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Scenario analysis of hydrochar production for incorporation into boreal soils: a life cycle and technoeconomic assessment

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Agriculture and forest ecosystems are significant contributors to greenhouse gas (GHG) emissions, making mitigation strategies essential for sustainable land application. This study assesses the sustainability impact of converting wood residues into hydrochar for use as a soil amendment to reduce GHG emissions and enhance carbon sequestration. Through a comprehensive life cycle assessment (LCA) and technoeconomic analysis (TEA) of establishing hydrothermal carbonization (HTC) process in pulp and paper mills, this research addresses a critical knowledge gap. The LCA indicates that applying hydrochar in boreal soils without additional fertilizers is advantageous in terms of climate change mitigation, resulting in net CO_2-equivalent savings of up to 300 kg per year. The TEA indicates that although advanced technologies for wastewater treatment from the HTC process entail higher initial costs, they yield greater financial returns compared to conventional methods. These findings suggest that HTC units have the potential to offer climate change mitigation benefits and improved economic performance when valorizing wood residues compared to the mono-incineration process.

KEYWORDS
economic viability, hydrothermal carbonization, pulp and paper mills, sustainability assessment, wood residues

1 Introduction

Agriculture, forestry, and other land use (AFLOU) have contributed considerably, up to ~21% of total (55.9 ± 6.1 Gt CO_2-eq year^{-1}) anthropogenic GHG emissions between 2010 and 2019 (Kang et al., 2023). While CO_2 is the most abundant GHG in the atmosphere, CH_4 and N_2O, the second and third most abundant GHGs, have greater warming potential compared to CO_2 in a 100 years of time scale (Myhre et al., 2013). Increased GHG concentrations in the atmosphere lead to a rise in global surface temperature causing warming, food insecurity, biodiversity loss and soil degradation (Myhre et al., 2013). These GHG-induced effects are crucial, especially considering the sustainability of agriculture and forest ecosystems, which are tightly associated with the survival of increasing human population. Therefore, strategies with effective mitigation options associated with land-use are urgently needed to ensure the sustainability of agriculture and forestry.

While application of biochar and its effect on soil GHG emissions and C sequestration have received considerable attention (Joseph et al., 2021), similar information associated with hydrochar applications is lacking. Studies investigating the effects of hydrochar on soil GHG emissions remain limited, as highlighted in the comparative analysis by Aller (2016). That study also emphasizes the need to prioritize hydrochar research, both short- and long-term, on par with biochar in future investigations related to organic amendments and soil processes. Previous studies on hydrochar have reported contrasting results, showing that GHG emissions can either increase or decrease, similar to the effects observed for biochar (Mukherjee and Lal, 2013). For instance, Kammann et al. (2012) found that the application of hydrochar from beet root and bark chips can enhance GHG emissions when compared to biochar made from beech, maize or peanut hull, applied to amended and control (no char amendment) soils. Contrary to this finding, other studies have shown a reduced soil emissions of N_2O from sewage sludge hydrochar (Joshi et al., 2022) and of CO_2 and CH_4 from digestated hydrochar amendments (Adjuik et al., 2020). Furthermore, increased positive effect of hydochar towards lowering soil CO_2 emissions can be expected if hydorchar produced at high processing temperature and long residence time are used as an amendment (Joshi et al., 2022). These findings indicate that hydrochar could have the potential for lowering soil GHG emissions. However, various factors such as the raw material utilized for making hydorchar, the hydrochar generation parameters and soil inherent properties would ultimately determine the mitigation potential of hydrochars (Kammann et al., 2012).

To place our research in context, we performed a literature review on the impacts of hydrochar application as a soil amendment, with a particular focus on the boreal region, which is the second most forested area on the planet [covering approximately 27% of total land area (Food and Agriculture Organization of the United Nations, 2020)]. Only one study to date has examined the influence of hydrochar on soil GHG emissions in this region (Bhattarai et al., 2025). In contrast, biochar has received considerably more attention regarding its effects on soil GHG emissions and carbon sequestration in boreal environments, including both forestry (Soinne et al., 2020; Zhu et al., 2020) and agricultural systems (Kalu et al., 2022; Karan et al., 2023; Tammeorg et al., 2014). Although several studies from other climatic regions have reported both increases and decreases in soil GHG emissions following hydrochar application – depending on factors such as feedstock type, production conditions, and soil characteristics (Adjuik et al., 2020; Joshi et al., 2022; Kammann et al., 2012) – its effects in boreal soils remain largely unexplored. This highlights the need for further investigation into hydrochar's potential to mitigate GHG emissions across diverse soil types and ecosystems, including boreal systems.

Furthermore, the boreal region provides abundant feedstock sources in the form of forest residues. Utilizing these residues for hydrochar production could strengthen the regional circular bioeconomy. While hydrochar addition has been shown to enhance plant growth in both agricultural (Islam et al., 2021) and forest production systems (Eskandari et al., 2019), assessing its overall sustainability requires integrating soil GHG emission data into life cycle assessment (LCA) and techno-economic analysis (TEA). These complementary approaches are essential for evaluating environmental performance, economic feasibility, and the scalability of hydrochar production processes at the industrial level.

A limited number of studies have explored the LCA and TEA of hydrochar production, with various feedstocks such as food waste (Sangaré et al., 2024; Sultana and Reza, 2022), microalgae (Masoumi and Dalai, 2021), rice husk (Unrean et al., 2018), and paper sludge (Mohammadi et al., 2019) and with applications differing from the current study such as energy purposes (Kempegowda et al., 2017; Mohammadi et al., 2020) and adsorption in water (Nadarajah et al., 2024). Notably, these investigations have not thoroughly addressed the potential of integrating wood residues as feedstock within existing industrial frameworks. Notably, these studies have not thoroughly investigated the potential of using wood residues from pulp and paper mills as feedstock within an integrated industrial framework.

In the present study, the evaluated waste stream consists of wood residues generated during pulp and paper production, including bark, wood chips, and fines from debarking and screening processes. These residues are typically underutilized or used for low-value purposes such as combustion for heat. Integrating an HTC unit into an existing pulp and paper mill allows on-site conversion of these residues into hydrochar. This integration provides several advantages: it enables valorization of residues, reduces transportation requirements, utilizes existing infrastructure such as energy and wastewater treatment systems, enhances energy efficiency, and supports circular resource use while contributing to decarbonization and carbon sequestration. To fully realize the benefits of hydrochar production from wood residues, it is essential to evaluate both environmental and economic performance. Integrating soil GHG emission data into LCA allows assessment of the environmental impacts, while TEA provides insights into the profitability and scalability of hydrochar production within a pulp and paper mill context (Shurpali et al., 2025).

Accordingly, the aim of this study is to quantify the environmental impacts and economic viability of producing hydrochar from wood residues using an HTC unit integrated into a pulp and paper mill. The study scales up the production processes and analyzes various scenarios, including alternative wastewater treatment options and hydrochar application to boreal soils in forest and agricultural systems. By examining these scenarios, the research provides a comprehensive evaluation of the potential benefits and challenges associated with this innovative approach, thereby informing future industrial and environmental strategies.

2 Methodology

2.1 Life cycle assessment

We conducted an LCA to assess the environmental impacts of various scenarios for hydrochar production and utilization. The LCA followed guidelines from ISO standards (Finkbeiner et al., 2006) and ILCD instructions (WOLF et al., 2010), implementing the methodology through four essential steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

2.1.1 Goal and scope definition

The goal of this study was to quantify and compare the environmental impacts of different pathways for wood-based hydrochar production and utilization as a soil amendment. This assessment focuses on climate change impacts, expressed as carbon dioxide equivalents, as the primary intended benefit of the hydrochar system is climate change mitigation through carbon sequestration in soils and displacement of fossil-based products. A preliminary screening assessment indicated that other potential environmental impact categories were less significant within the defined system boundaries compared to the climate change impact and were therefore excluded from the detailed analysis. The functional unit was selected as processing 33,000 tons of wood residue on a dry weight basis per year, including bark, wood chips, and fines from debarking and screening processes, into hydrochar. The functional unit was selected to represent a typical annual availability of wood residues from a mid-sized pulp and paper mill. The geographical boundary was set to Sweden and Finland, with a temporal scope of 10 years. This study is classified as a long-term consequential LCA, incorporating future changes in technology, market trends, and other variables that affect environmental sustainability (Mathiesen et al., 2009). System expansion was used to address the environmental impacts of coproducts and multifunctionality issues. Marginal technologies were used to model the background system. The system boundary encompassed the entire supply chain, including the production of hydrochar as the main product and methane as a coproduct. The substitution of products with their marginal counterparts was implemented based on the mass of the products.

2.1.1.1 Scenarios (Sc.) description

Reference (avoided) scenario: Sweden's advanced forestry and wood industry generates a significant amount of wood residues, which are traditionally used for energy recovery through industrial combustion. Thus, heat recovery from wood combustion was considered the reference scenario, involving burning wood in a boiler to generate steam for district heating. The heat produced during this process is captured and used for district heating. The energy value of wood was considered 16 GJ/ton (Stachowicz and Stolarski, 2023), modelling the combustion process as an avoided process in system boundaries of the following scenarios (Figure 1A).

- *Scenario 1a and 1b*: In this scenario, wood residues in the form of wood chips are subjected to milling and sieving (Figure 1B). Subsequently, wood powder is subjected to HTC. The outlet from the HTC is filtered to separate the liquid and solid fractions. The liquid fraction which is rich in volatile fatty acids (VFAs) is delivered to anaerobic digestion (AD) unit to produce biogas (60% methane and 40% carbon dioxide). The generated biogas is upgraded biologically using hydrogen gas to react with carbon dioxide and produce methane (Ebrahimian et al., 2023). The methane obtained is used to substitute fossil-based natural gas. The residues from anaerobic digestion are combusted for heat recovery, where ammonia is added to clean the flue gas released from the combustion. The solid fraction, hydrochar, is dried and utilized for agricultural soil application without the addition of N fertilizer, Scenario 1a, and with the addition of N fertilizer, Scenario 1b. After anaerobic digestion, the slurry is centrifugated, the sedimented solid is combusted for heat recovery, while the water is recycled.
- *Scenario 2a and 2b*: In this scenario, hydrochar is produced and utilized similar to Scenario 1 (see Figure 1C). Hydrochar is utilized for agricultural soil application without the addition of N fertilizer, Scenario 2*a*, and with the addition of N fertilizer, Scenario 2*b*. The liquor from the HTC process is subjected to conventional aerobic treatment in which VFAs and other organic material were consumed by aerobic microorganisms. Afterward, the liquor is exposed to sedimentation. The sedimented solids are combusted for heat recovery and the water is recycled (Ebrahimian and Mohammadi, 2024).
- *Scenario 3 and 4:* These scenarios are similar to Scenario 1 and Scenario 2; however, the produced hydrochar is utilized as soil amendment in forest sites with unfertilized soils (see Figures 1D,E).

2.1.2 Life cycle inventory

The inventory data used in this study included both foreground and background data. The background data associated with the production of materials, chemicals, and energy carriers was retrieved from Ecoinvent database *v(3)*. The foreground data related to the mass and energy flows were obtained from the onsite experiments and the modelling using SuperPro designer (section 2.2). If specific data could not be collected from the case studies, such information was obtained through literature review. Table 1 presents the inventory data for the scenarios obtained from the process modelling. Additionally, Supplementary Table S3 provides the content of GHG emissions and nitrogen fertilizer. Process description is provided in the following sections.

2.1.2.1 Hydrochar production

Hydrochar was produced from crushed wood residues in the laboratory at the University of Eastern Finland (UEF) through hydrothermal carbonization (HTC) using a biomass slurry with a solid loading of 30 wt%, corresponding to a solid-to-water mass ratio of 30:70. The process was conducted at 220 °C, an average pressure of approximately 10 MPa, and a residence time of 4 h. The liquid phase generated during the HTC process plays the role of a reaction medium and heat transfer medium during carbonization. After separation from the solid hydrochar, the liquid phase was included within the system boundary and subjected to wastewater treatment via either anaerobic or aerobic processes.

After the process, the slurry was filtered and the solid fraction, hydrochar, was oven dried at 105 °C. Hydrochar was transferred to Natural Resources Institute Finland (LUKE) in Finland and Karlstad University (KaU) in Sweden to be utilized for agricultural soil amendment and forest soil amendment, respectively. Wood residues through the HTC process were converted to hydrochar in the form of solid (50%), liquid (15%), and gases (35%). Carbon and nitrogen contents of hydrochar were measured at 67.1 and 0.39% based on dry matter. The liquid fraction has a pH of 4.1. It contains VFAs in the form of 6,700 mg/L acetic acid, 130 mg/L propionic acid, 17 mg/L butyric acid, 20 mg/L iso-butyric acid, and less than 10 mg/L of valeric acid, iso-valeric acid, caproic acid, and iso-caproic acid, as measured by Eurofins Food & Feed Testing Sweden in accordance with Journal of Chromatography A, 963, 2002; it also contains ammonium 1.9 mg/L and total organic carbon (TOC) 11 g/L, analyzed in accordance with ISO 15923-1:2013 and SS-EN ISO 20236:2021, respectively. The gases emitted through HTC process were found from literature and are listed in Supplementary Tables S1, S2.

2.1.2.2 Agricultural soil application

Pot experiments were performed to evaluate the effect of hydrochar application as a soil amendment in legume grassland soil. A

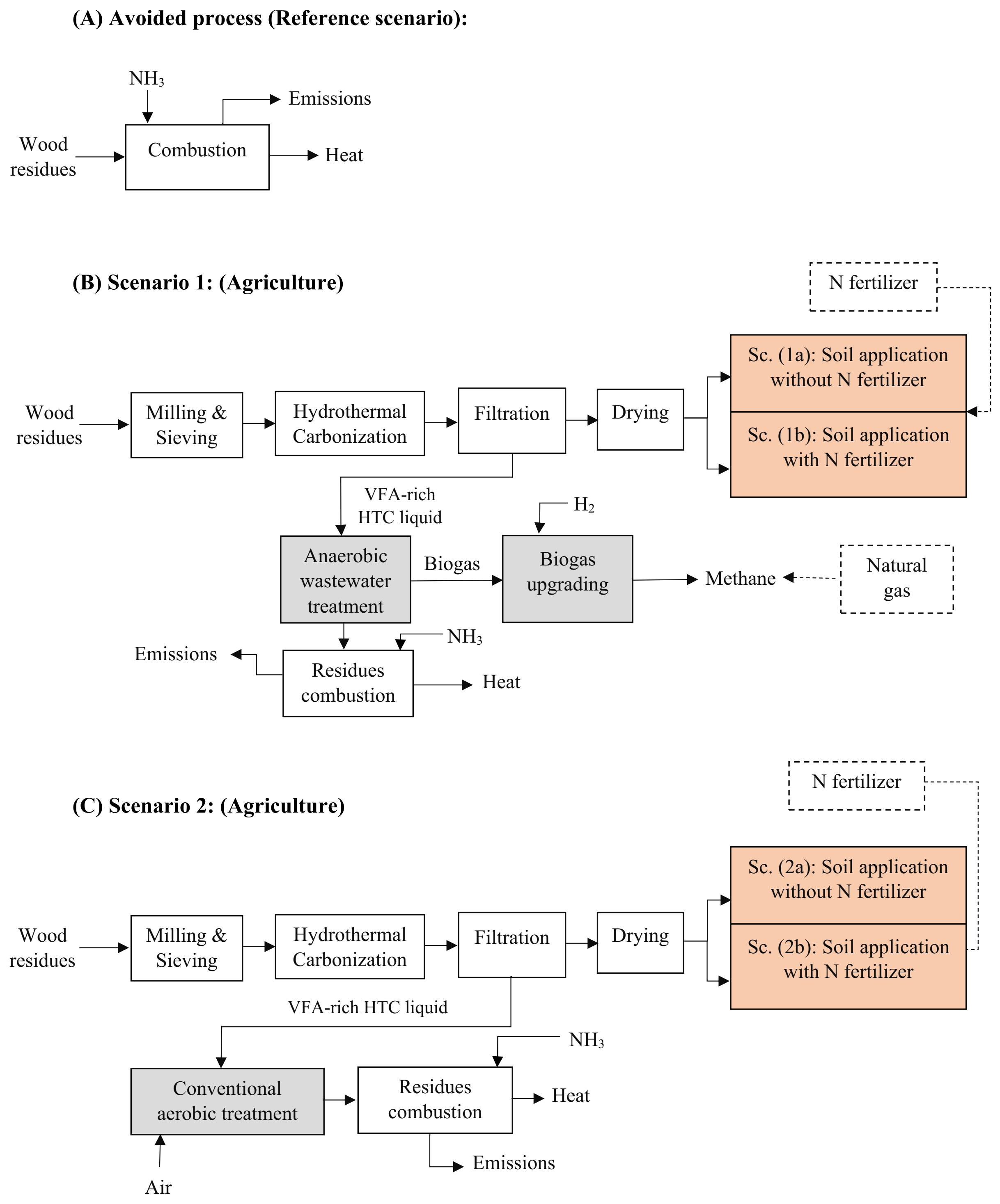

FIGURE 1 (Continued)

mesocosm study was conducted to assess the effect of hydrochar on all three greenhouse gas fluxes and carbon sequestration in the presence (TNH) and absence (TH) of chemical fertilizer nitrogen and compared it against control—the mesocosms that received only fertilizer N (TN) no hydrochar. The mesocosms were established using mineral soil with field bulk density (1.1 g cm^{-3}), regional N fertilization (75 kg N ha^{-1}) and seeding rates and were amended with ($n = 4$) and without ($n = 4$) hydrochar. Treatment control, that is, TN also had four replicates. We cultivated red clover (*Trifolium pratense*, ~4 kg ha^{-1}) and timothy (*Phelum pratense,* ~ 15 kg ha^{-1}) in the mesocosm pots, mimicking a boreal legume grassland on mineral soil. The measurement of GHG fluxes was conducted using a closed static chamber system in a greenhouse on 14 occasions in total during 99 days of the pot experiment. A dark chamber (992×10^{-4} m^3) was deployed over a mesocosm (Ø 0.18 m; id, 0.12 m) and four 20 mL gas samples at 5, 10, 30 and 30 min were collected from the chamber headspace into pre-evacuated exetainer vails. The gas samples contained in the vails were then analyzed for GHG concentrations with gas chromatography at Natural Resources Institute Finland (Luke) laboratory situated in Jokioinen. The flux rates of GHG gases were calculated using Equation 1 (Bhattarai et al., 2019).

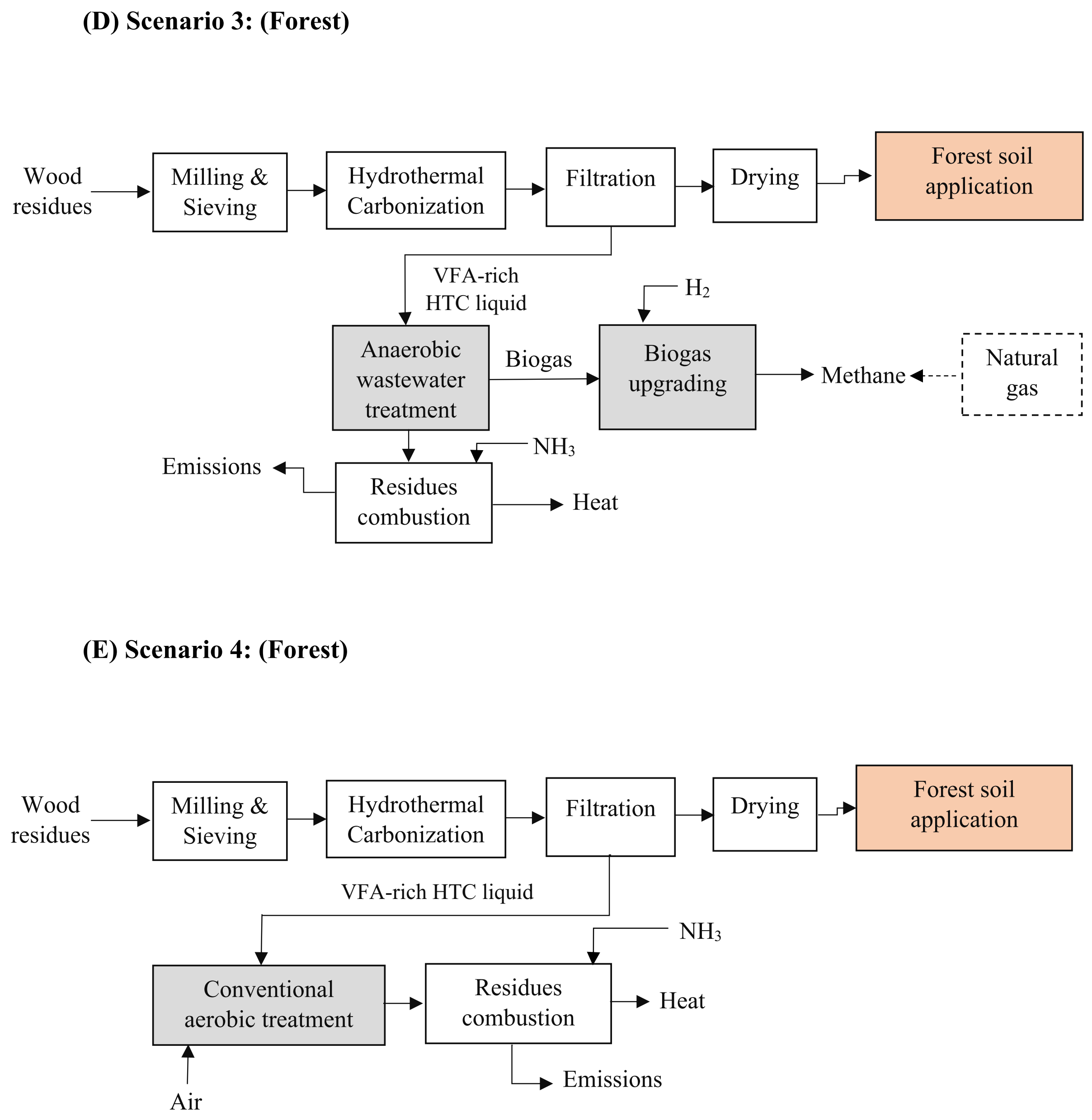

FIGURE 1
Block diagram for the proposed process; dotted lines represent avoided production.

$$F = \frac{p_0 \cdot k \cdot V \cdot M}{R \cdot T \cdot A} \cdot 60 \tag{1}$$

where T is the temperature (K) inside the chamber, p_0 is 101.3 kPa, 60 is the conversion from minute to hour, k is the slope of the headspace gas concentration *Vs* time curve (ppm h^{-1}), V is the volume of the chamber headspace (m^3), R is the ideal gas constant (8.314 J k^{-1} mol^{-1}), M is the molar mass (g mol^{-1}) of the respective gases and A is the area of the soil core (m^2). We filled the gap in GHG emissions data with an assumption of linear increase in GHG emission over time. The total amount of GHG emitted, that is, cumulative emissions was calculated summing the averages of the individual flux values of replicates in each treatment for the entire experimental period. GHG flux data measured from the mesocosm study were used in the LCA (Supplementary Table S3).

2.1.2.3 Forest soil application

Application methods used for hydrochar in forests include broadcasting, where hydrochar is spread evenly across the soil surface; incorporation, where hydrochar is mixed into the soil using equipment like plows; banding, where hydrochar is applied in concentrated bands often in conjunction with tree planting; top-dressing, where a layer of hydrochar is added on top of the soil without mixing; and slurry application, where hydrochar is mixed with water to create a slurry which is then applied to the soil. In this study, it was deemed important to have a uniform mix of hydrochar and soil, so incorporation was the application method used.

In Sweden, over 90% of forest sites are not fertilized. For this study, it was assumed that hydrochars would be applied in unfertilized forests at an average application rate of 5 t ha^{-1} (Mohammadi et al., 2019).

The impact of hydrochar on GHG emissions from forest soils is very limited in the literature. In this assessment, no response from hydrochar addition into forest soils were considered.

2.1.2.4 HTC liquid treatment

The liquid fraction from the HTC process, rich in volatile fatty acids and other organic material, was anaerobically digested in Scenario 1 and Scenario 3, leading to the production of biogas (40% carbon dioxide and 60% methane). The produced biogas is upgraded biologically, where carbon dioxide in reaction with hydrogen produces methane through Equation 2 (Ebrahimian et al., 2022):

$$CO_2 + 4H_2 \text{�} CH_4 + 2H_2O \qquad (2)$$

After this treatment, the wastewater is subjected to centrifugation, where the remaining sludge is combusted for heat recovery while water is recycled back into the unit processes. The combustion emissions are provided in Supplementary Table S4. In Scenario 2 and Scenario 4, the organic content of HTC liquor is aerobically digested. After centrifugation, the sedimented solid is incinerated and the water is recycled to the plant.

It is worth mentioning that the HTC liquid fraction exhibits a pH of approximately 4.1, which lies within the lower reported operational range for acidogenic bacteria. In the TEA, it is assumed that partial consumption of VFAs and stream's inherent buffering capacity allow biological treatment to process without chemical neutralization. However, pH adjustment may still be required to ensure stable long-term operation, particularly for anaerobic digestion. This introduces uncertainty in the TEA, as neutralization could affect both operating costs and process feasibility, and should be considered in future studies.

2.1.3 Life cycle impact assessment

The scenarios were modeled using SimaPro. CML-IA baseline, a European methodology for the impact assessment was employed. This method is commonly used in assessing biorefineries and waste management options (Ebrahimian and Mohammadi, 2023; Loy et al., 2021; Olukoya et al., 2014), rendering it appropriate to this research. For each scenario, the impact/saving were calculated by subtracting the savings from the impacts. Negative values indicate eco-friendly savings, whereas positive values indicate environmental impacts or burdens.

2.1.4 Sensitivity analysis for life cycle assessment

A sensitivity analysis was applied to assess the variation in climate change when the carbon content of hydrochar is changed by ±20% (baseline is 67.1% as per our experiments), stable carbon is 0 and 30% [baseline is 15% as per Mohammadi et al., 2019], and N_2O emission from soil is changed by ±20% (baseline value is −49834.8 kg/year for Scenario 1 and 9721.9 kg/year for Scenario 2 as per our mesocosm experimental results).

2.2 Technoeconomic assessment (TEA)

Hydrochar production process was designed for a daily plant capacity of 100 metric tons (MT) wood residue. Supplementary Figures S1A,B present the process flow of the developed scenarios. The analysis was carried out in the year 2024. The startup and construction period were assumed to be 6 and 18 months, respectively. The plant lifetime was considered 20 years, and annual working hours were assumed to be 7,920 h, that is, 330 working days (Ferreira et al., 2022). The inflation rate and taxation were assumed 4 and 30%, respectively. The economic evaluation parameters are presented in Supplementary Table S5.

The total capital investment is calculated as the sum of working capital cost, startup cost, and direct fixed capital cost (DFC). The calculation of DFC involves the addition of total plant indirect cost (TPIC), total plant direct cost (TPDC), and constructor's fee and contingency (CFC). TPDC consists of instrumentation, piping, buildings, auxiliary facilities, yard improvement, electrical facilities, and insulation which are 40, 35, 20, 15, 15, 10, and 3% of total equipment purchase cost, respectively. The indirect costs involve construction and engineering, which are 35 and 25% of direct costs. Other costs consisting of contingency and contractor's fee were ascertained at 10 and 5% of the total of direct and indirect expenses, respectively.

The summation of costs related to raw material, utilities, labor, consumables, facilities, and transportation determines the total operating cost. The unit price of raw material used in the process is provided in Table 1. The estimation of labor hours was in accordance with the labor requirements by different operation. The basic labor rate was assumed at USD 20/h. Equation 3 was used to calculate the labor cost:

$$\begin{aligned}&\text{Labor cost} =\\&\text{Labor use} \times \begin{pmatrix} 1 + \text{Supplies} + \text{Benefits} \\ +\text{Administration} \\ +\text{Supervision} \end{pmatrix} \times \text{Basic labor rate}\end{aligned} \qquad (3)$$

Where the benefits, supplies, supervision, and administration factors were assumed as 0.4, 0.1, 0.2, and 0.6, respectively. USD was chosen as the currency in the current study. The transportation cost of wood residues was deemed negligible since the proposed biorefinery is supposed to be established in a pulp and paper mill plant. However, an average distance of 250 km is considered between the hydrochar application sites and the plant. It is assumed that hydrochar is transported by trucks with a maximum loading capacity of 26 metric tons, a fuel consumption rate of 0.3 L/km, and a fuel price of USD 2.09/L. Consequently, the transportation cost is estimated at USD 6.02/MT. Moreover, loading and unloading labor costs at USD 6.7/MT were added. Thereby, the overall cost of transportation was calculated to be USD 18.77/MT (Mailaram et al., 2022).

Hydropower was selected as the source of electricity in all scenarios, as per (Swedish Energy Agency, 2021) the most preferred source of electricity in Sweden is hydropower. Additionally, district heating was chosen as the primary technology for the heat supply.

The profitability of the plant was evaluated by evaluating various economic indices such as total investment, total revenue, payback period (PBP), gross margin, return on investment (ROI), internal rate of return (IRR), and net present value (NPV). The revenue for the simulated plants came from hydrochar with the selling price of USD 1/kg and methane with the selling price of USD 1.3/m^3 (Ebrahimian and Mohammadi, 2024). A positive NPV indicates that the biorefinery plant is profitable throughout the entire lifetime (20 year in this case; Bharathiraja et al., 2022).

TABLE 1 Process materials and utilities requirements (inventory data) and costs per annum.

Item	Annual amount		Cost	
	Sc. 1 & Sc. 3	Sc. 2 & Sc. 4	Sc. 1 & Sc. 3	Sc. 2 & Sc. 4
Raw material				
Water (5 \$/m^3)	53,257 m^3	53,257 m^3	30,096	30,096
Hydrogen (3.8 \$/kg)	7,920 kg	0	26,628	0
Wood (0.2 \$/kg)	33,000 ton	33,000 ton	6,600,000	6,600,000
Utilities				
Heat (13.1 \$/GJ)	78323.5 GJ	64893.5 GJ	3,199,403	3,199,445
Electricity (0.1 \$/kWh)	4,730,545 kWh	4,195,818 kWh	473,054	419,581
Products				
Hydrochar (biofertilizer, 1 \$/kg)	16,686,000 kg	16,686,000 kg	16,686,000	16,686,000
Methane (natural gas, 1.3 \$/m^3)	7,917,487 kg	0	23,435,763	0

TABLE 2 Equipment specification and their costs.

Equipment	Name	Sc. 1	Sc. 2	Description	Unit cost (M\$)
Plug flow reactor	PFR-101	√		Vessel volume = 1,079 m^3	0.85
Anaerobic digester	AD-101	√		Vessel volume = 5.6 m^3	0.66
Centrifuge	CF-101	√	√	Rated throughput = 7,312 L/h	0.44
Stirred reactor	R-101	√	√	Vessel volume = 10.9 m^3	0.24
Drum dryer	DDR-102	√	√	Vessel volume = 10.5 m^3	0.17
Grinder	GR-101	√	√	Rated throughput = 4,167 kg/h	0.12
Vacuum filtration	RVF-101	√	√	Filter area = 4.03 m^2	0.08
Flat bottom tank	V-101	√	√	Vessel volume = 2.09 m^3	0.07
Flat bottom tank	V-101	√		Vessel volume = 0.005 m^3	0.04
Aeration basin	AB-101		√	Vessel volume = 7.1 m^3	0.94

2.2.1 Sensitivity analysis for economic assessment

A sensitivity analysis was carried out to evaluate the effect of variations in key parameters on the minimum selling price of hydrochar across the proposed scenarios. The analysis covered investigating the impact of ±20% variation in procuring wood residues (Hu et al., 2023), a ±20% variation in the plant's processing capacity, and ±20% variation in energy price. A discount cash flow analysis was used to determine the minimum selling price of hydrochar by adjusting the selling price of BDO until the NPV reached zero. The analysis relied on the economic parameters and assumptions from previous studies, including a discount rate of 10%, depreciation of 7 year, a plant lifetime of 20 year, a tax rate of 35%, a construction period of 3 year, and a start-up time of 3 months (Ebrahimian and Mohammadi, 2024).

3 Results and discussion

3.1 Technoeconomic assessment

The capital costs for establishing the biorefinery plants are shown in Figure 2A. Direct costs contributed approximately 50% to total investment, indirect costs 30%, and other costs 20%, consistent with previous studies on organic waste-based biorefineries (Gadkari et al., 2023; Mousavi-Avval and Shah, 2021). Equipment purchase cost followed by instrumentation and installation were the primary contributors to direct costs by about 37, 15, and 13%, respectively. Detailed equipment list and sizes of each equipment based on its inlet mass flow rate can be found in Table 2. Aeration basin in Scenario 2, accounting for about 26% of the total equipment cost, and plug flow reactor in Scenario 1, accounting for about 23% of the total equipment cost, were the most expensive equipment. Instrumentation and piping, estimated to be 40 and 35% of total equipment purchase cost, covered expenses related to the installation and maintenance of instruments, control systems, and the network of pipes and equipment needed to transport fluids within the facilities. The cost of plant construction and engineering, associated with the development and implementation of the plant, were the contributors to the indirect costs. Under other costs, construction fees, contingency, working capital, and start-up costs are estimated to contribute 19.4, 38.8, 19.6, and 22.3% in Scenario 1, respectively, and 20.1, 40.5, 15.9, and 23.3% in Scenario 2, respectively.

Comparing the scenarios, it is observed that Scenario 2, which involves conventional treatment of waste stream, resulted in the lowest total capital cost of USD 11.8 million (M), Table 3. In contrast, Scenario 1, which included anaerobic digestion and biogas upgrading,

TABLE 3 Profitability indicators of the scenarios.

Items	Sc. 1	Sc. 2
Total capital investment (M$)	15,772,000	11,796,000
Operating cost (M$/year)	14,650,000	12,941,000
Main revenue (hydrochar, M$/year)	16,686,000	16,686,000
Other revenues (methane, M$/year)	9,801,762	0
Total revenue (M$/year)	26,488,000	16,686,000
Gross margin (%)	44.69	22.36
Return on investment (ROI, %)	61.15	30.65
Payback period (PBP, years)	1.64	3.26
Internal rate of return (IRR, %)	61.16	31.5
Net present value at 7% interest (NPV, $)	75,881,000	22,964,000

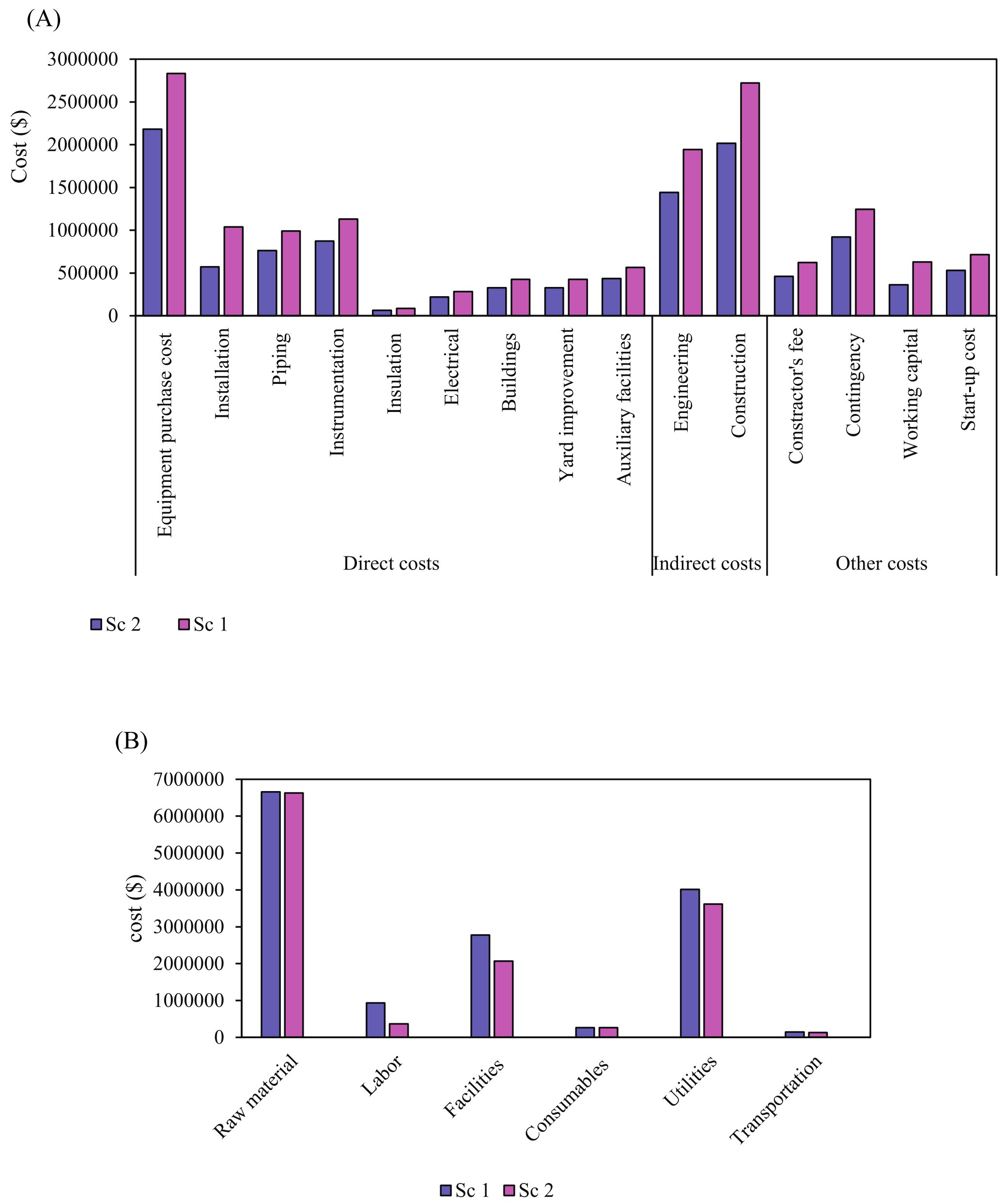

FIGURE 2
Total capital cost for establishment of the biorefinery plants **(A)**; total annual operating cost **(B)**.

resulted in the highest total capital cost of USD 15.8 million, mostly attributing to costs of building the anaerobic digester and plug flow reactor. Hence, conventional waste treatment approaches, as proposed in Scenario 2, are estimated to be the most cost-effective technique. On the other hand, advanced technologies such as biogas upgrading (Scenario 1) can considerably raise the capital cost. This suggests that although these innovative technologies offer environmental and energy recovery benefits, they require higher initial investment. Therefore, it is important to balance the long-term benefits of such technologies with their associated costs to identify the most appropriate approach.

The contributions of various cost items to the annual operating cost of the suggested scenarios are shown in Figure 2B. Raw material-related cost, accounting for 45.4 and 51.2% of total operating costs in Scenario 1 and Scenario 2, is the main contributor to the total operating costs. Utilities-dependent cost contributing to 27.4 and 27.9% of total operating cost in Scenario 1 and Scenario 2, respectively, served as the second main contributor to total annual operating cost. On the third place, facility-dependent cost referring to the expenses related to the equipment maintenance, depreciation, taxes, insurance, and other overhead cost, contributed to about 18.9 and 16% of the total operating cost is Scenario 1 and Scenario 2, respectively. The contribution of labor cost to the total operating cost was 6.4% in Scenario 1 and 2.8% in Scenario 2. Overall, Scenario 2 offers a lower total operating cost, that is, USD 12.9 M/year, compared to Scenario 1, that is, USD 14.6 M/year.

The economic analysis of the proposed scenarios is summarized in Table 3. Both scenarios are profitable as evident from their positive NPV. In Scenario 1, revenue comes from the sale of hydrochar (USD 16.7 M/year) and methane (USD 9.8 M/year). In Scenario 2, the source of revenue comes solely from the sales of hydrochar (USD 16.7 M/year). While Scenario 1 leads to higher capital investment and operating cost compared to Scenario 2, its higher revenue make it more financially feasible, as evidenced from its higher return on investment of 61.2% (as compared to 30.7 for Scenario 2) and shorter payback period (PBP) of 1.6 years (as compared to 3.3 years for Scenario 2). Overall, Scenario 1 reveals a shorter investment horizon due to its shorter PBP.

These results align with Medina-Martos et al. (2020) where the TEA of integrating HTC with AD showed higher costs in comparison to the conventional anaerobic digestion alternative. These results indicate the approach to integrate HTC with AD require further optimization in future studies.

3.2 Sensitivity analysis

A sensitivity analysis was also carried out to assess the impact of important variables on the MSP of hydrochar (Figure 3). At baseline condition, the MSP was determined to be USD 0.35/kg and USD 0.82/kg in Scenario 1 and Scenario 2, respectively. Considering a 50% higher purchasing price for the feedstock, the MSP of hydrochar was increased by 57.3% in Scenario 1 and 24.3%, in Scenario 2. These findings indicate the significant effect of feedstock costs on the minimum selling price of hydrochar, underscoring the need for efficient resource utilization and cost-effective sourcing strategies in the production of bio-based products.

The estimated selling price in this study, even with different sensitivity analysis parameters, is still below the breakeven selling price of hydrochar (USD 1.92/kg) reported by Sultana and Reza (2022). In their study, they chemically activated hydrochar using a char impregnation technique, where hydrochar is soaked in a potassium hydroxide (KOH) solution prior to thermal activation.

Increasing the processing capacity by 20% resulted in an 18.7% decrease in MSP of hydrochar in Scenario 1 and a 2% decrease in Scenario 2. Conversely, reducing the processing capacity led to a 16.7%% increase in MSP in Scenario 1 and a 6% increase in Scenario 2. These findings highlights that the scalability of hydrochar production considerably affects its economic feasibility, emphasizing the importance of optimizing production capacity. The MSP of hydrochar represented the least sensitivity to energy price, changing by 1.7% in Scenario 1 and 0.9% in Scenario 2.

Among the factors examined, the MSP of hydrochar was most sensitivity to the price of purchasing wood residues. Efficient resource

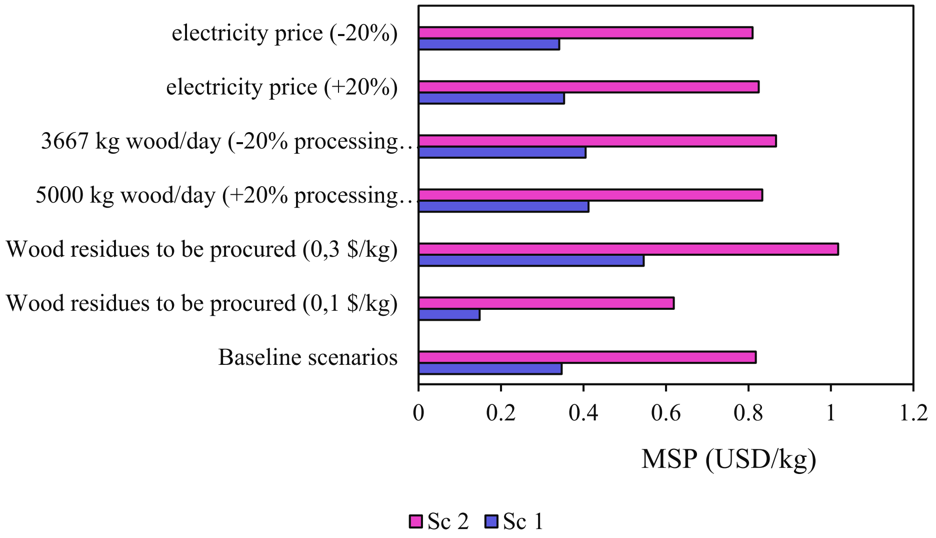

FIGURE 3
Sensitivity analysis of hydrochar minimum selling price over ±20% changes in wood price, ±20% changes in electricity price, and ±20% change in processing capacity.

utilization and process optimization are crucial for achieving cost-effective production and maximizing profitability in the manufacturing of bio-based products.

3.3 Life cycle assessment

LCA results are reported for the processing of a ton of wood residues. Figure 4 illustrates the contrast between the environmental sustainability of the proposed scenarios across climate change, kg CO_2 equivalent. All scenarios represented a negative net balance of CO_2 equivalent, referring to saving, indicating that all scenarios did not have negative impact on climate change. Among all scenarios, Scenario 1*a* and 2*a* in which the produced hydrochar was utilized without the fertilizer, demonstrated the best performance with an avoided impact of −318.5 kg CO_2 eq and −360.7 kg CO_2 eq per ton of wood residues, respectively (Figure 5). These scenarios benefitted

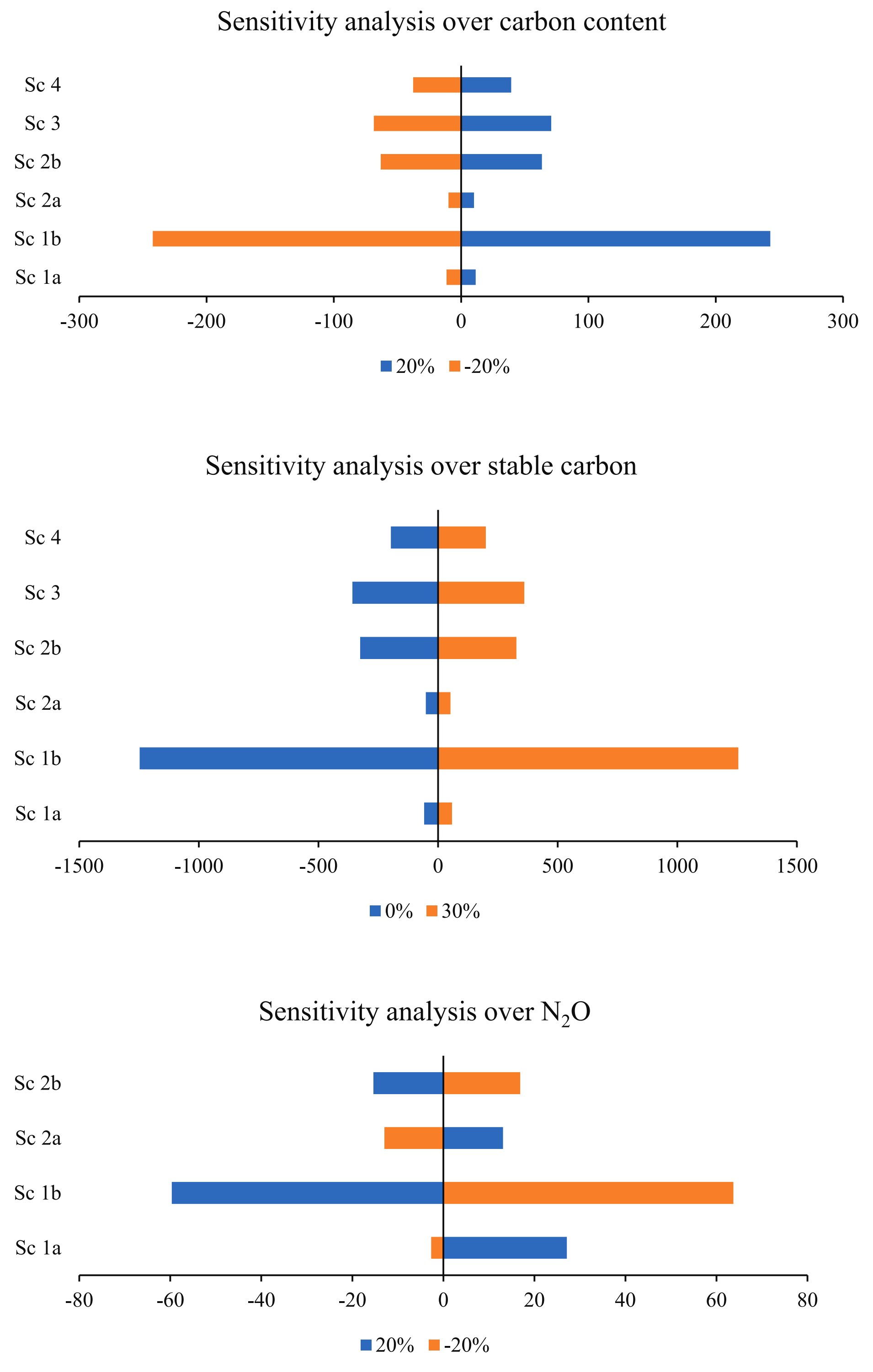

FIGURE 4
Sensitivity analysis (% compared to the base) over carbon content, stable carbon, and nitrogen oxide in climate change.

from avoided combustion, avoided fertilizer, avoided natural gas, and GHG emissions abatement, compensating for the environmental impacts caused by heat and electricity usage, hydrogen, ammonia, and transportation. The abatement of GHG emissions demonstrated the most significant contributor in saving CO_2 and benefitting the climate.

Other environmental impacts of the proposed scenarios are provided in Supplementary Table S6.

There are very few studies available in the literature (Mohammadi et al., 2019) regarding the environmental impacts of using hydrochar as a soil amendment, making direct comparisons with our current results challenging. However, our findings align with most LCA studies of biochar systems, which report that the net climate impact (including emissions and avoided emissions) of biochar systems is typically negative. This is because the avoided emissions are usually greater than the emissions, due to the recalcitrance of biochar and the avoided synthetic fertilizers in the case of agricultural use (Azzi et al., 2022; Zhu et al., 2022).

GHG (i.e., CO_2, CH_4, and N_2O) emissions/abatements from Scenario 1*a* and Scenario 1*b* are also illustrated in Figure 4. The saving from stabilized carbon, CO_2, and N_2O emission abatement from soil as a result of substituting hydrochar with chemical nitrogen fertilizer were the other contributors in environmental savings of Scenario 1*a* and Scenario 1*b*. As vividly demonstrated, Scenario 1*a* receives the highest credit from NO_2 abatement from soil, that is, −235.6 kg CO_2 eq, attributing to N_2O emission reduction from soil as a result of substituting hydrochar with conventional chemical nitrogen fertilizer. It worth mentioning that the growth yield of grass was higher when

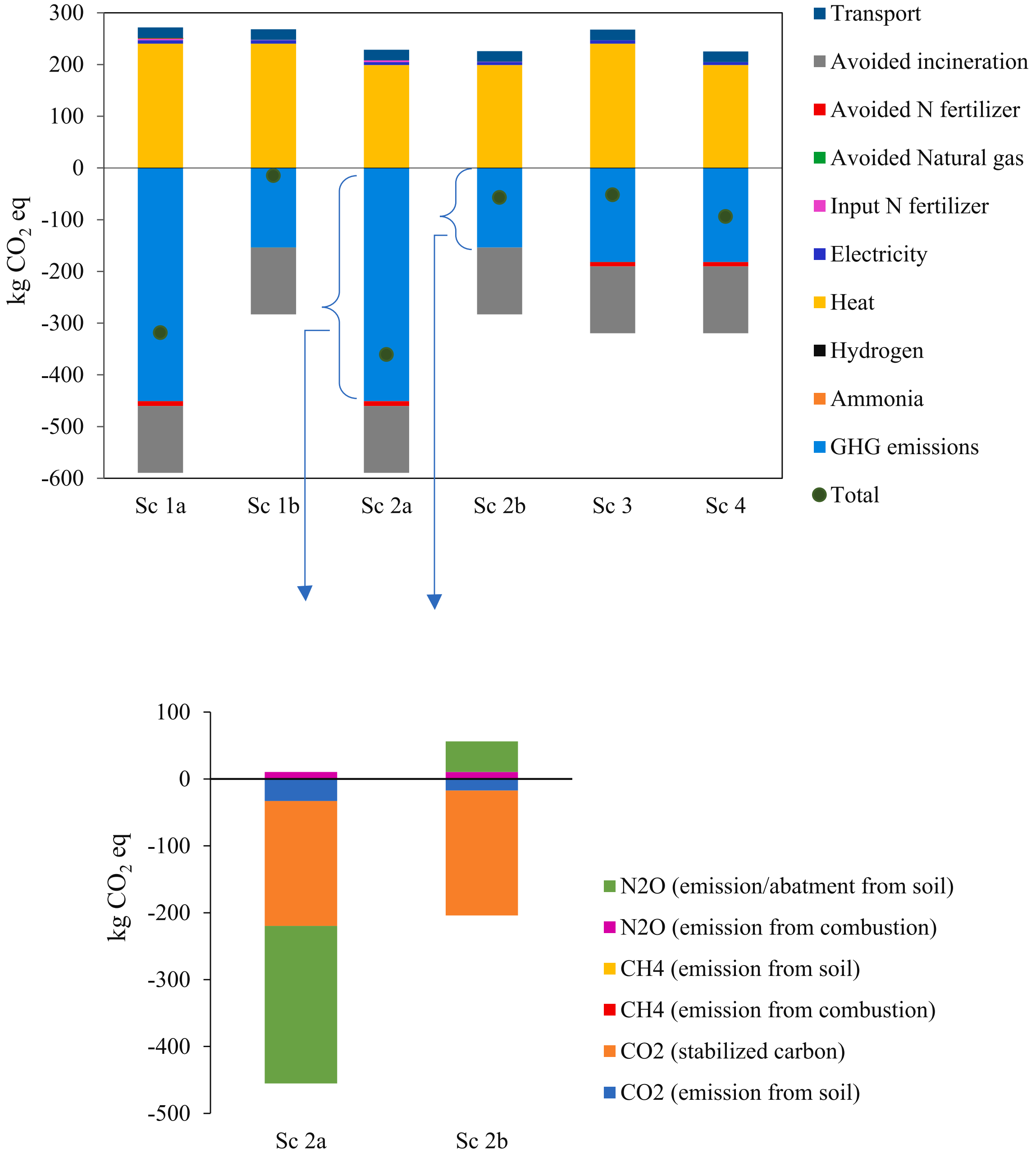

FIGURE 5
Comparison and contribution of the scenarios in climate change.

using hydrochar with nitrogen fertilizer (Scenario 1*b*); however, N_2O emission was highly increased as a result of using chemical nitrogen, leading to a positive N_2O emission (impact) of 46 kg CO_2 eq.

Drawing a comparison between Scenario 1 (*a* and *b*) and Scenario 2 (*a* and *b*), Scenario 2 with conventional wastewater treatment offered a higher net saving of about 13%. The saving from voided natural gas was not big enough to compensate for the higher heat requirement of Scenario 1 that was the main contributor to impact climate change.

Overall, it can be claimed that Scenario 2*a*, in which hydrochar was utilized without nitrogen fertilizer and wastewater from the HTC process was treated conventionally, offered the most environmentally viable option.

Similar results were reported by Gievers et al. (2019), where the global warming impact of hydrochar different applications of hydrochar produced from sewage sludge (5% dry matter) led to savings of 0.074 kg CO_2 eq/kg. The emissions from the agricultural use of hydrochar as a substitute for NPK-fertilizer was found to be 0.025 kg CO_2 eq/kg, without including soil impact of hydrochar addition in the calculations.

3.4 Sensitivity analysis for life cycle assessment

A sensitivity analysis was employed to assess the influence of variations in carbon content, stable carbon, and N_2O emission from soil on the results of assessment and identify the robustness of the LCA findings. As illustrated in Figure 4, among all the scenarios, Scenario 1b demonstrated the highest sensitivity of 242.5, 1255.4, and 63.7% to carbon content, stable carbon, and N_2O emission from soil, respectively.

The analysis applied a ± 20% variation to hydrochar carbon content and soil N_2O emissions to explore the robustness of the climate change results. For hydrochar carbon content, this range captures the reported variability in elemental composition of wood-derived hydrochars due to feedstock heterogeneity and HTC operating conditions, rather than analytical uncertainty (e.g., Guo et al., 2016; Saha et al., 2019). For soil N_2O emissions, the ±20% range represents a conservative estimate of flux variability typical of soil systems, rather than a statistical confidence interval from our mesocosm experiment (Tian et al., 2024). This exploratory analysis demonstrates that overall conclusions regarding climate change mitigation are maintained within these plausible uncertainty bounds, providing confidence in the robustness of the results.

3.5 HTC units establishment at pulp and paper mills

Establishing Hydrothermal Carbonization (HTC) units in pulp and paper mills to convert solid residues into hydrochar offers significant advantages and potential drawbacks.

HTC deployment in these facilities could reduce wood residues volume and improve its applicability as a hydrochar in carbon sequestration, energy recovery, or material and nutrient recovery as well as a filtrate in the generation of renewable energy. HTC processes also utilize wet biomass, making them particularly suitable for pulp and paper mills that produce substantial quantities of water-rich residues such as sludge. Previous studies have shown that hydrochar is technically and environmentally sustainable for converting sludge produced in Swedish and Finnish pulp and paper mills (Hämäläinen et al., 2022; Mohammadi et al., 2019; Mohammadi et al., 2020) for energy purposes or soil applications.

Although hydrochar is commonly used as a solid fuel and biosorbent, hydrochar produced from woody biomass can also serve as a valuable soil amendment (Bona et al., 2023; Islam et al., 2021), enhancing soil fertility and structure while sequestering carbon and mitigating soil GHG emissions. Furthermore, hydrochar can be mixed with ash in pelleted form (Eskandari et al., 2019; Mohammadi et al., 2022) or co-composted (Bona et al., 2023) for reuse in agriculture, forestry, and horticulture as a growth medium.

On the economic side, implementing HTC units can potentially reduce waste disposal costs and create additional revenue streams for pulp and paper mills through the sale of hydrochar and other byproducts such as biogas if HTC is integrated with anaerobic digestion units (Medina-Martos et al., 2020). The minimum selling price (MSP) of hydrochar could vary from USD 0.35 to USD 1.92/kg (Sultana and Reza, 2022) depending on the feedstock, processing capacity, and form of hydrochar, whether raw, pellet or chemically activated. The energy demands of HTC are relatively moderate compared to other thermal conversion technologies, and the process can be integrated with the mill's existing energy and wastewater treatment infrastructure (Hämäläinen et al., 2022), utilizing excess heat or steam, thus improving overall energy efficiency.

However, the initial capital investment for HTC units can be substantial, which may be a barrier for some pulp and paper mills, especially those with small processing capacities. Additionally, operational costs, including maintenance and the handling of byproducts, can add to the financial burden. Comprehensive environmental assessments are needed to understand the long-term impacts of hydrochar application on soil health and ecosystems, as well as carbon stability and sequestration. Potential challenges in the consistency and quality of hydrochar produced from varied feedstock types available in mills, such as wood residues, sludges, and black liquor, present another hurdle, necessitating rigorous process control and optimization. Further studies on both the production and application of hydrochar to address these challenges are recommended for future research.

4 Conclusion

This study highlights the potential of hydrochar as an effective strategy for reducing GHG emissions from boreal soils. The life cycle assessment reveals that applying hydrochar, particularly without the use of additional nitrogen fertilizers, can deliver significant environmental benefits. While the capital costs for advanced technologies, such as biogas upgrading, are higher, these approaches offer considerable long-term economic advantages for pulp and paper mills. Incorporating hydrochar into land management practices can improve soil health and contribute to climate change mitigation. The findings emphasize the need for further research into optimizing the hydrothermal carbonization-anaerobic digestion process and exploring hydrochar's impact on various soil types and ecosystems. This research could help utilize local forestry residues and promote circular bioeconomy.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

FE: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. HB: Investigation, Writing – original draft, Writing – review & editing. KG: Conceptualization, Writing – review & editing. NS: Investigation, Writing – review & editing. AM: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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Supplementary material

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References

Adjuik, T., Rodjom, A. M., Miller, K. E., Reza, M. T. M., and Davis, S. C. (2020). Application of hydrochar, digestate, and synthetic fertilizer to a *miscanthus X giganteus* crop: implications for biomass and greenhouse gas emissions. *Appl. Sci.* 10:8953. doi: 10.3390/app10248953

Aller, M. F. (2016). Biochar properties: transport, fate, and impact. *Crit. Rev. Environ. Sci. Technol.* 46, 1183–1296. doi: 10.1080/10643389.2016.1212368

Azzi, E. S., Karltun, E., and Sundberg, C. (2022). Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar* 4:18. doi: 10.1007/s42773-022-00144-3

Bharathiraja, B., Jayamuthunagai, J., Sreejith, R., Iyyappan, J., and Praveenkumar, R. (2022). Techno economic analysis of malic acid production using crude glycerol derived from waste cooking oil. *Bioresour. Technol.* 351:126956. doi: 10.1016/j.biortech.2022.126956

Bhattarai, H. R., Honkanen, E., Ruhanen, H., Soinnie, H., Gil, J., Saghir, S., et al. (2025). Effects of biochar, hydrochar and nitrogen fertilization on greenhouse gas fluxes, soil organic carbon pools, and biomass yield of a boreal legume grassland. *Biochar* 7:114. doi: 10.1007/s42773-025-00496-6

Bhattarai, H. R., Liimatainen, M., Nykänen, H., Kivimäenpää, M., Martikainen, P. J., and Maljanen, M. (2019). Germinating wheat promotes the emission of atmospherically significant nitrous acid (HONO) gas from soils. *Soil Biol. Biochem.* 136:107518. doi: 10.1016/j.soilbio.2019.06.014

Bona, D., Bertoldi, D., Borgonovo, G., Mazzini, S., Ravasi, S., Silvestri, S., et al. (2023). Evaluating the potential of hydrochar as a soil amendment. *Waste Manag.* 159, 75–83. doi: 10.1016/j.wasman.2023.01.024

Ebrahimian, F., De Bernardini, N., Tsapekos, P., Treu, L., Zhu, X., Campanaro, S., et al. (2022). Effect of pressure on biomethanation process and spatial stratification of microbial communities in trickle bed reactors under decreasing gas retention time. *Bioresour. Technol.* 361:127701. doi: 10.1016/j.biortech.2022.127701

Ebrahimian, F., Lovato, G., Alvarado-Morales, M., Ashraf, M. T., Rodrigues, J. A. D., Tsapekos, P., et al. (2023). Iron limitation effect on H2/CO2 biomethanation: experimental and model analysis. *J. Environ. Chem. Eng.* 11:109529. doi: 10.1016/j.jece.2023.109529

Ebrahimian, F., and Mohammadi, A. (2023). Assessing the environmental footprints and material flow of 2, 3-butanediol production in a wood-based biorefinery. *Bioresour. Technol.* 387:129642. doi: 10.1016/j.biortech.2023.129642

Ebrahimian, F., and Mohammadi, A. (2024). Bioprocess design and technoeconomic analysis of 2, 3-butanediol production in wood-based biorefineries. *Waste Biomass Valoriz.* 15, 6635–6648. doi: 10.1007/s12649-024-02611-3

Eskandari, S., Mohammadi, A., Sandberg, M., Eckstein, R. L., Hedberg, K., and Granström, K. (2019). Hydrochar-amended substrates for production of containerized pine tree seedlings under different fertilization regimes. *Agronomy* 9:350. doi: 10.3390/agronomy9070350

Ferreira, W. S., Vigano, J., Veggi, P. C. (202). Economic assessment of emerging extraction techniques: Hybridization of high-pressure extraction and low-frequency ultrasound to produce piceatannol-rich extract from passion fruit bagasse. Chemical Engineering and Processing-Process Intensification, 174, 108850. doi: 10.1016/j.cep.2022.108850

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., and Klüppel, H.-J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* 11, 80–85. doi: 10.1065/lca2006.02.002

Food and Agriculture Organization of the United Nations (2020). *Global Forest Resources Assessment 2020: Main report*. Rome: FAO.

Gadkari, S., Narisetty, V., Maity, S. K., Manyar, H., Mohanty, K., Jeyakumar, R. B., et al. (2023). Techno-economic analysis of 2, 3-butanediol production from sugarcane bagasse. *ACS Sustain. Chem. Eng.* 11, 8337–8349. doi: 10.1021/acssuschemeng.3c01221

Gievers, F., Loewen, A., and Nelles, M. (2019). “Hydrothermal carbonization (HTC) of sewage sludge: GHG emissions of various hydrochar applications” in Schebek, L., Herrmann, C., and Cerdas, F. (eds.) Progress in life cycle assessment, Cham, Switzerland: Springer 59–68.

Guo, S., Dong, X., Wu, T., and Zhu, C. (2016). Influence of reaction conditions and feedstock on hydrochar properties. *Energy Convers. Manag.* 123, 95–103. doi: 10.1016/j.enconman.2016.06.029

Hämäläinen, A., Kokko, M., Kinnunen, V., Hilli, T., and Rintala, J. (2022). Hydrothermal carbonization of pulp and paper industry wastewater treatment sludges-characterization and potential use of hydrochars and filtrates. *Bioresour. Technol.* 355:127258. doi: 10.1016/j.biortech.2022.127258

Hu, J., Jåstad, E. O., Bolkesjø, T. F., and Rørstad, P. K. (2023). Impact of large-scale bio-CCS deployment on forest biomass competition and forest industry production. *Biomass Bioenergy* 175:106896. doi: 10.1016/j.biombioe.2023.106896

Islam, M. A., Limon, M. S. H., Romić, M., and Islam, M. A. (2021). Hydrochar-based soil amendments for agriculture: a review of recent progress. *Arab. J. Geosci.* 14:102. doi: 10.1007/s12517-020-06358-8

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., et al. (2021). How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* 13, 1731–1764. doi: 10.1111/gcbb.12885

Joshi, A., Breulmann, M., Schulz, E., and Ruser, R. (2022). Effects of sewage sludge hydrochar on emissions of the climate-relevant trace gases N2O and CO2 from loamy sand soil. *Heliyon* 8:e10855. doi: 10.1016/j.heliyon.2022.e10855

Kalu, S., Kulmala, L., Zrim, J., Peltokangas, K., Tammeorg, P., Rasa, K., et al. (2022). Potential of biochar to reduce greenhouse gas emissions and increase nitrogen use efficiency in boreal arable soils in the long-term. *Front. Environ. Sci.* 10:914766. doi: 10.3389/fenvs.2022.914766

Kammann, C., Ratering, S., Eckhard, C., and Müller, C. (2012). Biochar and hydrochar effects on greenhouse gas (carbon dioxide, nitrous oxide, and methane) fluxes from soils. *J. Environ. Qual.* 41, 1052–1066. doi: 10.2134/jeq2011.0132

Kang, S., Li, X., Fan, J., and Chang, J.Intergovernmental Panel on Climate Change (IPCC) (2023). Agriculture, forestry and other land uses (AFOLU). In Climate change 2022: Mitigation of climate change (Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge University Press.

Karan, S. K., Osslund, F., Azzi, E. S., Karltun, E., and Sundberg, C. (2023). A spatial framework for prioritizing biochar application to arable land: a case study for Sweden. *Resour. Conserv. Recycl.* 189:106769. doi: 10.1016/j.resconrec.2022.106769

Kempegowda, R. S., Tran, K.-Q., and Skreiberg, Ø. (2017). Techno-economic assessment of integrated hydrochar and high-grade activated carbon production for electricity generation and storage. *Energy Procedia* 120, 341–348. doi: 10.1016/j.egypro.2017.07.223

Loy, A. C. M., Alhazmi, H., Lock, S. S. M., Yiin, C. L., Cheah, K. W., Chin, B. L. F., et al. (2021). Life-cycle assessment of hydrogen production via catalytic gasification of wheat straw in the presence of straw derived biochar catalyst. *Bioresour. Technol.* 341:125796. doi: 10.1016/j.biortech.2021.125796

Mailaram, S., Narisetty, V., Ranade, V. V., Kumar, V., and Maity, S. K. (2022). Techno-economic analysis for the production of 2, 3-butanediol from brewers’ spent grain using pinch technology. *Ind. Eng. Chem. Res.* 61, 2195–2205. doi: 10.1021/acs.iecr.1c04410

Masoumi, S., and Dalai, A. K. (2021). Techno-economic and life cycle analysis of biofuel production via hydrothermal liquefaction of microalgae in a methanol-water system and catalytic hydrotreatment using hydrochar as a catalyst support. *Biomass Bioenergy* 151:106168. doi: 10.1016/j.biombioe.2021.106168

Mathiesen, B. V., Münster, M., and Fruergaard, T. (2009). Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. *J. Clean. Prod.* 17, 1331–1338. doi: 10.1016/j.jclepro.2009.04.009

Medina-Martos, E., Istrate, I.-R., Villamil, J. A., Gálvez-Martos, J.-L., Dufour, J., and Mohedano, Á. F. (2020). Techno-economic and life cycle assessment of an integrated hydrothermal carbonization system for sewage sludge. *J. Clean. Prod.* 277:122930. doi: 10.1016/j.jclepro.2020.122930

Mohammadi, A., Anukam, A. I., Granström, K., Eskandari, S., Zywalewska, M., Sandberg, M., et al. (2022). Effects of wood ash on physicochemical and morphological characteristics of sludge-derived hydrochar pellets relevant to soil and energy applications. *Biomass Bioenergy* 163:106531. doi: 10.1016/j.biombioe.2022.106531

Mohammadi, A., Sandberg, M., Venkatesh, G., Eskandari, S., Dalgaard, T., Joseph, S., et al. (2019). Environmental analysis of producing biochar and energy recovery from pulp and paper mill biosludge. *J. Ind. Ecol.* 23, 1039–1051. doi: 10.1111/jiec.12838

Mohammadi, A., Venkatesh, G., Sandberg, M., Eskandari, S., Joseph, S., and Granström, K. (2020). A comprehensive environmental life cycle assessment of the use of hydrochar pellets in combined heat and power plants. *Sustainability* 12:9026. doi: 10.3390/su12219026

Mousavi-Avval, S. H., and Shah, A. (2021). Techno-economic analysis of hydroprocessed renewable jet fuel production from pennycress oilseed. *Renew. Sust. Energ. Rev.* 149:111340. doi: 10.1016/j.rser.2021.111340

Mukherjee, A., and Lal, R. (2013). Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy* 3, 313–339. doi: 10.3390/agronomy3020313

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013). “Anthropogenic and natural radiative forcing” in *Climate change. The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen and J. Doschunget al. (Cambridge: Cambridge University Press), 659–740.

Nadarajah, K., Rodriguez-Narvaez, O. M., Ramirez, J., Bandala, E. R., and Goonetilleke, A. (2024). Lab-scale engineered hydrochar production and techno-economic scaling-up analysis. *Waste Manag.* 174, 568–574. doi: 10.1016/j.wasman.2023.12.024

Olukoya, I. A., Ramachandriya, K. D., Wilkins, M. R., and Aichele, C. P. (2014). Life cycle assessment of the production of ethanol from eastern redcedar. *Bioresour. Technol.* 173, 239–244. doi: 10.1016/j.biortech.2014.09.100

Saha, N., Saba, A., and Reza, M. T. (2019). Effect of hydrothermal carbonization temperature on pH, dissociation constants, and acidic functional groups on hydrochar from cellulose and wood. *J. Anal. Appl. Pyrolysis* 137, 138–145. doi: 10.1016/j.jaap.2018.11.018

Sangaré, D., Moscosa-Santillan, M., Aragón Piña, A., Bostyn, S., Belandria, V., and Gökalp, I. (2024). Hydrothermal carbonization of biomass: experimental study, energy balance, process simulation, design, and techno-economic analysis. *Biomass Convers. Biorefinery* 14, 2561–2576. doi: 10.1007/s13399-022-02484-3

Shurpali, N., Li, Y., Tampio, E., Lappalainen, R., Mohammadi, A., Sandberg, M., et al. (2025). From fossil-based to circular bioeconomy: a Swedish and Finnish pathway. *Environ. Sci. Pollut. Res.* 32, 11308–11316. doi: 10.1007/s11356-025-36336-0

Soinne, H., Keskinen, R., Heikkinen, J., Hyväluoma, J., Uusitalo, R., Peltoniemi, K., et al. (2020). Are there environmental or agricultural benefits in using forest residue biochar in boreal agricultural clay soil? *Sci. Total Environ.* 731:138955. doi: 10.1016/j.scitotenv.2020.138955

Stachowicz, P., and Stolarski, M. J. (2023). Short rotation woody crops and forest biomass sawdust mixture pellet quality. *Ind. Crop. Prod.* 197:116604. doi: 10.1016/j.indcrop.2023.116604

Sultana, A. I., and Reza, M. T. (2022). Techno-economic assessment of superactivated hydrochar production by KOH impregnation compared to direct chemical activation. *Biomass Convers. Biorefinery* 15, 1957–1969. doi: 10.1007/s13399-022-02364-w

Swedish Energy Agency. (2021). Energy in Sweden 2021 – An overview. Retrieved February 10, 2025.

Tammeorg, P., Simojoki, A., Mäkelä, P., Stoddard, F. L., Alakukku, L., and Helenius, J. (2014). Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. *Plant Soil* 374, 89–107. doi: 10.1007/s11104-013-1851-5

Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., et al. (2024). Global nitrous oxide budget. Canberra (Australia): Global Carbon Project.

Unrean, P., Fui, B. C. L., Rianawati, E., and Acda, M. (2018). Comparative techno-economic assessment and environmental impacts of rice husk-to-fuel conversion technologies. *Energy* 151, 581–593. doi: 10.1016/j.energy.2018.03.112

Wolf, M.-A., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D., et al. (2010). International reference life cycle data system (ILCD) handbook — General guide for life cycle assessment: Detailed guidance. Luxembourg: European Commission — Joint Research Centre. doi: 10.2788/38479.

Zhu, X., Labianca, C., He, M., Luo, Z., Wu, C., You, S., et al. (2022). Life-cycle assessment of pyrolysis processes for sustainable production of biochar from agro-residues. *Bioresour. Technol.* 360:127601. doi: 10.1016/j.biortech.2022.127601

Zhu, X., Zhu, T., Pumpanen, J., Palviainen, M., Zhou, X., Kulmala, L., et al. (2020). Short-term effects of biochar on soil CO 2 efflux in boreal Scots pine forests. *Ann. For. Sci.* 77, 1–15. doi: 10.1007/s13595-020-00960-2