic, environmental and political situation of the countries they hail from and work in. The quintet of articles from China in addition to being spread over the time-period under consideration, also encompasses a wide range of feedstocks, demonstrating the possibility for a country to apply the carbonization methods in diverse contexts. China has been a trendsetter when it comes to applying pyrolysis and HTC, at the confluence of solid waste management and renewable energy production, paving the way forward to a circular bio-economy. This has been part of its efforts to truncate its greenhouse gas footprint (for which it has been getting the flak for some time now). It can be mentioned at

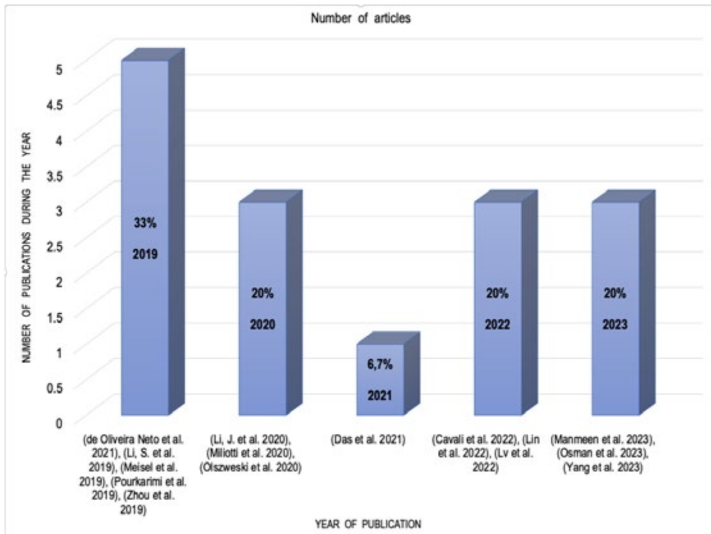

Figure 1. The distribution of the 15 articles over the 2019-2023 period

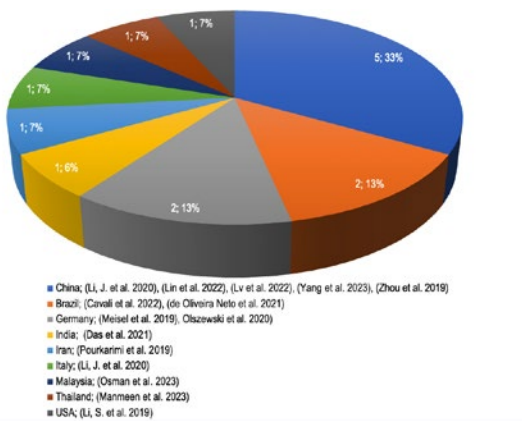

Figure 2. Geographic distribution of the 15 reviewed articles, based on the affiliation of the first author

this juncture that the five articles from 2019, trace their origins to five different countries – Brazil, China, Germany, Iran and the USA (refer Figures 1 and 2).

Among the 15 articles, there are six case studies, one each from Brazil (Oliveira Neto et al. 2019), Italy (Miliotti et al. 2020), Germany (Olszewski et al. 2020), China (Lin and Cheng 2022), Thailand (Manmeen et al. 2023), and Malaysia (Osman et al. 2023). All these studies focus on the pyrolysis of different feedstocks, which are looked upon as wastes and are abundant in the countries those studies originate from. These case studies do not focus so much on a specific final product (output) but are rather more interested in exploring the possibilities for harnessing a particular feedstock (input). The other articles, on the contrary, are focused more on ways and means of increasing the yield of a particular product (demand-driven, price-driven), or altering the properties (constituents) of the same. By and large, all the articles discuss potential environmental and economic benefits/disadvantages, while a small minority also highlight positive and negative social impacts.

All the articles are exploratory in nature and adopt both qualitative and quantitative methods – systematic literature reviews, prospective and retrospective studies, and laboratory-based or review-based approaches. Mention must be made here of one particular study (Meisel et al. 2019) which is an environmental life-cycle assessment (E-LCA) of the HTC process, based on both primary data and secondary data from literatures.

The target readership – as intentioned by the authors of the articles, who are specialists in materials science, agriculture, bio-based resources, environmental and chemical engineering – comprises researchers and other stakeholders genuinely interested in sustainable development, as well as entrepreneurs in the energy and waste management sectors around the world, who may be interested in applying these carbonization technologies to valorize wastes into energy products, and contribute to the advancement towards a clutch of SDGs in a circular bioeconomy in the future. The studies have been conducted to disseminate knowledge about alternative biofuels, the valorization of a diverse range of feedstocks to biochar, bio-oil, and pyrogas, advanced solid waste management, and new products for soil remediation and water purification. The product portfolio of a small-scale pyrolysis / HTC setup can be composed of adsorbents (for water purification and wastewater treatment), soil amendments, building materials, oil blends, gasoline and diesel, electricity and heat, alcohol fuels, and ammonia (Yang et al. 2023). As Pourkarimi et al. (2019) have observed, if microalgae and macroalgae (edible seaweed) are employed as feedstocks, liquid biofuels can be produced.

Some articles compare pyrolysis and HTC when it comes to carbonizing bio-waste, biomass, and inorganic material. Only one article (Oliveira Neto et al. 2019) has addressed rubber tire waste (an inorganic material) as a potential feedstock (in Brazil). This is not biodegradable, and hence does not yield bio-products after carbonization. The other feedstocks in the fray are industrial sludge (Lv et al. 2022; Osman et al. 2023), sewage sludge (Meisel et al. 2019), sawdust from pine (Li et al. 2020), by-products from beer production (Olszewski et al. 2020), agricultural residues like manure from various animal species (Lv et al. 2022; Zhou et al. 2019), crops and food waste (Cavali et al. 2022; Yang et al. 2023). Some agricultural residues undergo anaerobic digestion to form pyrogas and digestate (Cavali et al. 2022; Miliotti et al. 2020), while others are subjected to pyrolysis – animal wastes (Li, S et al. 2019), weeds (Das et al. 2021; Lin and Cheng 2022), algae (Pourkarimi et al. 2019), durian and palm kernel shells (Manmeen et al. 2023; Osman et al. 2023), and woody and herbaceous crops (Das et al. 2021; Li, S et al. 2019).

3.2. Process Parameters of Importance

The yield of the final product is influenced by various parameters. As gathered from Das et al (2021), factors that predominantly affect the composition of pyrochar are the choice of feedstock and the temperature in the carbonization step. In Figure 3, the yields of pyrochar, bio-oil and pyrogas for slow pyrolysis with a residence time of 1 hour on three different feedstocks – at two different temperatures, have been shown.

While addressing and acknowledging the importance of temperature as a parameter in pyrolysis and HTC processes, several articles have maintained a constant temperature and tested the effect of variations in the composition of the feedstock, on the yield and quality of the final product/s. Likewise, there are articles which have tested the effect of temperature variations, while holding the feedstock composition constant (like the ones referred to in Figure 3, for instance). Subjecting agricultural manure to HTC to obtain hydrochar along with the highest possible energy yield, calls for reaction temperatures in the range 180–210°C, with the maxima of this range being the desired optimum (Zhou et al. 2019). However, in cases where HTC is used as

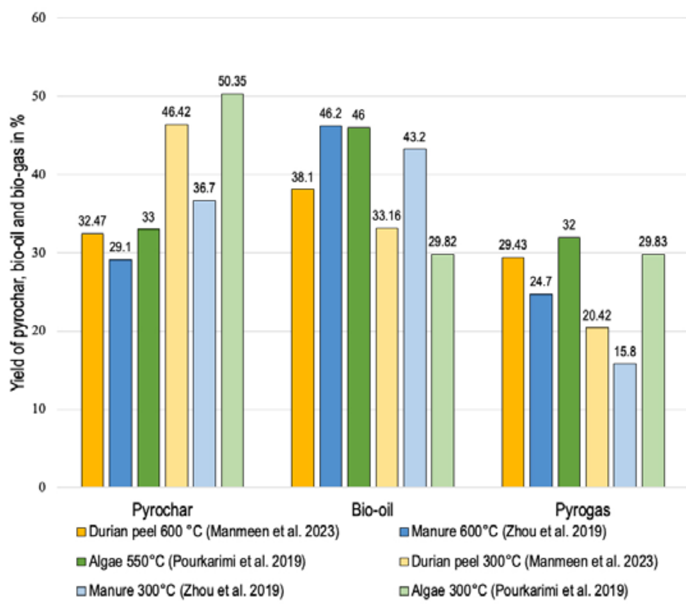

Figure 3: Yield of Pyrochar, Bio-oil, and pyrogas for durian peel, manure, and algae subjected to temperatures of 300°C and 600°C

an upstream adjunct to pyrolysis (Olszemski et al. 2020), higher temperatures (240–260°C) are recommended to maximize the energy efficiency (Li, J et al. 2020); bearing in mind that energy densification (specific energy values) rise with higher HTC temperatures (Lv et al. 2022). The cooling temperature also affects the yield of products, with a higher cooling temperature generating more biochar and less bio-oil (Manmeen et al. 2023). The article referred to in the previous sentence further notes that the residence time also influences the composition of the “basket of end-products” – a prolonged residence time generates more pyrogas, at the expense of the yields of biochar and bio-oil. Another comparative graph constructed by the authors based on results gleaned from six different articles is shown in Figure 4. It presents the chemical characterization of the solid bio-product – biochar/hydrochar/carbon black – as a function of method, residence time, temperature and the feedstock subjected to carbonization.

The topmost stacked-bar in Figure 4, representing scrap tires, shows that rubber tires when carbonized have the highest percentage of fixed carbon in the solid end-product. Brewer’s spent grain (BSG) – the lowest stacked-bar – comes a close second. The ash content of pyrochar with agricultural manure as its provenance, was the highest; while algae subjected to carbonization, registered the highest volatile matter and moisture contents in the solid bio-product.

3.3. Pursuit of Sustainable Development

The authors detected links – both implicit and explicit – to different SDGs in the articles reviewed, and the findings have been tabulated concisely in Table 2. It must be mentioned here that all the 15 articles dwelt on one or more of the SDGs to some extent, but only those with a very conspicuous connection (specifically referred to) have been shown.

The articles address (explicitly and implicitly) several SDGs – the most common ones being #7, #9, #11, and #13 – as gathered from Table 2. The leitmotif and the underlying motivation of some articles is to resort to pyrolysis and HTC, as one of several strategies to replace fossil fuels and contribute

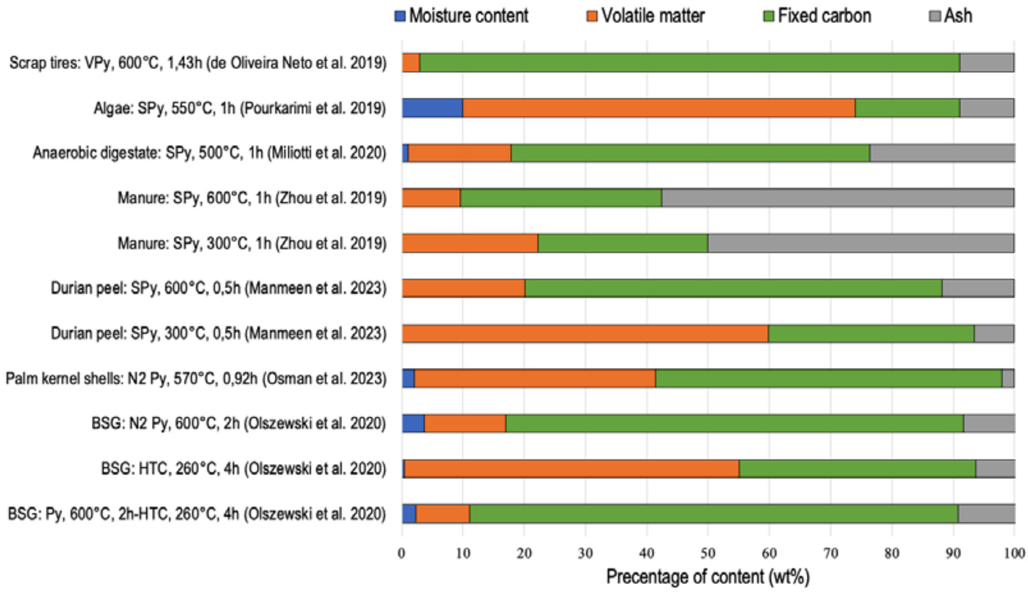

Figure 4. A synthesis of results from different articles. Chemical characterization (as %) of the solid final products (pyrochar, hydrochar, or carbon black). (Abbreviations used in the graph: *BSG* **= Brewer's Spent Grain,** *VPy* **= Vacuum Pyrolysis,** *SPy* **= Slow Pyrolysis,** *N2 Py* **= Nitrogen Atmosphere Pyrolysis,** *wt%* **= Percentage by Weight.)**

to the generation of cleaner energy (with a lower GHG footprint), with the possible added advantage of reducing the energy-poverty of developing-world countries. There, we have SDG 7, with the two adjectives "affordable" (the socio-economic dimension) and "clean" (the environmental dimension). SDG 13 is directly correlated with SDG 7, and is benefited thereby, thanks to the reduction of adverse environmental impacts caused by, for instance, open burning of agro-residues in the developing-world countries (India, for instance; China, till not very long ago). Finding an economically feasible and environment-friendly way to handle (and valorize) municipal, agricultural and industrial wastes, feeds into social sustainability, and addresses SDG 11 – Sustainable Cities and Communities.

Setting up HTC and pyrolysis facilities (in biorefineries in a circular bioeconomy) and relentlessly researching and innovating, brings one within the scope of SDG 9 – Industry, Innovation, and Infrastructure. The two carbonization technologies being studied in this review, are unarguably, valuable methods for industries to leverage waste materials to create new bio-products. However, the availability of, and the accessibility to the right feedstocks, may be bottlenecks. Some parts of the world may be better endowed in this regard, and thereby would be looked upon to set the ball rolling at a brisker clip. Continued research will eventually improve the economic feasibility of investments in carbonization of organic wastes to supply a range of bio-outputs to a flourishing market in a global bioeconomy in the future. This may seem utopian at the time of writing, but persistent efforts are sure to get us there some day.

3.4. The Economics of Carbonization

The market for pyrochar has expanded in recent years and is expected to grow even further due to increased demand for renewable energy. It is projected to be worth 6.3 trillion USD by 2031 in the global pyrochar

Table 2: The implicit/explicit links to SDGs detected in six of the fifteen articles.

Paper	SDGs addressed
Cavali et al. (2022)	#2, #3, #8, #9, #11, #12, #13, #15, #16, #17
de Oliveira Neto et al. (2019)	#7, #12, #13
Lin et al. (2022)	#2, #4, #7, #8, #9, #11, #12, #13, #15, #16
Manmeen et al. (2023)	#7, #9, #11, #13, #15
Osman et al. (2023)	#6, #7, #8, #15
Pourkarimi et al. (2019)	#7, #8, #11, #12, #13, #14, #15

market. Production costs vary between pyrolysis technologies and HTC. The production cost for a portable pyrolysis process with biomass from fruit and garden waste can range between 448.78 – 1846.96 USD per ton of pyrochar, with a selling price (SP) of 59.46 – 909.43 USD per ton. Garden waste can, however, also be subjected to HTC – at a much lower cost, vis-à-vis pyrolysis. The total levelized life-cycle cost (present value) would then be 113.90 USD per ton of hydrochar, saleable on the market at a profit margin of 4 USD per ton (Cavali et al. 2022).

Investing in slow pyrolysis of durian peel was shown to be economically feasible by Manmeen et al. (2023) – Net Present Value or NPV of 26,222 USD, with an IRR (internal rate of return) of 26% and a discounted payback period of less than 2 years. The Brazilian study by Oliveira Neto et al. (2019) – the only one which dealt with an inorganic waste material – also showed that vacuum pyrolysis of tire wastes can result in a total annual profit of 1.3 million USD (with total annual income reaching 3.45 million USD).

While all the above were in the black, Pourkarimi et al. (2019) observed that the production of liquid biofuel by carbonizing algae was a loss-making venture in Iran, owing to the relatively lower prices for fossil fuels on the market. Algae as feedstock introduces certain challenges – the high energy consumption called for, to dry the feedstock being a prime one. In general though, in 10 of the 15 studies, the authors have reported that HTC and pyrolysis are economically profitable options to be explored further and adopted in circular bio-economies. One also hopes that process innovations will make the adoption of algae – a promising third-generation source for biofuels – as feedstock, favorable for investors in the years to come.

4. Discussions and Gleanings

4.1. Technologies – Solo or in Tandem

Hydrochar and pyrochar with high carbon content and thereby a greater energy density (specific energy), are potential replacements for coal, petroleum-oil, and natural gas in the years to come. Countries like India where there is an abundance of feedstock (positive factor), and over 50% fossil-content in its electricity mix (compelling driver), can consider investments in HTC and pyrolysis in right earnest. When comparing slow pyrolysis and HTC, several articles suggest that HTC is a more favorable alternative as it does not require as high temperatures and process steps as pyrolysis does. As mentioned earlier (and alluded to in sub-section 3.4), HTC technologies are able to produce hydrochar at a lower unit-production-cost (owing to much lower energy requirements). If the demand for hydrochar spikes in the years to come, the profitability of HTC (the NPV in other words) will increase. The raw feedstock in pyrolysis requires pre-drying, making it easier to achieve continuity and regulate the reaction rate in the pyrolysis process compared to HTC. When examining BSG as a feedstock, a combination of both HTC and pyrolysis was tested, where an HTC method with low temperature was applied as a pre-treatment step before pyrolysis (Olszewski et al. 2020; refer Figure 4). This approach was also studied with feedstocks such as cattle manure and industrial sludge, by Chinese researchers in Li J et al. (2020). On the lines of tests carried out by Correa et al. (2019) with sawdust from pinewood, the effect of different pre-treatment HTC temperatures on the output of pyrolysis carbonization of the feedstock, can be studied. While Manmeen et al. (2023) showed that the HTC-pyrolysis duo did not change the pyrochar yield, vis-à-vis pyrolysis acting solo, they considered the lowered ash content in the final product as a possible motivation for using the two technologies in tandem.

4.2. Time, Temperature and Type of Feedstock

As gathered from some of the articles, higher carbonization temperatures generally lead to products with higher energy density. However, the optimum temperature ranges differ from one type of feedstock to another, and only experimental trials (which this paper recommends as an interesting area of research in the future) can enable a reasonably accurate determination of the same. As reported by Manmeen et al. (2023), there indeed are upper limits (optima in other words) which need to be adhered to, as excessively high temperatures can lead to increased ash formation and an increase in surface porosity of the pyrochar. The ash formed clogs these pores, affecting the pyrochar's adsorption capacity and rendering it unsuitable for use as a soil amendment and in water/wastewater treatment. The sensitivity of the final output to process parameters and the delicate balance which needs to be struck as technologies keep improving over time, can never be underestimated. The number of researchers around the world working in this field of research, and the number of peer-reviewed articles already published, is a clear bellwether pointing in the right direction.

High temperatures are invariably associated with high energy input, and thereby high operational expenses. Time, too as mentioned earlier, is a vital influencing factor. Optimizing the residence time is necessary to ensure that the quality of the output is not compromised. (Fast) pyrolysis can be conducted rapidly within an hour and more slowly over several hours, affecting the moisture content of the pyrochar. The quanta of water removed, depends on the original composition of the feedstock (algae for instance have higher moisture content to begin with), and the pyrolysis process (parameters like temperature, residence time etc.). If the intended output is pyrochar (primary product), and the residence time needs to be increased based on other factors (feedstock, temperature, method), the cooling temperature can also be increased. Despite the greater residence time, the pyrochar yield will increase, at the expense of that of the bio-oil (Manmeen et al. 2023).

While Figure 3 reveals that among algae, manure and durian peel, the former resulted in a higher yield of pyrogas and pyrochar, one would have to interpret with some caution, as the temperatures here are not the same for all the three feedstocks (550 °C for algae, and 600 °C for the other two). One may also derive from Figure 3 that a lower temperature of 300°C results in more pyrochar, and lesser bio-oil and pyrogas for all the investigated feedstocks. While manure seems to yield more bio-oil vis-à-vis durian peel and algae, one must again remember that "manure" is a generalized term, and this result will most likely vary from the type of domesticated animal, which generates it. Still on manure, considering that this type of feedstock is usually laden with a lot of moisture, HTC which is insensitive to the initial moisture content of the feedstock, would be a better bet than pyrolysis. For that matter, the duo in tandem would work even better, if pre-treatment by HTC is followed by pyrolysis on the downstream, as some articles have contended and demonstrated. It is also apt to mention at this juncture that feedstocks with higher moisture and volatile matter content, may not be attractive starting materials for the production of biofuels.

4.3. Tuning in to Sustainable Development

The final product can be tailored to contribute to what is needed locally, for developing countries this is important as it could lead to safer and more sustainable accessible energy-alternatives, than using coal for instance. In order for it to become a reality, it is necessary to apply cheaper methods for HTC and pyrolysis. Developing countries should also clearly map availability of resources from the point of view of optimizing production and transportation costs, and maximizing profits for the entrepreneurial producers of hydrochar, pyrochar and by-products. The countries in question can, simultaneously, minimize environmental hazards and mitigate a range of social ills associated with unsound waste management, pollution and energy poverty. Depending on whether more energy (SDG 7) or food production (SDG 2) is needed, carbonization methods can be optimized through temperature and feedstock, to yield more or less of pyrochar/pyrogas/bio-oil. Adding this sub-sector – if it could be called so and looked upon as an industry in itself with its dedicated streams of inputs and outputs – into the circular bioeconomy, will create new jobs (SDG 8). However, all this is dependent on the availability of and accessibility to feedstock. For example, the raw material durian peel is abundant in Thailand without a designated use (Manmeen et al. 2023), while toxic crofton weed in China needs to be done away with in a sustainable fashion (Lin and Cheng 2022). Obviously, carbonization technologies could kick off with these feedstocks in these two Asian countries before evolving to accommodate others subsequently.

Harnessing scrap tires for energy-products (or pyrochar as soil amendment, for that matter), does away with the need for landfills (SDG 11, SDG 15, and SDG 6) which contaminate groundwater and affect the pedosphere adversely in the longer run. Oliveira Neto et al. (2019) also refer to SDG 3 indirectly, by stating that open landfills (in developing countries) are breeding grounds for disease-causing insects like mosquitoes and flies. It is, however, very necessary to tailor supply to demand – produce sustainably – as otherwise, a glut of unwanted products on the marketplace would result in the emergence of a new challenge!

Carbonization processes can be energetically self-sufficient as the bio-oil and pyrogas (at least a part of these two products) can be utilized for the processes themselves (Osman et al. 2023). This confers economic and environmental sustainability to the processes themselves. Pyrochar and hydrochar are effective carbon sinks, rendering the life-cycle carbon-negative (Cavali et al. 2022). As carbon sinks amending the arable soil, they enhance plant and crop growth, allowing them to absorb more carbon dioxide (SDG 13). They have nitrogen and phosphorus, in addition to micronutrients in them, and thus are also sources of nutrients to the flora – obviating at least in part, the production and supply of synthetic chemical fertilizers. Pourkarimi et al. (2019), from a holistic sustainability point of view, have recommended micro-, and macroalgae as preferred feedstock, to circumvent the food-feed-fiber-fuel impasse that rears its ugly head now and then. However, as mentioned earlier, any conflict with SDG 14 must be minimized, and if possible, completely averted.

4.4. Towards a Market – Fledgling to Flourishing?

The most expensive process, as gathered from Cavali et al. (2022), is portable pyrolysis (1847 USD/ton pyrochar). Slow pyrolysis is 61% cheaper than portable pyrolysis (Manmeen et al. 2023), and vacuum pyrolysis is about 20 USD/ton cheaper than slow pyrolysis (Oliviera Neto et al. 2019). HTC, on account of its ability to utilise wet feedstock directly, registers 114 USD/ton hydrochar (Cavali et al. 2022), which enables the selling price to be just under 118 USD/ton, at a slim margin of 4 USD/ton. Vacuum pyrolysis raked in the highest income, if one assumes that the feedstock (rubber tires, in this case) can be obtained free of charge. Further, carbon black (the solid end-product) has more inherent value than biochar owing to its higher carbon content. But it must be pointed out at this juncture that assuming that the tires are entirely free of charge would be fallacious. On a per-ton-of-pyrochar basis, slow pyrolysis garnered the highest profits, if the pyrochar can be sold at a maximum value of around 909.43 USD/ton (Cavali et al. 2022).

Carbonization reduces transportation costs, and handling the bio-products becomes easier vis-à-vis the direct application of raw materials (Das et al. 2021). HTC is cheaper than pyrolysis for reasons mentioned earlier on in the article (Cavali et al. 2022; Li, J et al. 2020; Miliotti et al. 2020). The benefits of HTC must thereby not be offset by choosing the wrong type of feedstock – manure for instance, which owing to its high moisture content, will incur high transport costs (Zhou et al. 2019).

A two-step process with HTC and pyrolysis in that order, reduces the moisture and ash contents in the raw material and economizes the transportation step in the process chain (Olszewski et al. 2020). But one needs to give something to get something – the total capital investment required to set up both the pyrolysis and the HTC processes will be greater. Ash content may also be reduced by pelletizing and compacting the biochar. This also counteracts rapid nutrient release to the soil, while increasing its ability to sequester carbon dioxide (Yang et al. 2023). As hydrochar has a greater ability to store nutrients, it attracts a higher value in the market (for agricultural uses) compared to pyrochar (Zhou et al. 2019; Miliotti et al. 2020).

If the price of pyrochar or hydrochar is comparable to fossil fuels, it would not be incentive enough for energy-users to switch to the bio-products. If the selling price can be lowered, the transition to non-fossil fuels can be speeded up (Yang et al. 2023). If the price of the organic wastes that need to be purchased for use as feedstocks are lowered, if parameters (time, temperature, feedstock-blends etc.) can be effectively manipulated to produce more of the high-value, in-demand products (bio-oil, biogas etc.), the pyrochar (albeit lower in quantity) can be sold at a lower price to eat into the market share of fossil fuels (Cavali et al. 2022).

Conclusions and Recommendations

Based on a careful, comparative analysis of the articles reviewed in this paper, the authors list some take-home messages for the readers, which would serve as motivations for further necessary and highly-recommended research in HTC and pyrolysis – two processes which are likely to entrench themselves in the biorefineries of the circular bio-economies of tomorrow, hopefully in many countries of the world.

- Many of the case studies which the authors came across in the articles reviewed, achieved positive results in the trials carried out to produce pyrochar by pyrolyzing different types of feedstocks. Further studies on HTC need to be done, as that is considered to be more energy-efficient and cost-effective than pyrolysis.
- Algal biofuel has the potential to compete with petroleum-based liquid fuels, if technology can develop rapidly to make conversion of algae (micro-, and macro-) to bio-energy products become economically viable for commercial use. However, problem shifting of any sort must not be overlooked – the possible negative impacts of large-scale algaculture on marine ecosystems must be forestalled and obviated. This could very well turn out to be a conflict with SDG 14, if not detected and guarded against.
- Scrap tires have been subjected to vacuum pyrolysis in Oliviera Neto et al. (2019). Other pyrolysis methods can

very well be tested, in comparison to vacuum pyrolysis.

- Most tests in the articles reviewed are laboratory-scale, except de Oliviera et al. (2019) and Lin & Cheng (2022). Conclusions about performance and economic feasibility are difficult to predict based on the results obtained from them. Scaling up may uncover emergent obstacles which cannot be pre-empted.
- Prior to commercialization, a comprehensive multi-parameter economic analysis is indispensable. As discussed, the type of feedstock, the method adopted, the energy mix and the transport infrastructure, will influence the feasibility – both socio-economic and environmental – of any long-term investment committed to these waste-valorization technologies.
- More studies are needed on the impact of pyrochar and hydrochar on plants and ecosystems when used as soil improvement alternatives. The long-term effects of pyrochar and hydrochar on soil fauna and flora can only be determined by carrying out long-drawn-out trials.
- Pine sawdust has been studied by Correa et al. (2019). Similar tests can be conducted using birch and oak, with the medium-term of goal of expanding the resource base. In case the trials show that birch and oak are also attractive raw feedstocks to consider.
- Pyrolysis and HTC can be instrumental for developing countries to harness energy from biowaste (like the instance of India referred to earlier), while developed countries can avail of these methods to create products for the markets of a sustainable circular bioeconomy in the near future.

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