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Business and Market Analysis of Hydrothermal Carbonization Process: Roadmap toward Implementation

Gianluigi Farru [1,*], Fabiano Bisinella Scheufele [2,3,*], Daniela Moloeznik Paniagua [3,4], Fritz Keller [5,6], Changyoon Jeong [7] and Daniele Basso [8]

1 Department of Civil and Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
2 Postgraduate Program in Bioprocess Engineering and Biotechnology, Federal Technological University of Paraná—UTFPR, Campus Toledo, Cristo Rei Str. 19, Vila Becker, Toledo 85902-490, PR, Brazil
3 Leibniz Institute of Agricultural Engineering and Bio-Economy e.V. (ATB), 14469 Potsdam, Germany; d.moleznikpaniagua@tu-berlin.de
4 Chair of Circular Economy and Recycling Technology, Technische Universität Berlin, 10623 Berlin, Germany
5 Association Act4carbon e.V., Berliner Ring 73, 72076 Tuebingen, Germany; f.keller@4c-chem.com
6 4C-Chem Dr. F. Keller, Berliner Ring 73, 72076 Tuebingen, Germany
7 Red River Research Station, Louisiana State University AgCenter, Bossier City, LA 7112, USA; cjeong@agcenter.lsu.edu
8 HBI Srl, Via A. Volta 13/A, 39100 Bolzano, Italy; d.basso@hbigroup.it
* Correspondence: gianluigi.farru@unica.it (G.F.); fabianob@utfpr.edu.br (F.B.S.)

Abstract: This study assesses the status of hydrothermal carbonization (HTC) technology and identifies barriers hindering its commercial viability. Conducting a global survey among HTC companies (with a total of 24 surveys sent), the research evaluates the current landscape, challenges, and future prospects of large-scale HTC operations. Furthermore, it presents a detailed global inventory of existing HTC facilities, illustrating geographical distribution and trends in application. Most of the companies are located in Europe, followed by Asia and North America. With substantial participation from HTC companies, exceeding 62% in the survey (15 companies), the study provides a comprehensive overview of diverse companies, their business models, regulatory challenges, and the overall state of HTC technology. The majority of companies in this study, approximately 80%, offer services in the field of waste management. This paper also explores the potential of HTC in transforming waste management practices, carbon sequestration methodologies, and the development of new materials. Employing a thorough SWOT analysis, the paper advocates for a broader adoption of HTC, emphasizing its transformative capacity in fostering sustainable management of urban, industrial, and agricultural residues, promoting circular economy principles, mitigating climate change, and offering a robust foundation for informed decision-making and sustainable development strategies.

Keywords: hydrothermal processes; HTC companies; sustainable technology; hydrochar; carbon sequestration; circular economy; renewable energy; waste management

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1. Introduction

Hydrothermal carbonization (HTC) is a thermochemical process that operates in aqueous media under relatively low temperatures (180–260 °C) and autogenous pressures (10–50 bar) that stands out as an innovative technology that offers a promising approach to sustainably managing organic residues; it is particularly versatile and suitable for wet biomasses [1], which are commonly a drawback for other technologies [2]. As a result, a solid carbonaceous material known as hydrochar, along with a liquid phase generally referred to as process water, is produced. Besides the waste management of wet biomasses, the HTC technology is associated with multiple applications including energy (biocoal), soil amendment, carbon removal, platform chemicals, and advanced materials.

The scientific literature reveals a vast body of work on HTC published in the past decade. Moreover, an exponential growth in the number of HTC-related patents from 1996 until today, wherein more than 500 patents were deposited, highlights the preeminent industrial interest in this technology. Nevertheless, the transition from laboratories to commercial implementation remains slow and largely uncharted [3]. The growing interest in this process has necessitated discussions about its future. As a result, several international conferences and workshops involving stakeholders from the scientific, business, and market sectors have been conducted.

The International Workshop on Innovative Hydrothermal Systems to Valorize Agricultural Residuals: Roadmap Towards Implementation—Achievements and Barriers, supported by the OECD (Organization for Economic Cooperation and Development), held in Seoul, Republic of Korea (15–16 May 2023) [4], explored the future of the hydrothermal carbonization process, focusing on business and market aspects. Policy aspects were also discussed since business depends on policy (limit values, permits, and product characteristics, among other elements).

The workshop brought together 29 participants from eight different countries and various backgrounds, providing a comprehensive and multidisciplinary discussion on the business and market aspects of HTC. The workshop's primary objective was to critically assess the current state of knowledge regarding the application of HTC in managing agricultural residues and to identify barriers and challenges hindering its commercial development.

The workshop format emphasized collaboration and interactive sessions, with specialized breakout groups (BGs) focused on technology (BG1), research (BG2), business (BG3), and policy (BG4). The outcomes of these group discussions were synthesized into a comprehensive roadmap for the future development and implementation of hydrothermal technologies in agricultural production systems.

This paper focuses on the business and policy aspects of HTC, exploring its current landscape in various applications, discussing factors influencing successful business development, and highlighting necessary changes for expanding HTC business applications. The workshop-derived roadmap, encompassing vision, milestones, and actions, offers a framework to advance the HTC industry and realize its potential in effectively managing agricultural residues.

In a continuation of the deliberations during the workshop, the objective of this paper is to systematically collect data directly from HTC industrial companies. The purpose is to offer a comprehensive and holistic perspective on the current status, identify potential drawbacks, and establish directions and future outlooks for the technology at a global scale in the forthcoming years.

The insights and recommendations in this paper serve as a valuable resource for researchers, industry stakeholders, policymakers, and those interested in promoting the adoption and commercialization of HTC technologies. Overall, this paper contributes to the growing knowledge base on the business and market aspects of HTC. By fostering collaboration and knowledge exchange, it aims to unlock the full potential of HTC in transforming urban, industrial, and agricultural residue management practices toward sustainability in the circular economy. The paper intends to recommend future steps to promote the implementation of HTC plants.

The paper begins with a detailed description of the methodology employed in this study. This is followed by a comprehensive background overview of HTC, providing essential context for understanding its applications and potential impact. Subsequently, the paper delves into an examination of various business cases to illustrate real-world implementations and outcomes. The obtained results are then meticulously discussed and analyzed, shedding light on key findings and implications.

2. Materials and Methods

An extensive review of available literature was conducted to gather the data used in this study. However, online research became necessary due to the limited availability of scientific work on the subject. A survey was distributed to 24 worldwide companies actively involved in HTC operations to supplement the data collection process, identified through online sources. The survey consisted of 5 sections: 1. General information about the company, 2. Technical information about the company, 3. Information about processes and plants, 4. Policy, and 5. Complementary Information. The survey was set up using Google Forms, with a link sent via email to each company. Companies had the option to answer in their preferred language. Some companies chose to answer via telephone. The survey questions are available in the Supplementary Materials.

The maps produced were drawn using Python 3.10.12 in Google Colab using Pandas and GeoPandas libraries [5] to manage and plot the geospatial data. The location of the plants was obtained by Google Maps, based on the address provided by the company through the survey or on the website. For the plants, in some cases, when the exact location was not disclosed in detail, it was considered the closest possible position (i.e., city or country).

The survey answers from the companies together with proceedings and the materials created in the workshop on "Innovative Hydrothermal Systems to Valorize Agricultural Residuals: Roadmap Towards Implementation—Achievements and Barriers", held in Seoul, Republic of Korea, in May 2023, were utilized to identify strengths, weaknesses, opportunities, and threats in the area of commercialization and policy for the development of the HTC technology. Moreover, a vision for business and market and for policy was elaborated and the milestones to achieve the vision were identified.

3. Results

3.1. Hydrothermal Carbonization

Hydrothermal carbonization is a thermochemical process that converts biomass or organic waste into a carbon-rich material known as hydrochar (or biochar, when applied on soil [6]) in the presence of water at relatively low temperatures and pressures. The process mimics the natural geological process of coal formation, but it occurs on a much shorter timescale, typically within a few hours [1]. The HTC process belongs to the hydrothermal processes (HTPs) that vary based on the operative conditions in carbonization, liquefaction (HTL), and gasification (HTG), especially due to temperature ranges. HTC operates at milder temperature and pressure conditions (180–260 °C and 20–50 bar), HTL at intermediate operating conditions (240–375 °C and 50–250 bar), and HTG at more severe conditions, above supercritical conditions of water ($T > 380$ °C and $P > 250$ bar) [7]. Additionally, recent advancements in HTPs include hydrothermal humification (HTH) and hydrothermal fulvification (HTF), defined based on the pH of the solution due to the presence of alkaline agents (e.g., KOH) [8–12]. Due to the wide range of combinations of operative conditions, the field of applications is even wider.

The hydrothermal carbonization process involves the following steps: (i) feedstock preparation, (ii) heating and pressurization, (iii) reaction and carbonization, (iv) solid–liquid separation, and (v) hydrochar post-treatment/process water treatment.

Biomass or organic waste materials, such as agricultural residues, animal manure, municipal sewage sludge, municipal solid waste (MSW), wood chips, or algae, are collected and prepared for the process. The feedstock should have a high-water content to facilitate the reaction. In fact, the process can successfully operate with a water content up to 90% and beyond. When the water content is insufficient, a co-processing (co-HTC) method using a mixture of different feedstocks (low-water content + high-water content) can be employed to adjust the water content instead of using fresh water [13]. Recycling strategies involving the reuse of PW from previous operations have also been studied [14]. The amount and supply method of water can define another HTP, the vapothermal carbonization (VTC) process [15], in which vapor is used instead of liquid water. This substitution generally reduces the amount of process water produced, and therefore, the amount to be treated.

The feedstock source, availability, and properties are crucial factors for the techno-economic feasibility of HTC. Specifically in the context of urban and agricultural residues, the logistics for the feedstock supply may boost or impair the technology. Concentrated and pre-established logistics feedstocks, such as for sewage sludge, are the most likely to thrive in the short term. These raw materials cannot be transported over long distances (low-value-added material, high volume, and therefore high costs) to generate profit and require a focus on smaller de-centralized plants close to their source.

Also, in the case of waste, the tipping fee stands out as a significant income source for the HTC process that may be even higher than the other energy or product incomes in the process [16]. In fact, tipping fees are charges levied for the disposal of waste in a landfill or waste processing facility. These fees are generally based on the weight or volume of the waste being disposed of. The concept behind tipping fees is to cover the cost of operating waste disposal facilities, including expenses related to landfill maintenance, recycling, and hazardous waste handling, as well as to encourage waste reduction and recycling efforts by making the disposal of waste more expensive. The fees can vary significantly based on the type of waste, the location of the facility, and local environmental regulations. In addition, ease of transport (i.e., pumping) strongly impacts process feasibility, especially in large-scale and continuous processing, which can achieve efficiencies from scale. In this sense, pumpable or easily transported feedstocks with well-understood rheological properties are essential. However, it has been reported that this challenge can be overcome by recycling process water to low-moisture content feedstock [17].

Besides feedstock availability, the utilities for processing, such as water availability and costs, are also major concerns for business development. Therefore, water reuse strategies such as recycling HTC process water are salient concerns [18].

Prepared feedstock is loaded into a reactor and if necessary, water is added to achieve a high moisture content. The reactor is then sealed, and heat is applied to elevate the temperature and pressure. The typical temperature range is around 180 °C to 250 °C, and the pressure is usually between 10 and 50 bar, generally under autogenous conditions [1]. These reactors can be either operated continuously or in batches. The former demands a rheology of the raw material that is more controlled and offers more energy efficiency as the applied heat can be reused more efficiently compared to batch processing.

The reactor's high temperature and pressure conditions facilitate a series of chemical reactions. These reactions include the hydrolysis, dehydration, decarboxylation, and polymerization of the organic compounds present in the feedstock [19]. The result is the conversion of biomass into a solid carbonaceous material, hydrochar, and liquid and gaseous byproducts, mainly carbon dioxide. The carbon efficiency, i.e., the percentage of organic carbon contained in the starting product and found in the hydrochar after the HTC process, is approx. 80%. The remaining 20% is mainly present in the process water, with a smaller fraction found in the process gas. In contrast, pyrolysis exhibits significantly lower carbon efficiency, with only around 30% of the carbon being retained in the pyrochar. The remaining 70% is found in combustion gases and, if separated and not burnt, in the tar [20]. This difference in carbon efficiency explains why the HTC process is overall only slightly exothermic, while pyrolysis is typically pronouncedly exothermic.

After the carbonization reaction, the mixture is cooled down. The hydrochar settles as a solid material, while the liquid phase, known as process water, contains water-soluble organic compounds and nutrients, which can be treated and used for various purposes, such as irrigation, nutrient-rich fertilizer production, or the extraction of valuable chemicals [18,21,22]. Nutrients like ammonia may be vapor-stripped from the process water. Phosphorus—a very limited resource—may be obtained by the coprecipitation of ammonium and phosphorus by adding magnesium salts to the acidified reaction mass as Struvite, adjusting the pH to alkaline values (pH > 9) [7].

The hydrochar is separated from the liquid phase and further processed to remove excess water. Depending on its intended application, the hydrochar may be washed, dried, and pelletized or left in its raw form [23].

For fuel purposes, the HTC technology presents an energetically favorable scenario since hydrochar is more hydrophobic than its precursor feedstock, considerably reducing the difficulty and cost of water removal [24,25]. This is related to the dehydration and decarboxylation reactions that cause a decrease in hydrophilic functional groups (e.g., hydroxyl and carboxyl groups), making the product easily dewatered. Overall, hydrophobicity is enhanced by temperature and acid addition to the HTC process [26]. However, for advanced materials applications, HTC products can present more complex hydrophobicity/hydrophilicity behaviors, as reported elsewhere [27].

Hydrothermal carbonization offers several advantages, demonstrated by several authors. When used in waste management, one of the primary benefits of HTC is the reduction in volume of the feedstock [24,28,29]. Due to its properties, hydrochar can be utilized in various applications. This includes the use as a soil amendment to improve soil fertility and carbon sequestration [21,30]. Additionally, hydrochar can serve as a renewable fuel source [23,31] with an increased energy content that varies depending on the feedstock and process conditions. This increase can range from 3% to 38% more than the original feedstock [32], making it comparable to common solid fuels. Notably, the energy values of traditional solid fuels range from 5 to 33 MJ/kg, with lower values for biomass and lignocellulosic materials, and higher values for coals and coke [33]. Furthermore, hydrochar can also be used as a precursor for the production of activated carbon or other carbon-based materials in various industries [34–36]. However, the final usage mainly depends on the feedstock composition. Hydrothermal carbonization could play a significant role in the business and market landscape, primarily due to its potential as an innovative and sustainable technology for biomass conversion and waste management. By diverting organic waste from landfills and incineration, HTC contributes to a more sustainable waste management system by reducing greenhouse gas emissions and environmental pollution [37].

Overall, the role of hydrothermal carbonization in business and markets is multifaceted, offering potential solutions for waste management, renewable energy, sustainable agriculture, and advanced material production. As environmental concerns and sustainability goals continue to gain importance, HTC will likely find increasing relevance in various sectors and contribute to a more circular and environmentally responsible economy.

3.2. Overview of Application Business Cases

Existing HTC plants and companies worldwide and relevant information on their plant facilities and processes are summarized in Table 1. The information provided has been directly sourced from the respective companies or their official websites.

It must be highlighted that the list is not exhaustive as several HTC (and related technologies) companies, startups, and spin-offs continuously emerge worldwide. Moreover, some companies are generally reluctant to disclose internal data. Notably, precise knowledge of the plants is challenging to obtain due to (i) some plants operating during a specific period (as demonstration plants) and are currently non-operational, (ii) some plants resulting from collaborations between at least two companies or other research institutes/organizations, (iii) some plants belonging to associated groups/shareholders, and (iv) some plants being provided by equipment and technology developers/suppliers, who are not willing to disclose their proprietary technology. Despite these obstacles, 24 companies were identified as key players in the HTC market, of which 15 completed the survey, providing direct information for this research (63%).

Based on the companies' information, one may notice the dominance of companies located in Europe, totaling 19 companies (79.2%). Among these, nine are situated in Germany; two each in Italy, Spain, Switzerland, and the United Kingdom; and one each in Sweden and the Netherlands. In Asia, three companies are from Japan, and one is from the Republic of Korea. Finally, only one company is located in North America in the USA. Figure 1 presents a choropleth map showing the distribution of HTC companies and plants worldwide (Figure 1a) and specifically in Europe (Figure 1b), and in Asia (Figure 1c).

Table 1. Existing hydrothermal carbonization (and similar technologies) companies and plants worldwide.

Company	Location (Since)	Type of Technology *	Type of Service **	Feedstock	Plant Type (Location, Startup)	Capacity and Operation Mode	Process Conditions	Ref.
Antaco	Guildford, UK (2011)	HTC	W-M, EN, FER, A-MAT, C-REM, ETD&S	Organic wastes (food, garden cuttings, sewage sludge, agricultural, manure)	Pilot Plant (undisclosed location, 2014) First HTC plant in UK [4]	Pilot Plant - Operation: Continuous Modular and mobile, compact plants	T = 200 °C P = 25 bar t = 4–10 h Modular continuous reactors	[38]
Artec-HTC GmbH	Bad Königshofen, Germany (2019)	HTC	W-M, CHE, ETD&S, RD&I	Sewage sludge, MSW	Full Plant (Halle Lochau, Germany, 2013) Demonstration Plants (2010, 2009, 2019)	Full Plant (currently not in operation) - Reactor(s) Size: 3000 L - Capacity: 18,000 L/day - Operation: Continuous Multiple demonstration plants - Reactor(s) Size: 50–300 L - Capacity: 300–420 L/d - Operation: Continuous	n.a.	[39], §
AVA Biochem	Zug, Switzerland (2014)	HTC	CHE	C6 sugars from different streams	Demonstration Plant (Switzerland, Muttenz, 2016)	Demonstration Plant 30-ton final 5-HMF (related to 100% HMF)	Water-based patented COBRIS^{TM} process	[40], §
Calpech	Alicante, Spain (2021)	HTC	A-MAT	Industrial residues	Pilot Plant (Alicante, Spain, 2021)	Pilot Plant - Reactor Size: 50 L	n.a.	[41], §
Carbensate	Stuttgart, Germany (2024)	HTC	W-M, FER, C-REM	Sewage sludge, residues (animal, food, industrial)	Prototype Plant (Stuttgart, Germany, exp. 2024)	n.a.	Plant from Artec GmbH	[42], §
Carborem Srl	Lavis (Trento), Italy (2017)	HTC, HTT	W-M, EN, FER, ETD&S, RD&I	Sewage sludge, residues (animal, food, industrial), wet organic wastes	Demonstration Plant (Trento, Italy, 2020) Full Plant (Milan, Italy, exp. 2024)	Demonstration Plant - Reactor(s) Size: 1 m^3 - Capacity: 700 L/h (C-700) - Operation: Continuous, Semi-Batch, Batch Full Plant - Reactor(s) Size: 9 m^3 - Capacity: 5500 L/h (C-5000) - Operation: Continuous, Semi-Batch, Batch	T = 180–210 °C (HTC), 70–210 °C (HTT); P = 10–24 bar (HTC), 1–24 bar (HTT); t = 0.5–2 h (or higher if requested by customer in batch mode) (HTC); t = 0.5–8 h (HTT); Catalyst: none (HTC), if requested by customer (HTT)	[43], §

Table 1. *Cont.*

Company	Location (Since)	Type of Technology *	Type of Service **	Feedstock	Plant Type (Location, Startup)	Capacity and Operation Mode	Process Conditions	Ref.
C-Green AB	Solna, Sweden (2014)	HTC, HTC+WO	W-M	Lignocellulosic residues, sludge from pulp and paper WWTP	Demonstration Plant (Heinola, Finland, 2020)	Demonstration Plant - Reactor Size: 5 m^3 - Capacity: 18,000 t/year - Operation: Continuous	T = 200 °C P = 20 bar t = 1 h Catalyst: none	[44], §
CPL Industries	Sheffield, UK	HTC	W-M, EN	MSW	Pilot Plant (Immingham, UK, 2018)	Pilot Plant - Partnership with Ingelia	T = 200–225 °C P = ca. 20 bar	[45,46]
Da Invent Co., Ltd.	Nagoya, Japan (1992)	HTC	W-M, ETD&S	Multiple (MSW, feathers, carcass, oil extraction residue, agriculture residues, food residue)	Full Plants (Chiba and Gifu, Japan; Xining, Liaoning, and Wuhan, China)	Pilot and Full Plants - Reactor(s) Size: from 2 L to 15 m^3 - Capacity: 200 t/day Multiple Plants (projects, since 2006)	T = 200–240 °C P = 20–30 bar t = n.a.	[47]
DBFZ—Deutsches Biomasse-forschungszentrum gemeinnützige GmbH	Leipzig, Germany (2008)	HTC, HTL	RD&I	Sewage sludge, lignocellulosic (straw), manure, food residues, urban biowaste	Pilot Plant (Leipzig, Germany, 2023)	Pilot Plant - Reactor(s) Size: 1 × 500 L, 1 × 100 L - Operation: Batch (STR)	T = 240 °C P = 0–40 bar(g)	[48], §
GRegio Energie AG	Chur, Switzerland (2018)	HTC	W-M, EN, FER	Wet biomasses, sewage sludge, liquid manure	Pilot Plant (Chur, Switzerland, 2019)	Pilot Plant - Reactor(s) Size: 5.5 m^3 - Capacity: 4–33 t/day (outputs: 750 tons of fertilizer concentrate and 3500 tons of bio-coal) - Operation: Continuous	T = ca. 200 °C P = ca. 20 bar t = 4–6 h Catalyst: n.a. Tubular continuous reactor	[49,50]
Grenol GmbH	Ratingen, Germany (2007)	HTC, VTC, HTT, HTC+G	W-M, EN, FER, CHE, A-MAT, RD&I	Biogas residues	Full Plant (Stuttgart–Hohenheim, Germany, 2023)	Full Plant - Reactor(s) Size: 40 in diameter - Capacity: 15,000 t/year - Operation: Continuous	T = 200 °C P = 20 bar t = 3 h Catalyst: none	[51], §
HBI Srl	Bolzano, Italy (2016)	HTC+G	W-M, FER, ETD&S, RD&I	Sewage sludge, industrial residues	Demonstration Plant (Venice, Italy, 2022)	Demonstration Plant - Setup: 4 HTC reactors + 1 gasification reactor - Capacity: up to 1000 t/year - Operation: Continuous	T = 200 °C P = 24 bar t = 1 h	[52], §

Table 1. *Cont.*

Company	Location (Since)	Type of Technology *	Type of Service **	Feedstock	Plant Type (Location, Startup)	Capacity and Operation Mode	Process Conditions	Ref.
Hokuto Kogyo	Hokkaido, Japan	HTC	W-M, EN, FER, A-MAT (bioplastics)	MSW; medical waste; industrial waste; farming, fishery, ranch wastes	Pilot Plant (undisclosed location)	n.a.	T = 200 °C (steam)	[53]
HTCycle	Murchin, Germany	HTC	W-M, EN, FER, A-MAT	Sewage sludge (and other wet biogenic residues)	Full Plant (Relzow, Germany, 2017)	n.a.	n.a.	[54]
Ingelia	Valencia, Spain (2010)	HTC	W-M, EN, FER, ETD&S	Multiple (sewage sludge, MSW, plant wastes (gardening and pruning), agricultural, food residues)	Full Plant (Valencia, Spain, 2010) Also provides equipment for other companies	Full Plant - Capacity: 14,000 t/year (outputs: 750 tons of fertilizer concentrate and 3500 tons of bio-coal) - Operation: Continuous (claimed to be the first industrial plant to operate continuously)	T = 180–200 °C P = n.a. t = 4–12 h Catalyst: acid (not specified) Modular continuous reactors	[55]
Kinava	Seoul, Republic of Korea (2019)	HTC and HTA	W-M, EN, A-MAT, ETD&S	Livestock manure (pig, cow, chicken), agricultural byproducts, sewage sludge	Pilot and Full Plants (Republic of Korea, 2019–2021; Yangju Dyeing Factory Complex, Republic of Korea, 2021; Thailand, 2022)	Multiple Sizes (depending on project and costumer) Full Plants (in progress)	T = 220 °C P = 25 bar t = n.a. Catalyst: hybrid catalyst (not specified)	[56]
KS-VTCtech GmbH	Ganderkesee, Germany (2017)	VTC	W-M, EN	MSW, food residues, biogenic residues	Full Plant (near Berlin and Großbritannien, Germany, 2023)	Full Plant - Reactor(s) Size: 6 × 60 m^3/16 × 140 m^3 - Capacity: 212 t/day/2160 t/day - Operation: Batch	T = 220 °C P = 23 bar t = 3–4 h (reaction); 6 h (whole batch) Catalyst: none	[57], §
Revatec GmbH	Geeste, Germany	HTC, VTC	W-M, EN, FER, A-MAT, C-REM, RD&I	Biogenic residues (green waste or landscape maintenance material)	Full Plant (undisclosed location)	Full and Pilot Plants - Reactor(s) Size: 2.3 L, 400 L, and 3200 L (HTC) - Reactor(s) Size: 70 L, 1 m^3, and 77 m^3 (VTC)	T = ca. 200 °C P = ca. 18–20 bar t = n.a.	[58]

Table 1. *Cont.*

Company	Location (Since)	Type of Technology *	Type of Service **	Feedstock	Plant Type (Location, Startup)	Capacity and Operation Mode	Process Conditions	Ref.
Shinko Holdings Co., Ltd.	Japan, Aichi (1996)	HTT	W-M, EN, FER, ETD&S, RD&I	Food residues (restaurant waste, vegetable waste from market)	Full Plant (Taoyuan, Taiwan, 2021)	Full Plant - Reactor(s) Size: 10 m^3 - Capacity: 24 t/day - Operation: Batch	T = 160–180 °C P = 5–10 bar t = 0.5 h Catalyst: none	[59], §
SoMax BioEnergy LLC SoMax Circular Solutions	Spring City, USA (2018)	HTC	W-M, EN, FER, ETD&S, RD&I	Sewage sludge	Full Plant (Phoenixville, USA, 2023)	Full Plant - Capacity: 48 t/day (w.b. 15% solids) - Operation: Continuous	T = 195–205 °C P = 20–25 bar t = 3 h Catalyst: none Tubular reactor	[60], §
SunCoal Industries GmbH	Ludwigsfelde, Germany (2007)	HTC, HTT	CHE, A-MAT, ETD&S, RD&I	Lignocellulosic residues	Pilot Plant (Ludwigsfelde, Germany, 2008)	n.a.	n.a.	[61], §
TerraNova Energy GmbH	Duesseldorf, Germany (2008)	HTC	W-M, FER, ETD&S, RD&I	Sewage sludge, municipal solid waste (MSW)	Full Plants (Jining, China, 2016; Mexico City, Mexico, expected by 2024) Demonstration Plants (Podegrozie, Poland, and Japan)	Full Plants Several capacities (for different projects) - Capacity: max 72 t/day - Operation: Continuous	T = 180–210 °C P < 32 bar t = 4–5 h Catalyst: 0–2% H_2SO_4 Continuous stirred and jacket-heated reactor	[62], §
Torwash B.V.	Burgerbrug, the Netherlands (2020)	HTT	W-M, EN, FER, ETD&S	Sewage sludge	Demonstration Plant (Land van Cuijk, the Netherlands, 2023)	Demonstration Plant - Capacity: 12.5 kg/h - Operation: Continuous	T = 170–220 °C Catalyst: none	[63], §

n.a.: not available; § direct information was provided by the company through the survey; for the companies that did not respond to the survey, information was sourced from their official website (see References). * Type of Technology: HTC—Hydrothermal Carbonization, VTC—Vapothermal Carbonization, HTT—Hydrothermal Treatment, WO—Wet Oxidation, HTC+G—HTC Coupled with Gasification, HTA—Hydrothermal Activation; ** Type of Service: A-MAT—Advanced materials, C-REM—Carbon removal, CHE—Chemicals, EN—Energy, FER—Fertilizers, ETD&S—Equipment and technology developer and supplier, RD&I—Research, development, and innovation, W-M—Waste management.

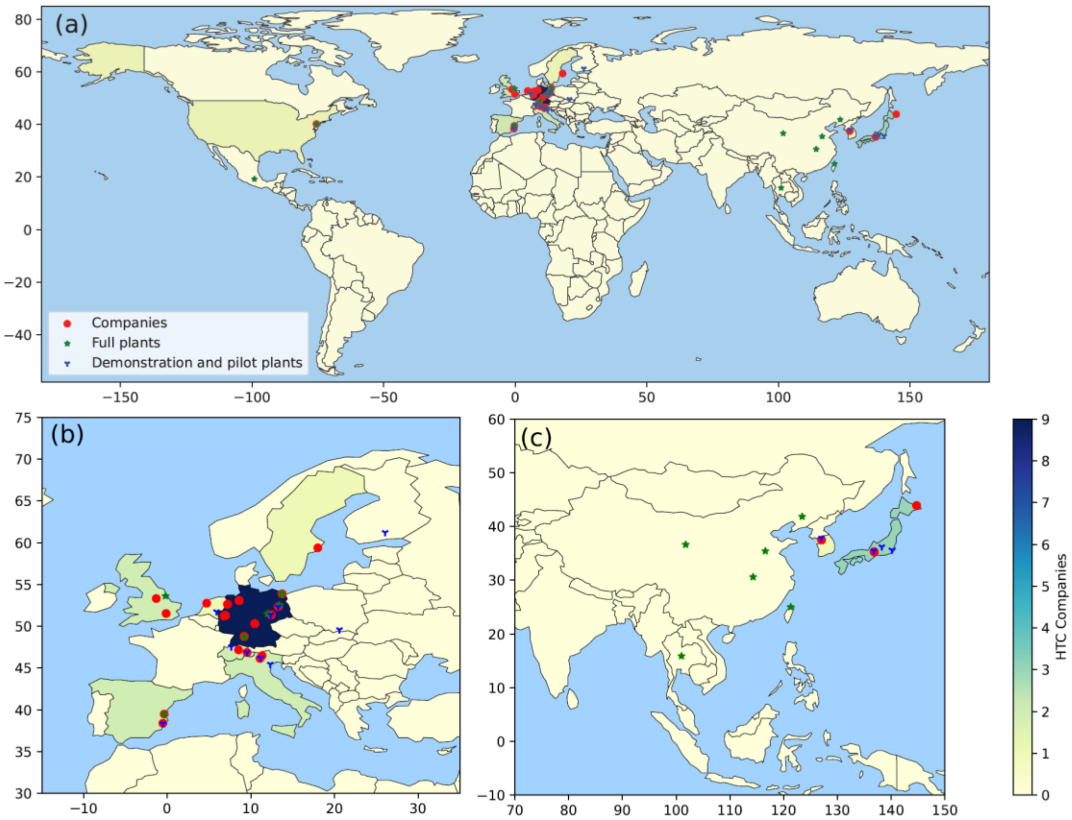

Figure 1. Distribution of HTC companies and plants: (**a**) worldwide, (**b**) in Europe, and (**c**) in Asia.

The high concentration of facilities in Europe, and mainly in Germany, is expected given the origin of the HTC process and the development of the several research groups and institutions that emerged there in the 2000s. This is further justified by the significant increase in the number of scientific publications in Scopus from European countries, indicating a growing interest and investment in this field. It must be mentioned that there are several disclosed plants operating in various Asian countries (e.g., China, Japan, the Republic of Korea, Thailand, Taiwan) by local or foreign companies. One may notice a wide unexplored market in the Americas, and particularly in the Southern Hemisphere. No companies are officially reported to operate in South America, Africa, or Australia continents. Even though, these regions can be promising given the availability of residual feedstocks and also lower investment and labor costs that are typically less expensive in developing countries.

Of these companies, 11 already have at least 1 full plant (totalizing 14 full plants), and many others have large-scale demonstration or near commercial-level plants, evidencing the industrial development of the HTC technology. It must be highlighted that 50% of the disclosed plants are full-industrial plants. Evidently, some companies have additional plants, but no details are provided/available; hence, they were not considered in this analysis. Also, several smaller pilot plants exist worldwide, especially in research institutes and universities. Another remarkable scenario is that several companies operate in continuous mode in their full operational plants, which strongly impacts on the operational costs and profitability of the process.

In general, the HTC companies operate within temperature ranges between 180 and 240 °C (or lower for hydrothermal treatment—HTT), pressure ranges between 10 and 25 bar, and residence times between 0.5 and 12 h, depending on the different feedstocks and technologies applied by each company/plant (see Table 1).

In addition to the operational plants (as presented in Table 1), several new companies, projects, and joint ventures are constantly emerging in recent months/years. For instance, Ingelia recently announced the commissioning of a new plant in Oostende, Belgium, in partnership with Renasci [64]. Also, other ongoing projects can be mentioned through one of Ingelia's societal partners in Italy named Green Carbon SpA, which is in the final steps of two HTC facilities, namely, Piombino (10 reactors with a processing capacity of 60,000 t/year, to produce biocoal and fertilizer) in collaboration with CREO-HTC, Milan, Italy, which is on the way to the final authorization [65]; there is also a planned plant to process 80,000 t/year of sewage sludge with eight reactors, aiming to produce biocoal and biofertilizer with high P and K content in Chiusi (Italy) [66]. Kinava also has ongoing projects in full plants' scale [56]. According to the company's responses of the survey, Carborem Srl expects to commission an industrial-scale plant to operate in continuous mode at the end of 2024 in Milan, Italy. Also, to the best of our knowledge, TerraNova's technology plant in Mexico City is on the way to be fully operational. The construction started in 2021 and it was expected to be in operation since October 2022 [3,67].

In general, hydrothermal carbonization (HTC) technology is the most widely applied by companies among the various hydrothermal processes (HTPs). However, there is some variation, such as the use of vapothermal carbonization (VTC), a process similar to HTC but utilizing vapor or steam; hydrothermal treatment (HTT), which can operate at lower temperatures and is generally used for less intensive transformations, such as pretreatments; or hybrid technologies such as coupling HTC with wet oxidation (HTC+WO), combining HTC with an oxidation process for additional breakdown of organic material, and with gasification (HTC+G), integrating HTC with gasification to produce syngas (see Table 1).

Regarding the type of service or primary goal of the companies, the vast majority use HTC for the waste management (~83%) of several biomasses and residuals. Besides waste management, HTC technology is used for energy purposes (~54%) (i.e., biocoal production), and another relevant group couples HTC with processes for nutrient recovery (N, P, K) (~58%). Finally, a group of companies apply the HTC process to produce advanced materials (~33%) (e.g., biochar, activated carbons, high-tech carbon materials, bioplastics, and building materials). Some companies use HTC technology to produce chemicals (platform chemicals) (~12%), and some focus on carbon removal (~12%). In addition, several companies are equipment developers and suppliers (50%); occasionally, some use equipment/technology from another. Overall, one may notice a great diversity of technologies and purposes for HTC processes, highlighting this technology's remarkable potential and versatility for several industrial applications and waste management.

Based only on the data directly provided by the companies to the survey, a relatively similar scenario can be observed, as presented in Figure 2. Regarding the type of technology (Figure 2a), the HTC followed by VTC and HTT are the most relevant technologies. Similarly, as disclosed in Figure 2b, for the type of services, waste management (W-M) leads as the main activity related to most companies, wherein a substantial part of companies develops RD&I and act as equipment developers and suppliers (ETD&Ss), followed by focusing on fertilizer (FER) and energy (EN) production.

There is much diversity in the feedstock sources used in these plants. Sewage sludge and municipal solid waste (MSW) are more frequent, particularly for waste management purposes, and associated with energy and nutrient recovery. Several companies claim to be able to process a wide range of feedstocks in their processes, including industrial, lignocellulosic, food, and agricultural (e.g., manure) residues.

The variety of HTC plants provides evidence of the remarkable potential of HTC technologies to add value to the supply chain of several sectors (urban, agricultural, industrial), mainly to deal with residues and wet biomasses, but also for generating sustainable energy, recovering valuable products, and producing added-value materials.

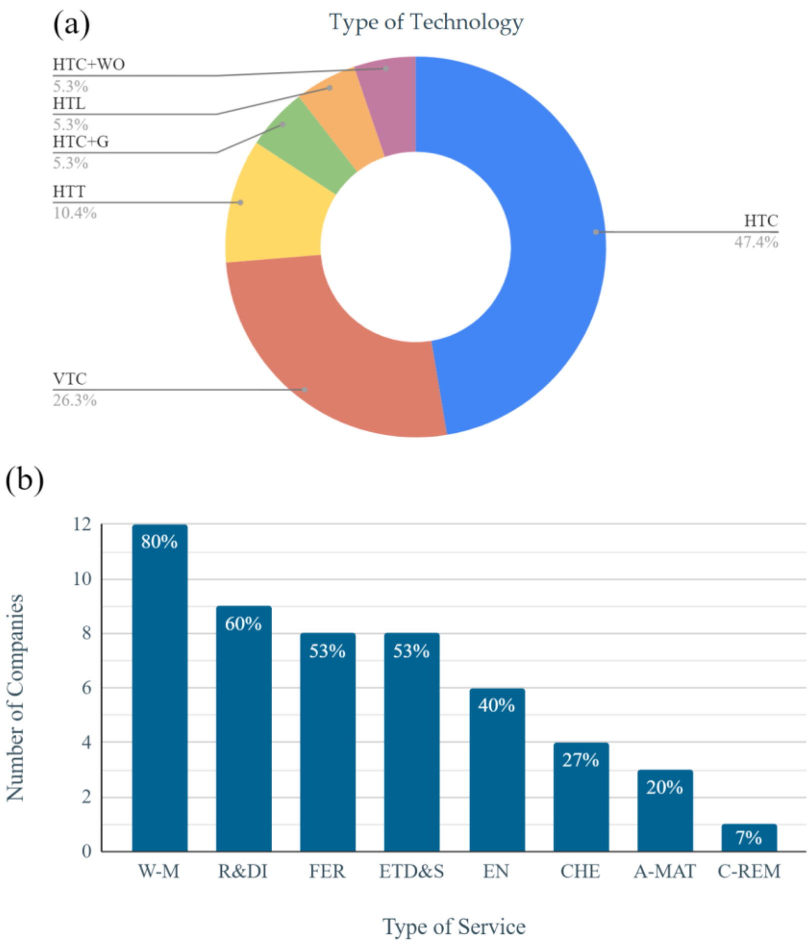

Figure 2. (**a**) Type of technology, and (**b**) type of service, developed by the companies from the survey. HTC—Hydrothermal Carbonization, VTC—Vapothermal Carbonization, HTT—Hydrothermal Treatment, WO—Wet Oxidation, HTC+G—HTC Coupled with Gasification, HTL—Hydrothermal Liquefaction, A-MAT—Advanced Materials, C-REM—Carbon Removal, CHE—Chemicals, EN—Energy, FER—Fertilizers, ETD&S—Equipment and Technology Developer and Supplier, RD&I—Research, Development, and Innovation, W-M—Waste Management.

Currently, the abundance and diversity of residual feedstocks, available in large quantities, suggests that there is relatively little competition among companies for these resources. This situation can be likened to operating in a "blue ocean" [68], a term used to describe a market environment that is relatively unexplored and untapped, in the hydrothermal carbonization sector. In this "blue ocean", existing and emerging companies are navigating a market with fewer competitors, providing ample room for innovation and growth. This context not only offers significant opportunities for companies to develop unique solutions in HTC but also represents a critical approach to addressing an urgent environmental challenge. The vast amount of residues generated by human activities is not just a market opportunity; it is a compelling necessity, presenting one of the most significant challenges of the century and a unique opportunity for sustainable waste management solutions.

In this sense, the competition for HTC technology in the years to come will probably be related to other existent and more established waste disposal and waste-to-energy technologies (i.e., external competition), such as landfilling, composting, anaerobic digestion (AD), and incineration.

The advantages and drawbacks between HTC and other technologies are discussed in the literature. Taking the two first and simplest methods (landfilling and composting), neither produces energy nor produces additional profits [17]. Moreover, these methods are sluggish when compared to HTC. Hence, they demand large areas and are related to substantial greenhouse gas (GHG) emissions. In addition, in 2014, the European Commission outlined landfilling as the least preferable option for waste disposal [17], even though it is still widely applied worldwide, particularly in developing countries.

Comparatively, HTC has been proven to be significantly more energetically viable than the incineration of wet biomasses (i.e., moisture contents > 10%) [17], given the lower energy requirements of the water removal, and is also associated with reduced greenhouse gas emissions [68]. Finally, HTC may mitigate the release of harmful and carcinogenic emissions that are known to be produced by the incineration of waste (e.g., acid gases, NO_x, dioxin, and furans) [17] since HTC produces mainly CO_2 (~70 to 90%) and minor quantities of CH_4, CO, O_2, H_2S (at trace levels) [69,70]. However, given the embryonic stage of HTC technology, in-depth research aimed at assessing the potential pollutants that might be produced by the process, such as polyaromatic hydrocarbons, is both needed and recommended [71].

Comparing HTC to anaerobic digestion (AD), HTC is a more robust and easily controlled process that is effective in treating persistent compounds such as antibiotics, PCBs, etc. [72,73]. Despite AD being a well-established technology with access to solid investments through technological initiatives, AD is sensitive to process conditions, such as temperature, pH oscillations, and feedstock composition (e.g., antibiotics) due to its biological nature. Also, similar to composting processes, AD is slow and thus demands high land usage [17]. In addition, AD also presents potential GHG emissions, as well as lower energy and carbon efficiencies compared to HTC [17,74].

Despite the potential competition between HTC and AD, several studies report the potential to integrate these processes to solve potential drawbacks of both processes. For instance, the HTC process water, rich in organic compounds, can be recycled into an AD reactor, improving the methanogenic potential [75,76] and mitigating its phytotoxicity [21,75,77,78]. Also, HTC can be applied as the digestate and provide recovery of valuable nutrients (e.g., N, P) [77,78], addressing the issues associated with the uncontrolled releases of nutrients (overload) in the soil, eutrophication, and spread of pathogenic organisms in the soil [79].

Therefore, the companies are advised to exchange information and technology rather than follow a lone wolf modus operandi. Through cooperation, they may synergistically thrive, and consequently, HTC can be consolidated as a relevant technology/player for waste management, renewable energy, carbon removal, and circular economy on a global level.

3.3. Commercial Factors Influencing Successful HTC Development

A multitude of factors contribute to the trajectory of business development. For instance, the presence of clear and conducive regulations promotes investment and innovation while ensuring (e.g., environmental) compliance. Moreover, continuous research and development leading to technological innovations drive efficiency improvements and cost reduction, making the technology more competitive in the market.

A useful tool to understand the potential business opportunities is represented by the SWOT analysis, which is a strategic planning technique used to help identify strengths, weaknesses, opportunities, and threats. Strengths and weaknesses are, respectively, the positive and negative aspects of an industry, while opportunities and threats are external factors that could potentially benefit or hinder the business. A SWOT analysis was hence developed based on the survey's results and on the workshop discussion described. The SWOT analysis is also summarized in Figure 3.

Figure 3. Commercial strengths, weaknesses, opportunities, and threats (SWOT) identified for hydrothermal carbonization development.

Strengths: (1) it has cost-effectiveness in comparison to conventional methods for treating specific waste streams as sewage sludge; (2) HTC can promote the de-centralization of waste management plants, as for instance, with HTC movable plants; (3) it involves a well-established market for different feedstock streams (i.e., sewage sludge) and for different products such as energy (sell price to the grid); (4) HTC products can be used in several different applications, from renewable energy production to agriculture, to other industrial uses, such as filter materials and adsorbents [80] or filling material in composite materials [81,82]; (5) it involves an alternative production of substitute fuel (biocoal) or bio-derived carbon for carbon sequestration purposes, which both could play an important role in mitigating climate change [20]; (6) HTC is considered as an enabling technology with high value for price potential due to its low process severity and low residence times, and to its ability to treat a large variety of feedstocks.

Weaknesses: (1) there are still few industrial-scale HTC plants in operation, a fact that contributes to decrease industrial and banks' credibility; (2) there is a lack of a unique and strong value proposition, which increases adoption resistance both on the technology and on its products; (3) there is a lack of transparency from several HTC companies, which do not disclose information about critical aspects, such as the end-of-waste process, energy balances, the treatments on the HTC gas, or economic factors, impairing the overall process reputation; (4) there is a lack of expertise and skilled human resources to conduct the process; (5) only a few commercialized products based on the HTC-derived reaction have been successfully marketed to date (often buyer skepticism and thus no fixed market price has been established so far) and HTC products have additional often varying properties due to the varying raw materials; (6) in some sectors (waste disposal), traditional methods (such as incineration) are propagated as the only method and maintained without the consideration of sustainability criteria.

Opportunities: (1) it is a new innovative approach for wet residues' (more abundantly available than dry) treatment; (2) it offers a higher competitive advantage potential with respect to conventional technologies and treatment solutions; (3) it involves a large potential market due to broad process applicability; (4) the technology can help to close material cycles (carbon, nitrogen, phosphorus); (5) the law is raising the requirements concerning waste management and promoting circular economy.

Threats: (1) there is an underlying reluctance of stakeholders to embrace a new technology or application; (2) policies and subsidies favor other technologies and make them more profitable than the HTC process; (3) there is an unknown marketability of

HTC products; (4) there are sometimes very long investment periods for existing waste and sewage sludge treatment plants, and therefore little momentum for new approaches; (5) there is waste legislation in various OECD countries that prohibits the use of hydrochar as a valuable material or product straight away, due to the lack of legislation regarding the application of innovative technologies; (6) there is development of a directive in the EU that aims to exclude the use of hydrochar as a sequestration option using elemental carbon in favor of carbon capture and storage (CCS) and direct air capture (DAC).

The cost-effectiveness of hydrothermal processes in comparison to conventional methods plays a crucial role in attracting investments and market adoption. Factors such as feedstock availability, operational costs, and revenue generation greatly influence economic viability. In addition, the public perception of hydrothermal technologies, alongside their acceptance within communities and industries, influences market penetration. Awareness campaigns and effective communication about the technology's benefits are fundamental for gaining public trust and fostering acceptance. The availability of funding from diverse sources, including government initiatives, private investments, and research grants, significantly impacts the scale and pace of business development in the hydrothermal sector. Concurrently, strategic alliances and collaborations within the industry, academia, and government sectors facilitate knowledge exchange, technology transfer, and market expansion, fostering a conducive ecosystem for growth.

Another tool to evaluate commercial factors influencing a successful HTC development is the so-called Porter's Five Forces analysis, which is a framework for evaluating the competitive forces in an industry. These forces include (i) threats of new entrants, (ii) treatment of substitutes' competition, (iii) bargaining power of suppliers, (iv) bargaining power of buyers, and (v) existing industry rivalry [83]. The forces can be high, medium, or low.

The threat of new entrants is defined as high, because of the capital intensity needed to develop the HTC technology, complex and heterogeneous legislative framework, high distribution barriers for HTC products, risk of dumping by existing waste treatment players, and highly skilled human resources required.

Substitutes' competition force is evaluated as medium, because of shelf battles with competing technologies and low buyers' knowledge and authorization/legal difficulties bringing discouraging effects.

The bargaining power of suppliers is estimated to be high because the HTC technology requires specific hi-tech equipment, such as the reactors, and a rise in prices of which can significantly reduce profitability, and because the forward supply chain strongly depends on products' critical mass and quality.

The bargaining power of buyer's force is considered to be medium because of price sensitivity with respect to other treatment alternatives, high potential advantages for HTC application and HTC products, high switching costs for HTC-technology-related services, non-established and broadly recognized prices for the HTC products, such as hydrochar (e.g., HC price: ca. 200 EUR/ton [84,85]). However, the intensity of this force also strongly depends on the type of business model proposed by the HTC company.

The industry rivalry is considered to be medium because there are several companies that propose technologies for the treatment of the feedstocks commonly suitable for HTC. However, the industries of both the sustainable treatment technologies and potentially for HTC products are growing fast.

3.4. Policy Factors Influencing Successful HTC Development

To achieve more successful HTC business cases, a SWOT analysis for policy was also developed based on the survey's results and the results from the above-mentioned workshop. The analysis identified strengths, weaknesses, opportunities, and threats in the area of policy, and these are summarized in Figure 4.

Figure 4. Policy strengths, weaknesses, opportunities, and threats (SWOT) identified for hydrothermal carbonization development.

Strengths: (1) HTC reactors can be built as an extension of facilities already operating, which simplifies the process to obtain the permit that is required, for example, as an extension of a wastewater treatment plant; (2) HTC products can be utilized in a cascade together with well-established technologies, whose products have regulations and are well known in the market, such as HTC liquid in symbiosis with anaerobic digestion to increase biogas production or the HTC char in symbiosis with gasification to sell the produced energy or syngas; (3) there is already legislation concerning HTC in some parts of the world; (4) some products are already commercialized such as fertilizers.

Weaknesses: (1) there are difficulties to obtain a permit to build new HTC plants and connection into the grid; (2) the waste regulations are not updated and not standardized even inside a country (as, for example, in the USA, each State has their own regulation and therefore HTC can be valid in one State but for other States, the law should be created from zero); (3) there are challenges for the commercialization of the products derived from HTC (lack of certificates from products produced specifically from HTC technologies or even the prohibition to use them since they are defined as "waste"); (4) there is an absence of knowledge from politicians and society about HTC, and their lack of time and interest to discuss it; (5) there is the non-existence of lobbying work to dialogue with politicians to create new laws due to the elevated costs (time and resources); (6) there is skepticism toward new technology from lawmakers and society.

Opportunities: (1) HTC for specific feedstocks does not compete with any other technology, for example, sewage sludge: HTC is more efficient than the status quo of incineration; (2) there are climate changes and the urge for new renewable energy and a reduction in greenhouse gas emissions; (3) there is the need to treat wet waste, wastewater, sludges, and digestates in a profitable manner; (4) there is the carbon sequestration ability of HTC, which is similar to the natural way of coal production; (5) there is a recovery of critical raw materials such as phosphorus and closing nutrients' cycle.

Threats: (1) competition exists with other established and accepted technologies such as wind, solar power, anaerobic digestion, or pyrolysis, which have resources for lobbying, and they are involved deep in politics; (2) there are governmental subsidies and regulations supporting other technologies; (3) a stronger lobbying job exists from the well-established technologies.

In the survey, the respondents assured that to overcome threats and barriers, some policies should be changed:

- HTC should be recognized as a valid and sustainable way to sequestrate carbon as an alternative to carbon capture and storage (CCS) and direct air capture (DAC).

- A trading system for carbon sequestration should be set up in addition to the existing CO_2 emissions' one.
- Economical mechanisms should favor the most appropriate process. Therefore, subsidies and other economic supports, such as low-interest loans, should verify which technology brings more environmental benefits.
- The permit process for building HTC plants should be simplified and standardized.
- Regulations to specify minimum requirements for products from HTC should be established.

3.5. Visions and Milestones for HTC Business and Policy

Visions and milestones (MSs) identified during the workshop are displayed in Table 2. The workshop participants developed visions for both the HTC business sector and the policy.

Table 2. Visions and milestones identified for the HTC business and market development and policy.

Sector	Visions	Milestones *
Business and Market	HTC business will cover specific demands in residual feedstock handling, becoming more competitive by dropping in costs through learning curves, having more plants that are successful in operation, and finding new income options	MS1: New businesses should focus on urban residues (e.g., sewage sludge, MSW). MS2: Further businesses will focus on agro-industrial residues (manure, food processing waste, green waste, lignocellulosic residues). MS3: Price of HTC same as the state-of-the-art disposal by 2028 (price = full treatment price, inc. OPEX and CAPEX). MS4: 20% less costly than the state-of-the-art disposal by 2033. MS5: Share of products is 80% fuel and 20% high-valued products by 2030. MS6: 15–20 additional operating plants by 2028. MS7: 50,000 t/day of residual material treated worldwide by 2035.
Policy	VP1: Production of carbon from moist organic residues (with prior carbon binding by photosynthesis)—using HTC techniques and deposition in landfills to sequester the carbon contained in the hydrochar. Process can be accompanied by a digital documentation procedure (e.g., TrustTrail®) to be forgery-proof	MS1.1: Setup of a pilot plant to demonstrate the complete process that is necessary to sequester carbon: collecting biomass, HTC processing, ev. leaching/stripping nutrients (N/P), landfilling. MS2.1: Documentation and generation of CO_2 compensation tokens and developing a marketing mechanism. MS3.1: Acceptance by authorities/stakeholders/NGOs/potential customers that the process (MS1.1) is a valid method for carbon sequestration and offsetting unavoidable CO_2 release.
	VP2: Acceptance of HTC as alternative treatment for wastewater or sewage sludge treatment for extraction of nutrients and reducing water content and accredit hydrothermal treatments (HTTs) as a viable technology toward the green transition by 2035	MS1.2: Foundation of an HTC association with specific working groups. MS2.2: Development criteria and standards for feedstocks and HTC products. MS3.2: Publish a Best Available Technique (BAT) reference document for hydrothermal treatment technologies. MS4.2: Create a database and data standardization to serve as a base for policy formulation. MS5.2: Development of a law for carbon sequestration by means of biochar. MS6.2: Creation of HTC-wikis for dissemination of HTC novelties.

VP: Vision for policy; MS: Milestones; CAPEX: Capital expenditures, defined as the funds used by a company to acquire, upgrade, and maintain physical assets (e.g., property, plants, buildings, technology, equipment); OPEX: Operating expenses, which are shorter-term expenses required to keep a business running (e.g., labor, energy, inputs and raw materials, utilities, taxes and fees, maintenance, depreciation). * The data come from the discussions held during the mentioned workshop and reflect the participants' inputs; no supporting calculations are available.

The identified milestones serve as important targets for HTC business and market development and policy. These milestones provide a timeline for achieving specific objectives and are essential for monitoring the technology progress. The data provided were derived from the inputs of the experts during the brainstorming section of the workshop. The visions and milestones are also presented in timelines in Figure 5 for both business and market (Figure 5a) and policy (Figure 5b).

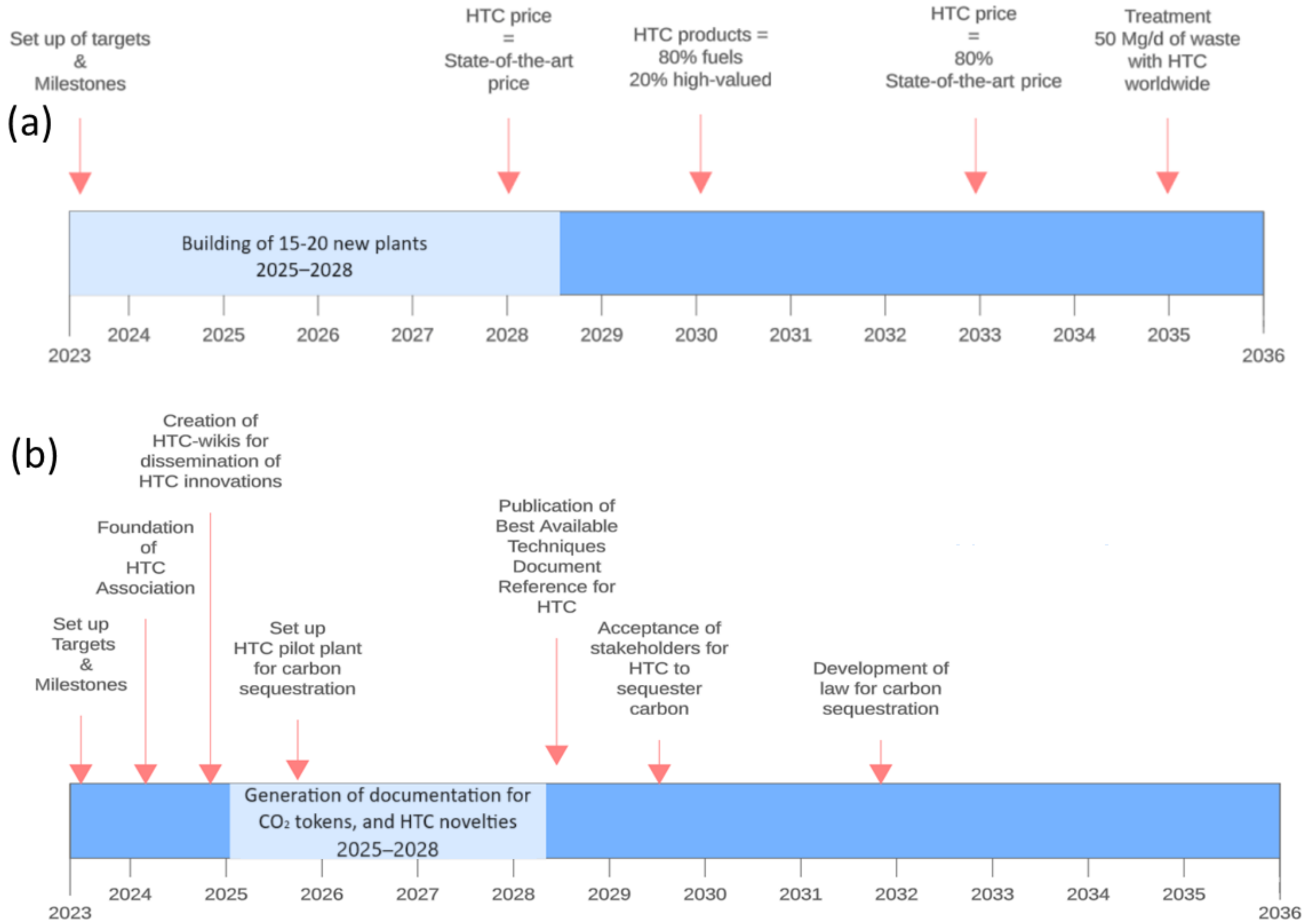

Figure 5. Timelines of visions and milestones for (**a**) business and market and (**b**) policy.

By 2050, the HTC business should cover a wide range of raw materials and develop into a competitive, cost-efficient, and recognized process for managing organic residues, taking a key position in the circular economy for converting wet residues into recyclable materials. Currently, research is actively exploring innovative applications for HTC, including the development of supercapacitors [86,87], the creation of specific catalysts and compounds [88,89], as well as the production of sustainable solar reactors [90] and cost-effective, safe reactors [91]. To bring these innovative applications to the industrial forefront, it is essential to establish and achieve more advanced and realistic short-term goals within the next decade. Indeed, to realize this vision, several crucial steps need to be taken. Based on data from the scientific literature, the HTC process is well established and considered mature for treating municipal residues such as sewage sludge and municipal waste, efficiently handling the current increase in their production. These materials form the initial basis for pilot projects, including implementing a waste-utilization-energy infrastructure. In parallel, product hydrochar must be developed and established as a valid method of carbon sequestration, as this business opportunity could develop soon as one of the most dynamic markets and most internationally scalable business models for the valorization of biogenic wet residues. If this market is developed, numerous plants would be built, and profitability would also be achieved quickly. This would also allow further research to be financed and increase the availability of various plants to conduct technical studies with different substrates, process parameters, and environments. This hydrochar for sequestering purposes could serve as the initial foundation for other successful HTC business operations.

As research progresses and the reputation of the process grows, companies are poised to expand their operations to process diverse materials like agro-industrial residues. This shift will focus less on waste treatment and more on developing new products and reclaiming valuable materials. Based on the discussion opened during the above-mentioned workshop and the current condition of the companies in Table 1, for HTC to be economically competitive, costs must match disposal expenses by 2028, decreasing by 20% within the subsequent five years (by 2033). Considering this progress, by 2030, 80% of HTC products will be used for carbon sequestration or energy production, while the remaining 20% will provide valuable materials. To establish HTC as a prominent process in the business and market landscape, the target for 2035 is to treat 50,000 tons of residues per day worldwide. This target could be significantly higher if hydrochar becomes established as a carbon sequestration tool. These data serve as strategic setpoints aimed at encouraging researchers and stakeholders to adopt and implement HTC systems in the next 10 years (by 2035). This is especially important since from 2035 onwards, around 10 Gigatons of CO_2 per year will need to be permanently removed from the atmosphere to achieve the climate goals. To achieve this, it is both economically and ecologically feasible to store carbon in a stabilized form such as hydrochar or pyrochar underground in landfills or old coal mines, as nature did millions of years ago with lignite in coal mines. Pyrochar has the property of being particularly stable (hundreds up to thousands of years) even in open agriculturally used fields forming the well-known "Terra Preta" [92]. In contrast, hydrochar exhibits lower stability against chemical and biological decay unless it is in a dry form, submersed under water, or further processed by pyrolysis [93]. However, hydrochar holds particular promise over pyrochar owing to its potentially lower cost and relaxed quality requirements, enabling the utilization of a broader spectrum of raw materials, including those available at a negative cost such as sewage sludge and municipal biowaste. This adaptability underscores its appeal for scalable and cost-effective carbon sequestration initiatives. These milestones represent decisive future steps toward realizing this visionary approach. Collaboration among stakeholders, including scientists, business professionals, and policymakers, remains integral for achieving these milestones.

By 2035, the hydrothermal processes (HTPs) (including hydrothermal carbonization, hydrothermal liquefaction, hydrothermal vaporization) are accredited as viable processes toward the green transition. To achieve this accreditation, different milestones should be achieved. The first milestone involves the creation of an HTC association to promote collaboration within the industry, academia, NGOs (non-governmental organizations), government sectors, and all stakeholders that want to be involved and facilitate knowledge exchange, technology transfer, and market expansion. This HTC association will also organize awareness campaigns to disseminate hydrothermal technologies to increase their acceptance within communities and industries. Among other functions, the association will do lobbying work to push for new legislation. Within the activities of the HTC association, other milestones should be achieved before the accreditation of HTPs, and these include (i) publishing a Best Available Technique (BAT) reference document for HTPs, (ii) creating a database and data standardization to serve as a base for policy formulation, (iii) developing HTC-wikis for the dissemination of HTC novelties. From these actions, a reaction from lawmakers is to be expected to develop standards for feedstocks and HTC products and to develop a law or trading system for carbon sequestration.

4. Discussion

Strategies and Actions for Overcoming Barriers

Several barriers pose challenges to the development of businesses in the field of HTC. Regulatory constraints are prominent due to the absence of specific policies and guidelines governing HTC and its derived products. It is critical to establish a robust infrastructure to officially accredit HTC as a thermal conversion process, along with the development of appropriate regulations and guidelines. However, the current state lacks definitive frameworks, creating ambiguity and slowing down the legitimization of HTC in industry standards.

Like other thermal treatments, hydrothermal processes operate at relatively high temperatures, necessitating substantial energy consumption. Yet, significant reductions in energy use are achievable, particularly in a continuous or semi-continuous process where part of the energy in the product stream can be utilized to heat the incoming raw material stream. Further research is needed to quantify these savings. One approach is to produce the required energy by burning hydrochar or syngas obtained through a prior gasification process. Another promising method involves integrating a wastewater treatment plant with a digestion tower for methane production, a combined heat and power (CHP) unit for electricity generation, and utilizing waste heat at a high level (below 200 °C) for the primary treatment of the sewage sludge and digestate. Additionally, recognizing the potential of utilizing waste heat from various sources, such as the hot fumes emitted from the chimneys of thermal plants, further enhances the energy efficiency of the process. This synergistic relationship between processes not only maximizes energy utilization but also minimizes environmental impact by reducing energy requirements significantly.

Market acceptance poses another substantial obstacle. Obtaining recognition and demand for HTC products necessitates intensive awareness campaigns, educational initiatives, and an effective demonstration of the advantages presented by HTC-derived materials. Yet, converting this awareness into widespread market acceptance remains a significant challenge. Collaborative efforts between stakeholders and comprehensive information exchange represent a hopeful guide in overcoming this challenge. However, implementing these collaborations and campaigns may face obstacles in funding and sustained interest from various stakeholders.

Regarding financial matters, securing sufficient investment remains arduous for expanding HTC operations. Despite the apparent potential of HTC technology, gaining financial support, especially from the public and private sectors, remains a challenge. The lack of visibility, ambiguity regarding returns on investment, and industry newcomers' hesitancy to invest due to the technology's early stage pose substantial doubts. Infrastructure development, including the establishment of processing facilities, logistics networks, and ensuring consistent feedstock availability, emerges as a prerequisite for successful HTC business operations. However, the upfront costs and logistical complexities in setting up such infrastructure present formidable challenges, especially for startups or small-scale companies.

The competitiveness of hydrochar as a renewable energy source and a substitute of conventional coal can strongly impact the success of the business. The recent intense oscillations of coal prices can represent both a threat and an opportunity for HTC development. For instance, in 2015, the price of coal was around 50 EUR/ton [3]. In 2021, Bevan et al. [17] concluded that the price of hydrochar was not competitive with coal in terms of equivalent energy. However, between 2021 and 2023, coal prices dramatically increased due to the global energy crisis, reaching values up to approximately 450 EUR/ton, a situation in which hydrochar as a biocoal would be highly competitive [3]. However, in 2023, the coal prices reduced, fluctuating between 150 and 200 EUR/ton in the second semester [94]. Clearly, the significant changes in coal prices will strongly impact the HTC business, but this apparent uncertainty can actually turn into an opportunity for the HTC as an energy vector. Firstly, because it is unlikely that coal prices will decrease in the long term, especially considering the worldwide policies for renewable fuel sources and climate change mitigation, along with a rising cost of CO_2 emission rights. Secondly, the versatility of HTC to multiple feedstocks can be a crucial factor, not to mention the waste management benefits (i.e., environmental and social benefits) [17,84]. This versatility also contributes to the decentralization of the energy matrix, providing more stability and reducing market dependence for individual countries. Finally, the HTC enables not only the energy income but also nutrient recovery (i.e., fertilizers), and other added-value materials. This biorefinery strategy is quite promising to improve plant efficiency and profitability [37,76,95].

Regarding nutrient recovery, serious efforts are being made to recover phosphorus from human urine, boosting a great interest in the development of novel and efficient wastewater treatment processes. For instance, in 2017, Germany enacted a new sewage regulation mandating the recycling of phosphorus from sewage after a 15-year transition period. However, the majority of phosphorus used in agriculture (ca. 80%) is not processed in sewage treatment plants, and the remaining 20% is not fully recovered due to process inefficiencies and economic constraints, making these solutions locally significant [96].

In contrast, secondary P sources for agricultural purposes derived from the energy–food supply chain (e.g., animal slurries and manure, digestate from biogas plants) are a much more relevant nutrient source, consisting of nearly 7 million tons per year, equivalent to around 40% of the total mined P [97,98]. Consequently, they represent abundant resources for the production of circular-based fertilizers.

Therefore, integrating HTC with waste management for nutrient recovery, particularly from agricultural residues, can pave a prosperous way to overcome the imbalanced relationship between increasing nutrient consumption and global supply, as well as mitigating the depletion of global nutrient reserves [98]. This approach could help with attenuating geopolitical tensions and strategically secure fertilizer independence for countries lacking significant mineral nutrient reserves. Notably, over 90% of global phosphorite reserves are concentrated in a few countries (Morocco—70%, China—5%, Syria—3%, Algeria—3%, and with Russia, South Africa, the US, Egypt, and Jordan each accounting for 2%) [96]. Additionally, it could address issues related to the over-fertilization of local fields due to an inadequate utilization of manures and digestates, which face logistical challenges and high transport costs related to their high water contents [99].

In addition to fossil coal substitution, several strategies have been proposed to address the HTC business challenges. Establishing a dedicated professional HTC association seems promising in standardizing processes, sharing best practices, and advocating for HTC recognition. However, such an association's formation and active participation might face challenges due to industry fragmentation and varying interests among stakeholders. Collaboration among stakeholders remains a widely accepted strategy, but the actual execution might face resistance or limited engagement from industry players concerned about revealing proprietary information or facing competitive disadvantages. For instance, in this study from the 24 companies contacted to answer the survey, only 15 were willing to share their information. Research and development initiatives could address critical knowledge gaps and enhance process understanding. Yet, dedicating resources and committing to long-term studies might face financial constraints or a lack of interest from stakeholders uncertain about the technology's long-term viability. Market analyses for HTC products could be beneficial, but the actual market landscape might be unpredictable or volatile. Additionally, identifying viable applications and assessing demand is complex and may not yield expected outcomes due to rapid market shifts or evolving consumer preferences. Policy advocacy and economic assessments present a promising strategy, yet engaging policymakers and regulators in a sector with ambiguous regulations might be challenging. Therefore, convincing legislative bodies about the necessity of specific regulations for HTC and demonstrating its economic benefits might face skepticism or bureaucratic delays.

5. Conclusions and Perspectives

This paper underscored the importance of addressing business and market aspects to unlock HTC's full potential. Of a total of 24 HTC companies identified in the market, 15 answered a survey to understand the status quo of the HTC industry. Most plants are located in Europe (79.2%) as waste management facilities (89%), but also to produce renewable energy (54%) and recover nutrients (58%). Most of the HTC companies already have a fully industrial-scale plant in operation or under construction, indicating that in recent years, the HTC technology is ultimately leaving the lab-scale research level to become an industrially relevant process.

Strengths, weaknesses, opportunities, and threats concerning commercialization and policy in order to push the HTC technology were identified. Additionally, a Porter analysis to identify the competition forces was included. Strategies and actions were proposed, based on the results.

The HTC business sector can overcome barriers, achieve the identified milestones, and contribute to the circular economy by treating a wide variety of feedstocks in sustainable and efficient management, sequestrating carbon, generating renewable energy, and substituting raw materials. Collaboration, standardization, market analyses, and policy advocacy will be crucial in driving the successful commercialization and widespread adoption of HTC in the forthcoming years.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14030541/s1, Section S1: General Information. Section S2: Technical Information of the Company. Section S3: Information about process and plants. Section S4: Policy section (additional section). Section S5: Other (Optional).

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