

REVIEW

Hydrothermal Carbonization of Sewage Sludge: A Pathway toward Sustainable Energy Transition and Regional Development

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ABSTRACT

The transition toward low-carbon energy systems requires technologies capable of converting residual biomass into value-added energy carriers. In this context, hydrothermal carbonization (HTC) of sewage sludge (SS) has emerged as a promising pathway for producing solid biofuels while addressing persistent challenges in waste management and sanitation. This study evaluates the technological basis, environmental implications, and regional development potential of SS-HTC within renewable energy and decarbonization strategies. HTC enables the direct processing of wet sewage sludge, avoiding energy-intensive drying steps and generating a carbon-rich hydrochar with reduced moisture content and improved fuel properties compared to the raw material. In addition to the solid fraction, the process produces a nutrient-rich liquid stream that can be further valorized, supporting circular resource management and integrated waste-to-energy systems. Although the estimated global production potential of SS-derived hydrochar (approximately 45 million dry tons) is insufficient to replace fossil coal on a large scale, its targeted use in selected industrial sectors can partially substitute mineral coal, contributing to greenhouse gas mitigation and incremental decarbonization. Beyond its technological advantages, SS-HTC offers opportunities for regional development, particularly in areas with expanding wastewater treatment infrastructure. Integrating HTC into sanitation systems enables localized biofuel production, reduces dependence on imported coal, and supports industrial diversification. The State of Paraná, Brazil, with a population of 11.5 million and sanitation coverage of approximately 81%, exemplifies a fa-

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avorable context in which SS-HTC can enhance regional competitiveness while advancing environmental sustainability and socio-economic development within the broader low-carbon transition.

Keywords: Circular Economy; Waste-to-Energy Systems; Energy Transition

1. Introduction

The race to transition to a low-carbon economy requires assertiveness and a considerable measure of boldness. In many cases, the driving force of the Quadruple Helix—academia, industry, government, and society—is essential to the success of this process, particularly when regional development and transition to a greener economy are envisioned^[1-4]. This transition entails integrating emerging technologies, strengthening innovation ecosystems, and enabling the creation of new companies capable of translating scientific advances into sustainable economic growth.

In the context of shifting from fossil fuels to renewable and sustainable alternatives, the escalating impacts of global warming—driven by rapidly rising greenhouse gas (GHG) concentrations—have intensified the urgency of this transition. Although the underlying causes are well understood, such as anthropogenic activities rooted in a global dependence on fossil fuels and an unsustainable economic model in which highly developed nations maintain patterns of excessive and unconscious consumption^[5], the Quadruple Helix still does not operate with the intensity required to drive the necessary innovations. Consequently, investing in the development of alternative technologies capable of partially replacing major GHG emission sources is imperative to mitigate climate change and steer the planet back toward a viable trajectory while time still permits effective action.

However, the road is long and full of obstacles. On the one hand, there is no shortage of calls for a greener mindset and signing sessions of important documents—such as those established during the iconic Paris Agreement in 2015—that shed light on the need for concrete actions to guide the planet toward a low-carbon economy. On the other hand, several factors can contribute to the slowness of the low-carbon transition. Some of these include resource availability, the costs of implementing and maintaining innovative technologies, employability,

the assertiveness of decision-makers, and a bit of political will. This hazy scenario is more than enough to overshadow the promise of green fuels and disappoint those who are more optimistic about the low-carbon transition process. Therefore, it is necessary to intensify efforts and mobilize all sectors of society, along with a wide range of technologies capable of contributing to global decarbonization, engaging the Quadruple Helix in a coordinated effort to increase our chances of succeeding in this race.

Meanwhile, thousands of tons of fossil fuels are burned every day, invariably casting a very dense smoke over the global environmental scene. In 2023, the world consumed around 505 exajoules (505×10^{18} J) of fossil fuels, which accounts for 81.5% of global energy consumption^[6]. The situation becomes even more concerning when coal, considered one of the dirtiest fuels, appears as the second-largest global energy source, representing 27% of the global energy matrix (GEM)^[7], 60% of China's electricity supply^[8], and reaching a new global all-time consumption of 8.70 billion tons^[9]. Despite the efforts of world leaders and remarkable actions to increase the share of renewable fuels in the GEM, some countries still display a deep dependence on this type of high-environmental impact fuel.

In Brazil, for example, which has one of the greenest energy matrices on the planet, with approximately 45% coming from renewable sources (compared with an average of only 15% for the rest of the world), coal is still present^[10]. In 2023, coal and its derivatives were responsible for producing 10.4% of the country's electricity in thermal power plants^[11]. At first glance, this is a relatively low percentage and would reinforce the image of a well-established green energy matrix. However, coal emissions accounted for 14% of CO₂ emissions from the Brazilian electricity sector^[12], reflecting the country's economic vulnerability, which is not self-sufficient in its production and must rely on periodic imports, reaching 16 million tons in 2023^[13].

Norway has an even greener energy matrix, with 90% of its internal demand supplied by hydroelectricity^[14]. In addition, it is one of the largest petroleum producers worldwide and, in 2023, imported 515 thousand tons of coal to meet its internal demand, especially for the iron and metals industries^[15]. Although coal remains part of the energy matrix of most countries, some have shown a significant drop in coal consumption over the last two decades, such as the European Union, Canada, and Australia. On the other hand, in East Asia, es-

pecially in China, coal consumption has been increasing substantially. **Figure 1** shows coal consumption for the largest consumers in the world, and two aspects raise concern^[16]. First, China has extremely high coal consumption, and second, its consumption has increased more than threefold over the last 23 years. Other Asian countries, such as India and Indonesia, also show sharp increases in coal consumption, although at much lower absolute levels.

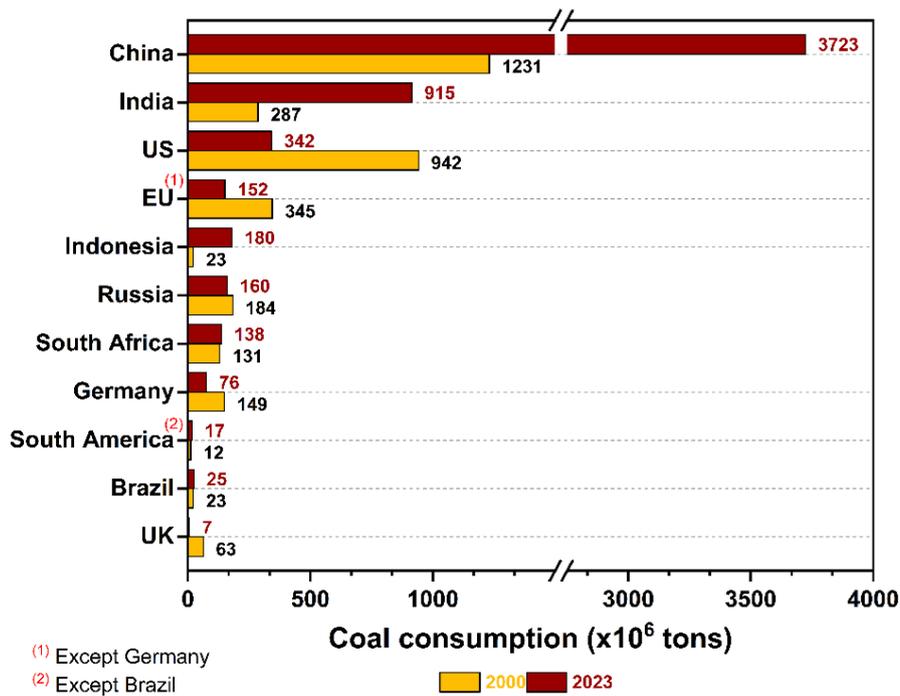


Figure 1. Comparison of coal consumption in 2000 and 2023 for the world’s largest consumers and selected reference countries.

Source: The values for tons of coal were obtained based on units and conversions available on National Academies^[17].

Coal has been brought into the spotlight because it is a widely used solid fuel that raises serious concerns. Furthermore, it is often considered the dirtiest fuel due to its high capacity to release a series of environmental pollutants, such as GHGs (CO₂, SO₂, and NO_x), particulates (fly ash and bottom ash), and heavy metals (mercury, lead, chromium, and cadmium)^[18].

The so-called new phase of globalization is more attuned to sustainability and net-zero goals. The industrial innovation process toward biofuel production, which embraces the use of renewable sources and the waste-to-energy concept, is welcome and expected to endure for the long term. Moreover, technologies that operate within the concept of open-cycle recycling, based on

the use of residual biomass to produce biofuels, can generate positive impacts across various production chains.

One representative example is the set of thermochemical technologies that can be applied to treat residual biomass generated in large urban centers and convert it into biofuels and other bio-products^[19]. This type of approach is especially favorable because it can address important issues related to the quality of life of communities, particularly those in vulnerable situations. Such technologies are fundamental for keeping the concept of sustainable development on the radar and honoring the foundations of this model outlined in the “Our Common Future” report and other reference documents^[20].

The following sections provide an overview of sewage sludge as feedstock, the hydrothermal carbonization process as a key technology for bio-based waste valorization, and the potential impact of this strategy on the regional development of Paraná State, Brazil. To struc-

ture the discussion presented in this critical review, a theoretical framework is proposed (**Figure 2**), illustrating the interactions between sewage sludge valorization via HTC, energy transition pathways, and regional development within a Quadruple Helix system.

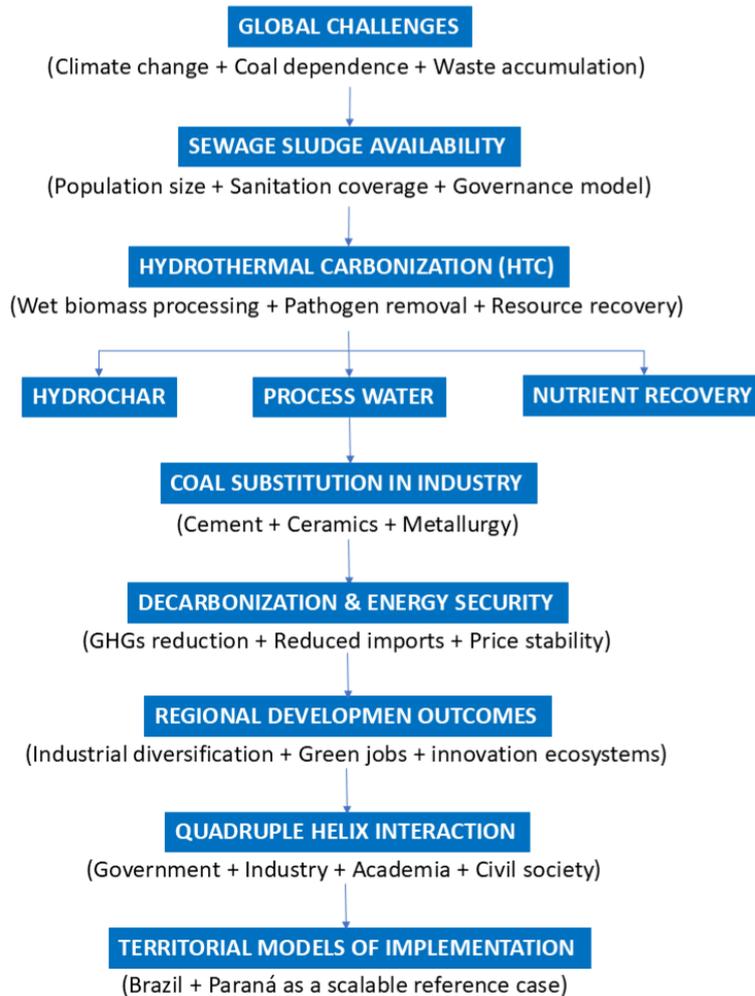


Figure 2. Theoretical framework diagram illustrating the role of hydrothermal carbonization (HTC) of sewage sludge within the sustainable energy transition and regional development context.

2. Green Innovation Based on Waste-to-Energy Concept

In the last few decades, there has been a strong effort to increase the share of biomass-based fuels in the GEM. Although this strategy results in biofuels essentially composed of hydrocarbons, biomass is an important resource for global decarbonization because emissions of carbon-based gases can be considered neutral or even negative^[21].

Among the various types of available biomass,

sewage sludge (SS) presents remarkable potential as a renewable source and fits well within the waste-to-energy concept for biofuel production. SS is the residual biomass produced in wastewater treatment plants (WWTPs) as a result of conventional domestic sewage treatment. Although SS is sometimes underestimated by generators and even neglected by authorities in many countries, it is most often disposed of in landfills^[22]. This means that environmental laws are generally respected; however, the most concerning aspect is that such a valuable biomass is simply not being used for en-

ergy or other valorization purposes.

In this context, SS has been considered a major environmental problem. Due to its high daily production, it is estimated that more than 45 million dry tons of SS are produced annually worldwide^[23]. However, because SS production depends sensitively on wastewater generation, collection, treatment, and reuse, and because these stages can show significant fluctuations in reported data, some estimates suggest a much higher production volume, potentially exceeding 1 billion dry tons per year. An interesting study published by Jones et al. (2021) helps support this perspective^[24]. The authors analyzed several datasets using different regression models to estimate the amount of wastewater produced, collected, treated, and reused worldwide based on information from global organizations, such as the Food and Agriculture Organization (FAO), Global Water Intelligence (GWI), United Nations Statistics Division (UNSD), and Eurostat. This work is highly comprehensive and provides valuable information, including the estimate that global wastewater production could reach up to $359 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$, of which 63% ($225 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$) would be collected and 52% ($188 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$) would be treated^[24].

Considering the volume of wastewater that can be treated, the average amount of SS produced per volume of wastewater treated in a typical WWTP (1.0–2.0%)^[25], and the average density of SS ($\sim 1.40 \text{ ton m}^{-3}$)^[26], the global potential for SS production could reach 3.9 billion wet ton yr^{-1} or 0.8–1.2 billion dry ton yr^{-1} . These numbers are very impressive because they reflect both the scale of the SS problem and its latent potential as a source of renewable energy.

SS production depends on several factors, but the population size and effective access to sewerage systems are key indicators of the potential in a given region. The significant annual volume of SS, along with ongoing uncertainties about the best disposal practices, raises concerns about the sustainability of the current predominant model. In addition to the challenge posed by high SS volumes, sewerage systems (collection and treatment) do not cover the entire population, an unfortunate reality that disproportionately affects developing countries^[27].

In general, populated areas offer the greatest poten-

tial for installing industrial units specialized in the use of SS in a combined approach with WWTPs. This can be advantageous, considering that these same regions tend to have higher levels of industrialization and a growing demand for energy. Moreover, in many developing countries, industrialization is not synonymous with income distribution, and thousands of people may live with severely limited access to sanitation services. Therefore, an increased demand for SS as a feedstock for biofuel production could attract the attention of stakeholders from both the public and private sectors, encouraging the expansion of the sewerage system of a given locality—ultimately, a win-win situation that positively affects the global energy matrix and supports human dignity.

Beyond landfill disposal, SS has been treated via incineration and evaluated as a soil amendment^[28]. However, the typical moisture content of 80–85 wt.% remaining after centrifugation or filtration represents a significant drawback for achieving energy efficiency in incineration technologies and maintaining favorable costs in soil application. Wet SS generally requires stabilization, thickening, dehydration, and drying, and these operations introduce costs that may be prohibitive for large-scale implementation. Despite the recovery of thermal energy during incineration, its potential to generate toxic emissions limits its widespread adoption. When used as a soil amendment, SS also presents vulnerabilities related to the presence of pathogenic microorganisms that remain viable after the conventional WWTP process. For these reasons, alternative technologies capable of processing wet SS while ensuring complete pathogen degradation can help address the continuous generation of SS and offer a promising renewable energy source.

Additionally, SS exhibits interesting physicochemical characteristics that make it a strong contender in the race toward a low-carbon economy (**Figure 3**). Although SS may show significant chemical heterogeneity due to factors such as population consumption patterns, sewerage system isolation, type and efficiency of treatment, residence time in primary decanters, and desander performance, among others, its carbon content, which usually ranges from 30 to 70 wt.%, is consistently high enough to enable its use in an energy recovery process^[29,30].

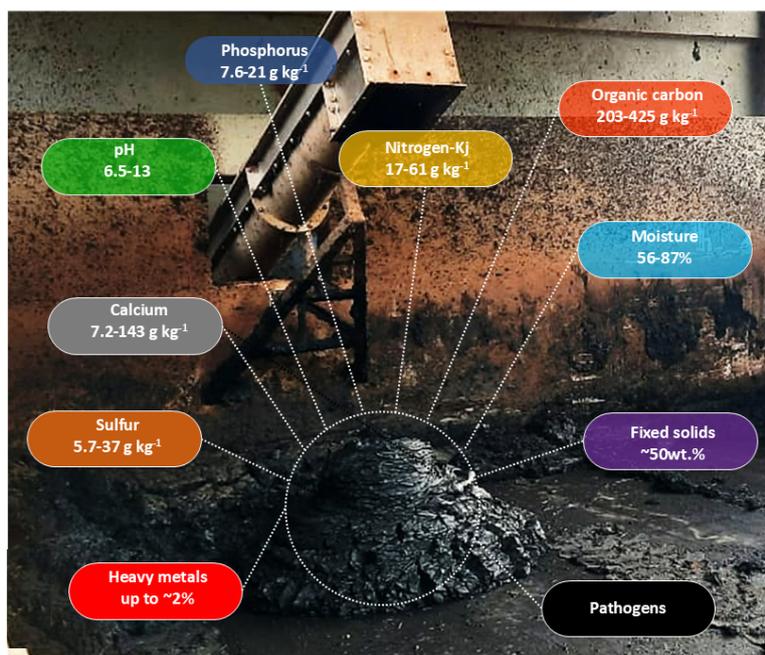


Figure 3. Composition of a typical Brazilian SS obtained by combined aerobic and anaerobic routes after centrifugation step in a conventional WWTP.

This closer examination of SS allows us to recognize that it holds substantial potential as a renewable source capable of increasing the share of biomass in the GEM. Indeed, the combination of SS with an appropriate processing technology can greatly advance our understanding of how to harness the potential of this continuously generated waste stream as a viable candidate to support the coal phase-out and promote low-carbon transition.

3. Hydrothermal Carbonization of Sewage Sludge

As previously mentioned, to properly manage sewage sludge (SS) and harness its full potential, the selected technology must be capable of processing wet biomass and ensuring complete pathogen degradation. Moreover, it should enable the production of value-added products while exhibiting high energy efficiency.

Hydrothermal carbonization (HTC) is an environmentally friendly technology recognized as an excellent alternative to conventional strategies for SS treatment. It belongs to the family of thermochemical technologies, and its main advantage lies in the fact that biomass processing occurs in the presence of water^[31], unlike other processes such as pyrolysis and gasification. This charac-

teristic is particularly advantageous for SS management, as the current approach adopted in most wastewater treatment plants (WWTPs) involves drying the sludge to reduce its volume prior to disposal; however, this step significantly increases energy demand (often from non-renewable sources) and operational costs^[32].

HTC is carried out in high-pressure reactors under subcritical water conditions, typically at temperatures ranging from 180 to 250 °C and autogenous pressures between 20 and 30 bar. The presence of water is essential to drive multiple chemical reactions, including hydrolysis, dehydration, decarboxylation, condensation, polymerization, and aromatization, among others^[33].

Under these conditions, one of the main products of sewage sludge (SS) hydrothermal carbonization is the solid phase known as hydrochar, typically a peat-like material ranging in color from dark brown to black. HTC also generates two additional phases, which are not discussed in detail here but are illustrated in **Figure 4**^[34]. Briefly, the process produces additional gaseous and liquid phases. The gaseous phase consists predominantly of carbon dioxide with minor amounts of other gases, whereas the liquid phase is an aqueous stream enriched with nutrients such as phosphorus, ammoniacal nitrogen, and carbon-based organic compounds originating

from the SS. Trace levels of heavy metals may also be present in the liquid phase, although typically at very low concentrations.

Hydrochar has the potential to replace coal in various industrial processes; however, like any technology, HTC presents limitations that are closely linked to a highly sensitive energy balance. Hydrochar is inherently a wet product, and its surface properties can be tuned to be either hydrophilic or hydrophobic depending on the experimental conditions employed^[35]. This characteristic strongly influences the overall energy balance of the process, as a substantial amount of energy is required during the drying step to convert the wet solid phase into a dry solid fuel following thermochemical con-

version. In fact, HTC requires two major thermal energy inputs that account for approximately 80% of the total energy consumed in a batch process, with nearly all remaining energy expenditure associated with the drying stage. In general, hydrochars produced under acidic conditions tend to exhibit more hydrophobic surfaces, enabling shorter drying times and lower energy demand. This condition can be achieved by using mineral acids, acidic biomasses, or other acidic wastes in a configuration known as co-hydrothermal carbonization (Co-HTC)^[36]. Regarding the energy required for heating, short reaction times and operational temperatures near the lower limit of the HTC range (180 °C) can also contribute to improved energy efficiency.

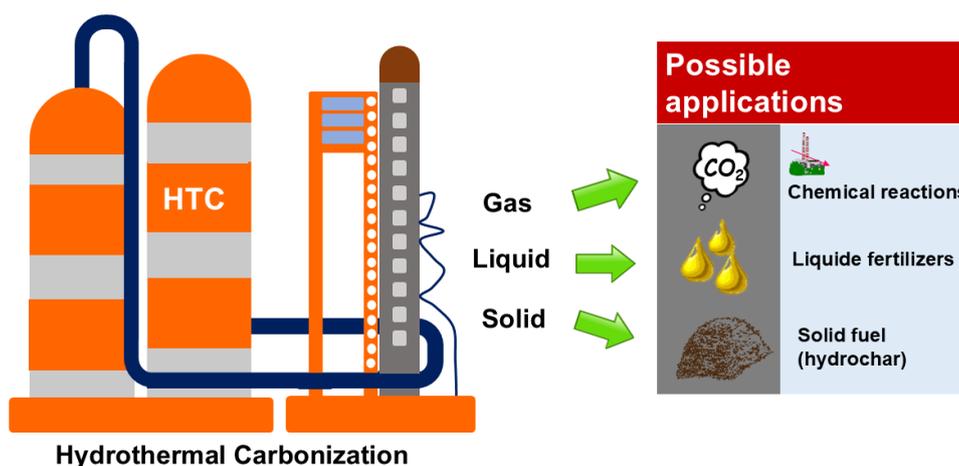


Figure 4. Perspective of bio-products derived from HTC technology using SS as a waste biomass source and their potential applications.

Source: Based on Martins et al.^[34].

Another fundamental aspect concerns the composition of the biomass. In many wastewater treatment plants (WWTPs), high-performance grit removal systems are absent, allowing mineral particles transported through the sewer network to enter the treatment reactors along with the sewage. Because these minerals are chemically and biologically stable, they remain largely unaltered and may account for approximately 20–60% of the dry mass of sewage sludge. These undesirable mineral fractions—primarily silica, kaolinite, and alumina^[37]—do not undergo chemical transformation during the residence time in the high-pressure reactor, thereby reducing the heating value of the resulting hydrochar and increasing its ash content.

The treatment pathway applied to SS in WWTPs also influences the heating value of the hydrochar. Typically, WWTPs employ aerobic and anaerobic processes alternately to maximize organic matter degradation; however, depending on plant configuration and the characteristics of the incoming sewage, the selected route may yield sludge with distinct degrees of stabilization. Less degraded sludge generally retains a higher fraction of carbon-based compounds, which in turn contributes to enhanced hydrochar heating values.

Although these variables can be optimized or improved through equipment upgrades and process innovations, even under the current operational conditions of conventional WWTPs, SS-derived hydrochar

commonly exhibits heating values in the range of 10–20 MJ kg⁻¹ [38], or even higher when co-HTC strategies with other biomasses are applied [39]. These values approach those of several commercial coal types. Coal is typically classified according to its carbon content and moisture level, with heating values ranging from approximately 15 MJ kg⁻¹ for peat to 32–33 MJ kg⁻¹ for anthracite. Intermediate grades also exist, such as sub-bituminous coal, which typically falls between 18 and 23 MJ kg⁻¹ [40], and accounted for about 46% of total U.S. coal production in 2022 [41]. The heating value of SS-derived hydrochar can be further increased by removing non-combustible mineral components such as silica and aluminosilicates; however, performing this separation after sludge formation is challenging, and pre-removal is generally advisable.

Under mild operating conditions, HTC often demonstrates favorable energy efficiency [42], meaning that the energy contained in the produced hydrochar exceeds the energy consumed during the process. Indeed, achieving positive energy efficiency is even more challenging when the biomass feedstock is SS, mainly due to the high content of inorganic constituents in its composition. This type of residual biomass is particularly rich in minerals such as silica (SiO₂), alumina (Al₂O₃), calcium oxide (CaO), iron oxide (Fe₂O₃), phosphorus pentoxide (P₂O₅), and magnesium oxide (MgO) [43]. During the HTC process, this inorganic fraction, commonly referred to as “ash”, tends to concentrate in the hydrochar, leading to a substantial increase in ash content and a proportional reduction in volatile matter and total carbon contents, ultimately resulting in a lower calorific value of the produced hydrochar [44]. Previous studies indicate that ash contents in hydrochars derived from SS, often regarded as an undesirable fraction, can range from 19 wt.% to as high as 87 wt.%, depending on the initial mineral composition of the sludge and the applied hydrothermal conditions [44–46]. Such accumulation of inorganic matter markedly compromises the energetic applicability of hydrochar, as elevated ash contents promote slagging and fouling phenomena, increasing the risk of deposit formation and reducing overall thermal efficiency [46]. Studies on HTC indicate that the higher heating value of hydrochar derived from SS typically ranges from 11 to 22

MJ kg⁻¹ [38,45], and may reach values close to 26 MJ kg⁻¹ under optimized experimental conditions [47]. This wide variability highlights that the energetic performance of hydrochar is strongly dependent on process operating conditions, including the biomass-to-water ratio, temperature, and residence time, as well as on the initial composition of the biomass. The interaction among these parameters governs not only the carbonization yield but also the accumulation of inorganic matter in the solid product.

Another important feature of HTC technology is its strong ability to eliminate pathogens present in sewage sludge [48]. Additionally, the incorporation of cellular material from inactivated microorganisms into the carbonaceous matrix contributes to increased carbon content in the final product.

Typically, the mass yield of an HTC batch process ranges from 40% to 60%, depending on the experimental conditions and the characteristics of the SS. A simple estimate can be made using global SS production: assuming a worldwide annual production of 1.0 billion dry tons of SS, approximately 400–600 million dry tons of hydrochar could be generated and made available for use. This corresponds to roughly 5% of the total coal consumed worldwide in 2023 (8.70 billion tons) and could avoid emissions on the order of 23.5–26.1 billion tons of carbon dioxide equivalent (CO₂e)—approximately ten times Brazil’s CO₂e emissions in 2022 [49].

HTC technology applied to SS treatment for hydrochar production has significant potential to replace coal in the global energy mix (GEM). However, to advance in the race toward decarbonization, HTC must rely on sustainable, renewable energy inputs and deliver high energy efficiency such that the energy produced exceeds the energy consumed during processing. This positive balance could enable countries with high SS generation (due to large populations and extensive sanitation coverage) to incorporate hydrochar as a renewable solid fuel within their energy matrices. Such a perspective—viewing SS as a valuable feedstock for biofuel production—could catalyze a new drive toward universal sanitation coverage.

The transition to a low-carbon economy is marked by strong complementarities among different biofuel

types, largely because their production processes are energy-intensive and require support from complementary energy sources. Although several biofuels—such as biogas, biosyngas, biodiesel, ethanol, and biochar—could potentially replace coal, hydrochar uniquely combines technical performance, relative production simplicity, and strong social benefits.

4. A Key Technical Challenge in Sewage Sludge HTC

Hydrothermal carbonization technology and sewage sludge together constitute a highly promising combination for renewable solid-fuel production. To advance their contribution within the GEM, it is essential that both evolve in parallel with complementary bio-fuel technologies. Although individual technologies may

demonstrate superior performance under specific conditions, their collective development is necessary to achieve a meaningful and sustained impact on decarbonization efforts. Ultimately, the central objective is to accelerate the global transition away from coal dependence.

The primary limitation is that the current global capacity for treatable sewage sludge and the corresponding potential hydrochar production remain far below the substantial demand for coal (**Table 1**). Nevertheless, HTC's application to SS can still contribute meaningfully to the gradual phase-out of this carbon-intensive fuel. In this context, the inherently slow pace of transition within the global energy matrix may provide an opportunity: it allows policymakers to better recognize the urgency of expanding sanitation infrastructure while giving the energy sector sufficient time to integrate HTC technology effectively.

Table 1. Global overview of sewage sludge production and coal demand in major consuming countries in 2023.

Country	SS Production Capacity ($\times 10^6$ t) ^a	Coal Consumption in 2023 ($\times 10^6$ t) ^b	Relative Consumption (%)
Australia	0.41	51.4	0.80
Brazil	2.5	19.5	1.28
China	11.2	3137.0	0.35
Colombia	0.15	5.3	2.83
EU	9.25	187.0	4.9
India	4.36	750.0	0.58
Japan	2.2	154.8	1.43
Mexico	0.11	9.0	1.22
UK	1.25	6.2	20.1
US	4.96	279.0	1.78
Total	36.3	4599.0	

Note: ^a and ^b based on data available in Feng et al. [50] and Our World in Data Home Page [16], respectively.

Table 1 indicates that the current availability of sewage sludge (SS) for treatment is insufficient to meet even 1% (0.87%) of the global coal demand. To raise this contribution to approximately 5%—a level consistent with the estimated global capacity for collecting and treating domestic wastewater—a substantial expansion in sanitation service coverage would be required. China and India dominate the global scenario, each with a population of roughly 1.4 billion. China generates the largest annual volume of SS worldwide (11.2×10^6 t) but simultaneously exhibits the highest coal consumption (3137×10^6 t; 65.3% of global use). With sewerage systems covering about 65% of its population, China could significantly increase the volume of SS available for HTC; however, this expansion would still fall short of meeting

its exceptionally high internal coal demand. India displays a similar pattern: coal consumption has sharply increased, reaching approximately 750×10^6 t yr⁻¹, while sanitation coverage remains limited to only 20–30% of the population. Given its demographic magnitude, India has a key role in the global landscape, although, like many developing countries, it faces substantial challenges in achieving universal access to high-quality public services.

In contrast, the United Kingdom exhibits a relatively favorable ratio between SS production and coal dependence, with SS corresponding to nearly 20% of its coal consumption. Nonetheless, with more than 97% of its population already covered by sanitation services, the UK is unlikely to experience significant future

growth in SS generation. Brazil presents three notable characteristics: substantial internal pressure to improve sanitation coverage, a large population (211 million), and comparatively low coal consumption, approximately half of which is supplied by imports. This combination positions Brazil as a country with considerable potential to incorporate hydrochar from HTC into its energy matrix, thereby reducing coal use and import dependency.

Incorporating hydrochar into national energy portfolios could influence the international fuel supply chain. Although the global coal trade is well established, the introduction of tens of thousands of tons of hydrochar into international markets could induce substantial structural changes. Two intuitive business models emerge from this scenario. In the first, countries with high SS productivity export hydrochar to less productive nations in exchange for carbon credits. This approach would reduce coal import operations and could contribute to a global decline in coal prices. Under such a model, up to 5% of coal consumed in the global energy matrix (GEM) could be replaced without constraining economic growth in China or other coal-dependent economies. Over time, as worldwide SS collection and hydrochar production expand, further coal substitution and additional greenhouse gas (GHG) reductions would be achievable. Although there is no formalized international arrangement that operates exactly according to the model described above, there are international mechanisms, negotiations, and instruments that are conceptually compatible and could support this type of model in the future, such as, (i) Carbon markets and international offsetting mechanisms, based on Article 6 of the Paris Agreement which allows for the international transfer of mitigation outcomes^[51]; (ii) International trade in biomass and biofuels, for example, global flows of biomass pellets involving North America and Europe, driven by climate policies^[52]; and (iii) Sectoral offset initiatives and industrial decarbonization, in which carbon-intensive sectors (cement, steel, ceramics) are exploring alternative fuels and compensation mechanisms, create a potential space for hybrid models of renewable fuel plus carbon credit^[53].

In the second model, countries retain their entire hydrochar output for domestic use, thereby reducing

coal imports without engaging in carbon credit transactions. This strategy would also exert downward pressure on international coal prices, decrease GHG emissions, and additionally reduce maritime shipping activity while lowering the economic vulnerability of coal-importing nations^[54,55].

HTC of SS represents only one among several technological pathways toward decarbonization. A diverse range of biomass sources could be integrated into HTC systems, further enhancing their capacity to support the transition toward a low-carbon global energy matrix. Unlike most feedstocks, however, SS offers a unique social dimension: its valorization through HTC directly incentivizes the expansion of sanitation infrastructure, thereby delivering substantial societal benefits to communities that currently lack adequate wastewater services.

5. A Pathway for Renewable Bio-Products and Regional Development

Brazil has strong potential to become a leader in the global energy transition. Several aspects are fundamental to this, including its high share of renewable electricity, diverse renewable resource base (hydropower, wind, solar, biomass, and biofuels), the rapid expansion of wind and solar capacity alongside hydropower, a well-established bioenergy and biofuels industry, and significant economic opportunities enabled by the country's overall "green-energy readiness"^[56]. These advantages are closely aligned with the interests of the actor and stakeholders that constitute the Quadruple Helix framework in Brazil.

Especially in Paraná state, which is one of Brazil's twenty-seven federative units, located in the southern region of the country and home to approximately 11.5 million inhabitants, the industry, academia, government, and civil society have demonstrated successful experiences. According to public agencies, about 80.8% of the state's population is served by sanitation systems and has access to treated wastewater^[57]. The Paraná Sanitation Company maintains a dominant position in the provision of sanitation services to the population and at

least one WWTP in 345 of 399 municipalities dedicated to wastewater treatment and a current annual production of 24 thousand tons of sewage sludge (dry base)^[58]. This context positions Paraná as a relevant case study for evaluating innovative sludge management strategies, especially technologies capable not only of mitigating environmental impacts but also of generating value-added bio-products aligned with regional development priorities.

For Paraná, the integration of HTC into the existing sludge management portfolio represents a strategic opportunity. As in most regions, the utility responsible for wastewater management in Paraná employs multiple sludge disposal routes, including agricultural land application after appropriate stabilization and hygienization, drying and combustion to obtain thermal energy, and other forms of conditioning depending on site-specific viability and environmental licensing^[59]. Although these strategies comply with national regulations and contribute to waste minimization, they exhibit inherent limitations—particularly the energy demand associated with drying, the restrictions on agricultural use due to contaminants, and the logistical burden of transporting large volumes of wet sludge^[60]. In this setting, HTC offers multiple advantages by simultaneously reducing mass and moisture, stabilizing contaminants, and generating a versatile solid bio-product^[61-63].

The potential impact of HTC implementation in Paraná can be analyzed from three interconnected perspectives: technological feasibility, environmental benefits, and regional socio-economic development aligned with state-level innovation policies.

5.1. Technological Feasibility and Integration into Existing Sanitation Infrastructure

Paraná's highly structured wastewater treatment network creates favorable conditions for the deployment of HTC facilities, with the Quadruple Helix framework fostering the development of novel technologies. With nearly universal sewage collection and high rates of wastewater treatment, the state manages substantial annual quantities of sewage sludge distributed across numerous WWTPs. This existing infrastructure provides a

reliable and continuous feedstock stream, a prerequisite for sustaining HTC operations at an industrial scale.

The feasibility of HTC integration is further enhanced by the centralized governance model used by the sanitation company. A single operator responsible for both wastewater treatment and sludge management simplifies logistics, decision-making, and long-term strategic planning^[64]. HTC units could be incorporated into existing large or medium-sized WWTPs or deployed in regional hubs receiving sludge from neighboring municipalities. This modularity supports flexible implementation strategies, ranging from pilot-scale demonstration units to full-scale continuous reactors depending on local needs and available infrastructure^[65].

5.2. Environmental and Resource Recovery Benefits

HTC offers multiple environmental advantages relevant to Paraná's sustainability targets. As discussed in previous sections, the process drastically reduces sludge volume—typically by more than 50%—and produces a hydrochar with stabilized organic matter and immobilized heavy metals^[66-68]. Such stabilization minimizes environmental risks associated with land application or long-term storage. Moreover, hydrochar's improved dewaterability and lower moisture content reduce transportation and handling costs, leading to lower greenhouse gas emissions across the sludge management chain^[31].

One of the most significant environmental benefits concerns potential carbon sequestration and the circular use of nutrients. Hydrochar retains a substantial fraction of the carbon originally present in the sludge in a recalcitrant form, providing opportunities for long-term carbon storage in soils or for controlled release in agricultural systems. Depending on process conditions, hydrochar may also exhibit enhanced sorption properties, making it suitable as a matrix for pollutant removal in water treatment or as a soil amendment capable of improving nutrient retention and soil structure^[27].

The liquid phase produced by HTC contains soluble organics, ammonia, and phosphate, which can be recovered through integrated systems such as struvite precipitation, membrane concentration, or anaerobic digestion.

Given Paraná's strong agricultural sector—particularly grains, livestock, and poultry—nutrient recovery from sludge-derived process water aligns with circular economy principles and reduces dependence on imported mineral fertilizers.

Lastly, HTC reduces pathogen loads due to its elevated operating temperatures and reaction times, offering a hygienically safe bio-product that meets or exceeds regulatory thresholds. This feature expands the range of permissible end uses for treated sludge compared to conventional biological stabilization processes, which may not achieve the same levels of sanitization.

5.3. Potential for Renewable Bio-Products and Industrial Innovation

HTC positions Paraná to explore a diversified portfolio of bio-products that support local industries and research agendas, as integral components of the Quadruple Helix system. Hydrochar from SS can be used as a solid fuel with energy content comparable to low-grade coals. This property is particularly relevant given that one of the priority areas identified by the Paraná Council of Science and Technology is the promotion of renewable and sustainable fuels. By substituting coal or other fossil-based fuels, hydrochar contributes directly to GHG mitigation and supports industrial decarbonization strategies in sectors such as cement, ceramics, and metallurgical processing^[69].

In addition to its direct use as a fuel, hydrochar serves as a precursor for advanced materials. Chemical activation can transform hydrochar into high-surface-area activated carbons suitable for the adsorption of contaminants in water and gas purification systems^[70]. Similarly, hydrochar can be engineered to function as a catalyst or catalyst support, particularly for environmental catalysis, biomass upgrading, and thermochemical conversion routes^[71]. These value-added applications increase the economic viability of HTC and stimulate technological innovation within the state's research institutions and industrial clusters. Particularly in the state of Paraná, whose economy is strongly based on agribusiness, HTC of SS could serve as a springboard for the sustainable development of its industrial sector and enhance the state's integration into Brazil's industrial land-

scape.

The process water generated by HTC also presents opportunities for biofuel production. Its high concentration of soluble organics makes it an ideal substrate for anaerobic digestion, potentially increasing methane yields compared to conventional sludge digestion^[72]. Integrating HTC with biogas systems would help Paraná expand its already growing biogas and biomethane sector, reinforcing state-level sustainability goals and contributing to energy diversification in rural and urban contexts.

5.4. Regional Development and Alignment with Public Policy Priorities

The operation of the Quadruple Helix system can be observed beyond the technical and environmental attributes. HTC has the potential to significantly influence regional development in Paraná. The state maintains a strong commitment to technological innovation, clean energy, and sustainable industrial growth, as evidenced by its strategic priority areas defined by the Council of Science and Technology. Among these priorities, the development of renewable and sustainable fuels is highlighted as a central axis for fostering economic competitiveness and environmental resilience^[73].

The deployment of HTC facilities can stimulate regional value chains by creating demands for engineering services, equipment manufacturing, chemical analysis laboratories, environmental consulting, and logistics. These high-technology sectors contribute to job creation and attract investments to municipalities hosting HTC plants. Public-private partnerships may also emerge as municipalities collaborate with research centers, universities, and technology-based companies to test novel applications of hydrochar and explore market opportunities for HTC-derived products.

Furthermore, HTC aligns with Paraná's broader circular economy strategies. By transforming sewage sludge (considered a problematic waste) into a portfolio of useful materials, the state strengthens its transition toward regenerative production models. The economic valorization of waste streams mitigates disposal costs, supports industrial symbiosis, and promotes sustainable development across the territory.

From a governance perspective, HTC adoption can

enhance the resilience of the state's sanitation system by diversifying sludge management routes. This flexibility is particularly valuable in the face of climate change, regulatory evolution, and potential restrictions on land application of sludge due to emerging contaminants such as microplastics and persistent organic pollutants. HTC's capacity to immobilize many contaminants and generate stable outputs provides a risk-mitigation strategy consistent with long-term environmental safety.

The state of Paraná presents a uniquely favorable environment for the integration of HTC into its SS management framework. With high wastewater treatment coverage, a centralized sanitation operator, and clear public policy priorities focused on renewable energy and technological innovation, Paraná can leverage HTC as a transformative tool. The technology not only addresses operational challenges associated with sludge handling and disposal but also unlocks new pathways for producing renewable fuels, advanced carbon materials, nutrients, and biogas.

By adopting HTC, Paraná stands to reinforce its leadership in sustainable sanitation, stimulate regional industrial development, and contribute to Brazil's broader goals of decarbonization and circular resource use. As global interest in bio-based economies intensifies, the state has the opportunity to position itself at the forefront of sludge-to-bio-product innovation, demonstrating how environmental management can simultaneously drive economic growth and societal well-being.

6. Conclusions

The valorization of sewage sludge (SS) through hydrothermal carbonization (HTC) represents a technically sound and socially relevant pathway for advancing low-carbon development. Globally, SS availability depends strongly on population size and the coverage of wastewater collection and treatment systems. At present, the amount of SS generated worldwide would be insufficient to replace even 1% of global coal demand; however, this share could increase to approximately 5% if the full potential of wastewater collection and treatment were achieved. Although HTC of SS cannot, by itself, resolve dependence on solid fossil fuels, it can

meaningfully contribute to the greening of the global energy matrix while simultaneously improving public health and social welfare. In this context, Paraná stands out as a strategic case, where a structured sanitation network, diversified economy, and institutional capacity enable HTC deployment near wastewater treatment plants. Supported by a Quadruple Helix framework, integrating government, industry, academia, and civil society, HTC can foster regional innovation, circular biofuel value chains, and sustainable industrial development.

Author Contributions

Contribution to the conception and the development of the manuscript: A.B., T.M.M.S. and A.A.G.F. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All authors declared no conflict of interest.

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