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Research Paper

Enhancing carbon removal via scalable on-site pyrolysis and well-plugging systems

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ABSTRACT

The United States has extensive biomass resources, with a potential for sustainable production exceeding 1 billion tons annually. The capacity for removal and permanent storage of carbon from the atmospheric carbon cycle is recognized as a key resource for stabilizing global temperatures and maintaining livable conditions by midcentury. Technological pathways that avoid high per-unit capitalization costs hold promise despite broader market uncertainty; building a comparison to the typical economies of scale proposed in the sector, this study investigates a technology development pathway using economies of numbers. This study investigates biomass fast pyrolysis for carbon removal and storage in the U.S.A, evaluating six common feedstocks: corn stover, switchgrass, clean pine, tulip poplar, hybrid poplar, and oriented strand board, supplied through a distributed network. Small-scale biorefineries convert biomass into bio-oil, biochar, and gas at 400–700 °C, with bio-oil transported to centralized storage. Process modeling, techno-economic analysis (TEA), and life-cycle assessment (LCA) reveal a base case (corn stover) bio-oil production of 5.3 tons/day and biochar production of 2.5 tons/day from 10 dry tons/day of feedstock. The base case capital cost is $1.28 million ($128,000/ton/day feedstock capacity; $241,000/ton/day bio-oil capacity), with a minimum bio-oil selling price of $175/ton at a 10 % IRR. The resulting carbon abatement cost is $83.6/ton CO_2 (including biochar sequestration) or $152/ton CO_2 (excluding it) for the base case. Feedstock production significantly impacts emissions for corn stover (0.20 kg CO_2/kg oil) and switchgrass (0.72 kg CO_2/kg oil). Switchgrass also has the highest carbon abatement cost, while woody feedstocks are around $100/Mt CO_2 (potentially $70/Mt CO_2 with a learning factor). Sensitivity analysis identifies feedstock price and production factors as key drivers of the marginal abatement cost (MAC). Small-scale pyrolysis systems are economically advantageous below 6,000 Mt CO_2/year, becoming less competitive with direct air capture (DAC) at larger scales. This technology offers significant potential for reducing greenhouse gas emissions by converting diverse biomass resources into bio-oil for long-term storage.

1. Introduction

1.1. Background: the urgency of carbon removal

Human activities, primarily burning fossil fuels, have resulted in significant greenhouse gas emissions. These emissions trap heat in the atmosphere, leading to a warming climate and subsequent environmental and societal disruptions [1]. The global atmospheric carbon dioxide concentration has surged from 280 parts per million (ppm) in the late 1700 s to 419.3 ppm in 2023 [2,3]. In 2021, fossil fuel combustion accounted for about 73 % of United States (U.S.) greenhouse gas emissions [2]. As the amount of CO_2 in the atmosphere continues rising, the earth's temperature keeps increasing. The 2023 Intergovernmental Panel on Climate Change (IPCC) sixth Assessment report projected that the global surface temperature will exceed 1.5 °C within the next two decades if no measures or actions are taken to reduce business-as-usual activities [4]. To remain below this threshold, carbon sequestration technology is the only option to remove historical emissions from the atmosphere.

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1.2. Existing carbon removal strategies and their limitations

Numerous carbon removal strategies have been proposed to reduce atmospheric CO_2 concentration to a safe level. The range of negative emission technologies or practices that have been implemented can be categorized by approach: i) nature-based solutions such as afforestation/reforestation, ii) Point-source carbon capture via direct air capture (DAC), and iii) Hybrid approaches that utilize biomass feedstocks and rely on a technological process to transform the material and concentrate carbon for permanent storage or into further products, such as bioenergy with carbon capture and sequestration (BECCS), Biomass Carbon Removal and Storage (BiCRS), or mass timber [5].

Although these pathways are technically viable, they have several drawbacks that hinder commercial adoption. Afforestation/reforestation involves establishing or restoring forests to increase carbon uptake by converting non-forested land into forested areas or restoring disturbed forests. Some companies have adopted afforestation/reforestation practices to counterbalance their carbon emissions [6]. It is relatively inexpensive for a cost range of $0-$20 per ton of CO_2 removed [5]. However, afforestation/reforestation is a slow process limited by the availability of land and ecosystems, and it is also vulnerable to disturbances such as wildfires [5]. Direct air capture technology removes CO_2 from the air through a solvent-based process, resulting in a pure stream of CO_2 for geological storage. DAC is an energy-intensive process, necessitating 4.5 to 17 kWh of energy for 1 kg of CO_2 captured [7,8]. In addition, DAC is one of the most expensive carbon removal approaches, with a cost ranging from $93 to $1000/t CO_2 [5,9].

Hybrid approaches rely on plants to capture CO_2 and then process the plant feedstock using engineered approaches that stabilize carbon for desired uses. BECCS refers to the conversion of biomass into fuel or energy while capturing the process-CO_2 emissions for geological storage. This pathway has shown promising results due to the economic incentive of selling the energy product, which provides a revenue stream that reduces the cost of carbon removal [10]. BECCS technologies include pyrolysis, gasification, hydrothermal liquefaction, and anaerobic digestion. The shortcomings that hinder the deployment of BECCS include lack of information on the supply chain costs and emissions of BECCS and the reliability of CO_2 storage [5,11]. The cost of CO_2 removal of BECCS ranges from $20-$200 per ton of CO_2 sequestered with revenue from the bioenergy products [12,13]. In recent years, a related strategy to BECCS has emerged, BiCRS has emerged as an alternative [14]. BiCRS encompasses processes that use biomass to capture and store carbon in geological formations or long-lived products; carbon management is the primary goal, rather than production of energy. This approach can potentially maximize the amount of carbon removed from the atmosphere while minimizing associated costs [14]. Among biomass conversion technologies, fast pyrolysis technology has gained more attention for its capacity for implementation at small scales, which is convenient with the decentralized nature of biomass supply [7].

1.3. The potential of U.S. biomass resources for carbon mitigation

Further, given the geographically diverse biomass resources available across the United States, exploring their potential for regional and national carbon emission mitigation presents a significant opportunity. The U.S. boasts a wealth of biomass options, ranging from agricultural residues like corn stover in the Midwest to forest residues in the West and energy crops with potential across various regions [15]. This diversity offers several advantages. Firstly, it allows for geographically distributed utilization, minimizing transportation costs and environmental impact. Secondly, it provides flexibility in feedstock selection based on availability and suitability for different conversion technologies. Most importantly, this diversity promotes a more sustainable approach by enabling the use of forest biomass materials and dedicated crops grown on marginal lands, minimizing competition with food production. By harnessing this diversity, the United States can develop a robust and geographically balanced bioeconomy that contributes significantly to reducing carbon emissions.

1.4. The opportunity of forest waste and orphaned wells

In addition to biomass availability from agriculture, forestry, and urban landscape management [16], there is a growing demand for biomass utilization as part of wildfire risk reduction, especially in the U. S. West. Western forests are dominated by fire-adapted ecosystem types, but a century of land management policy focused on fire suppression has resulted in more catastrophic wildfires over the past few decades. Catastrophic wildfires result in loss of life and property and contribute to significant environmental impacts, ranging from smoke hazards to the contamination of water sources. Federal, state, local and non-profit partners in western communities with fire risk have collaborated on shared management goals for wildfire risk reduction at a landscape scale. Much of this work calls for the reduction of fuel loads by removing a portion of biomass in forests. U.S. investments in wildfire mitigation and forest health treatments have increased in recent years, but are not keeping pace with the scale of the crisis[17].

A key implementation barrier is a lack of markets for this low-value biomass, exacerbated by the dispersed nature of biomass resources [18]. The substantial cost of transporting low-value biomass to a centralized mill often renders the mill uncompetitive with other forest products manufacturing facilities in other regions, which leverage economies of scale from higher biomass concentrations and larger mill capacity [19]. There is an urgent need for new strategies to utilize forest waste in economically viable ways, as well as solutions that reduce smoke and other environmental hazards and reduce the recycling of forest carbon into the atmosphere; BiCRS technologies hold promise in contributing to these goals through monetization of carbon removal credits. Fig. 1 shows the distribution of estimated biomass resources from the U.S. Billion-Ton 2023 update and USDA Forest Service studies [14,16].

The potential bio-oil CO_2 sequestered varies by feedstock and many other parameters. Based on average bio-oil yields, we can estimate the total CO_2 sequestered from various feedstock groups. As shown in Table 1, about 720 million metric tons (MM Mt) of CO_2 per year could be removed from forest biomass in the United States through biomass pyrolysis and bio-oil sequestration. This represents 15 % of the U.S.'s 4,800 MM Mt 2023 annual emissions [20]. Most of these resources are dispersed, which makes it difficult to scale up processing facilities. Technologies need to densify biomass into dense solid or liquid materials that are transportable and can be stored as stable long-term materials [21].

Fast pyrolysis is the rapid thermochemical deconstruction of biomass into liquid (bio-oil), gas, and solid (biochar), which can be upgraded into a wide range of value-added products [22–27]. Recent studies have explored the environmental and economic feasibility of biomass pyrolysis combined with carbon capture and storage (CCS) [28–31]. The process involves producing biochar for soil amendment to sequester carbon, upgrading the bio-oil for use as fuel, and capturing CO_2 emissions from gas combustion for injection into geological formations. This approach has a low carbon sequestration rate because most of the carbon in the biomass remains in the fuel and returns to the atmosphere. A novel approach is to produce bio-oil for plugging orphaned wells. This maximizes the carbon removal rate while freeing the biochar to benefit agricultural practices through soil amendment and soil organic carbon enrichment [7,31].

The Infrastructure Investment and Jobs Act of 2021 has allocated funds to close approximately 120,000 abandoned oil and gas wells [32]. Given the average size of a crude oil developmental well drilled in the US (around 4170 m deep and 0.5 m wide) [33], plugging each well would require approximately 216,390 gallons of water/oil. Based on the 2021 data, this amounts to a total of 26 billion gallons needed to plug these wells. The current average cost for plugging an orphaned well is about 1 million dollars. As of April 2022, the number of documented orphaned

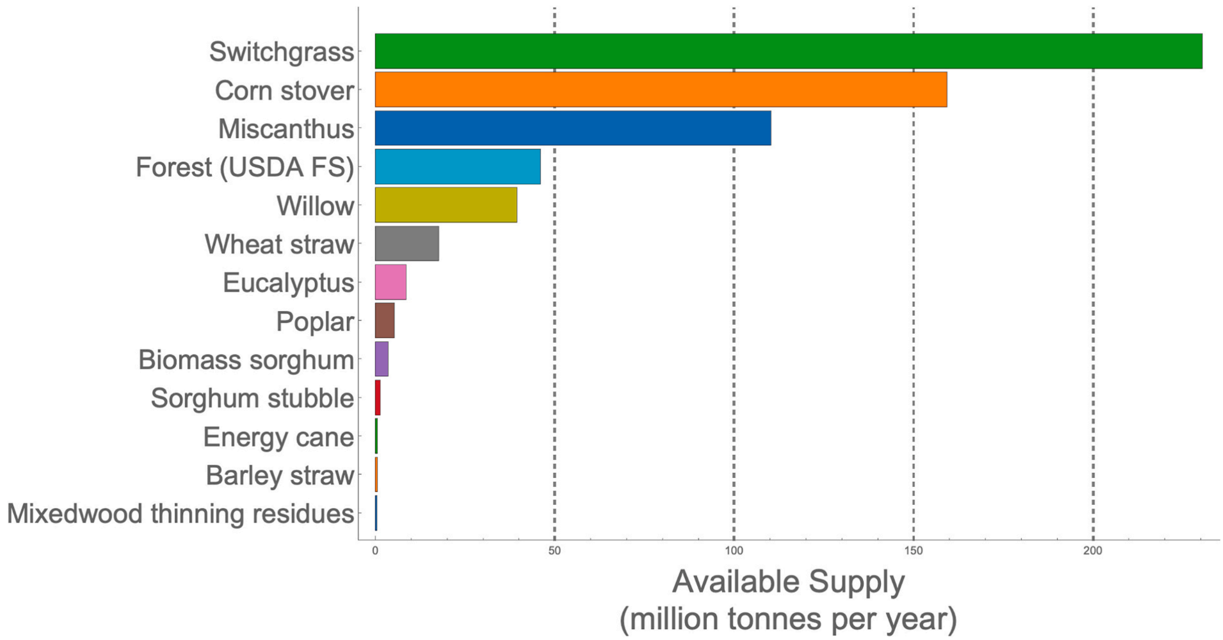

Fig. 1. U.S. Billion-Ton 2023 Update Biomass Supply Based on Mature Market Medium Scenario and USDA Forest Service Estimate for Annual Forest Biomass Supply.

Table 1
Estimation of CO_2 per year removed from biomass in the United States [22].

Feedstock	Quantity (MM Mt/ year)	Bio-Oil Yield (kg/ kg)	Bio-Oil Output (MM Mt/ year)	Bio-Oil Carbon (MM Mt C/year)	Bio-Oil CO_2 Sequestered (MM Mt CO_2/ year)
Forestry	303	40.8	124	61.8	227
Straws	263	40.8	107	53.6	197
Wood	205	35.4	72.5	36.3	133
Ag. Waste	89.8	53.1	47.7	23.8	87.4
Switchgrass	58.8	45.6	26.8	13.4	49.1
MSW	26.7	54	14.4	7.21	26.4
Total	**946.3**		**392.4**	**196.11**	**719.9**

wells increased to 123,318. However, estimates for undocumented orphaned wells range from 310,000 to 800,000[34].

1.5. Novelty and objectives of this study

This paper proposes a novel carbon removal pathway that utilizes fast pyrolysis technology for bio-oil carbon sequestration. The proposed system evaluates the operation of a network of small-scale pyrolysis biorefineries located in the U.S. The network consists of a baseline number of 200 facilities surrounding a centralized bio-oil terminal. The terminal serves as a central point where bio-oil is stored and transported via truck or pipeline to carbon storage locations. There are tens of thousands of abandoned oil and gas fields in the U.S., which can serve as bio-oil carbon storage [34,35]. The 2023 Billion-Ton Report highlights that approximately 159 million tons of corn stover are produced annually in the U.S., with a significant portion concentrated in the Midwest [15]. Therefore, the U.S. Midwest is selected as a site for gauging this technology's potential. In the proposed process, bio-oil is injected into deep geological formations that have successfully contained crude oil and gas for millions of years. These formations are located well below potable aquifers and are chosen for their capacity for storage, confinement from water or mineral resources, and compatibility with bio-oil. Additionally, bio-oil is denser than crude oil and tends to sink within the formation, potentially enhancing its long-term sequestration [36,37]. The current regulatory framework for properly sequestering bio-oil has redundant permitting, construction and operational safeguards that are designed to prevent migration of injected bio-oil, associated fluids or gases to the shallow subsurface or biosphere. These safeguards protect both groundwater and soils from any lixiviates that may form.

These studies collectively affirm that underground injection practices, when designed and operated with appropriate safeguards—particularly maintaining injection pressures below fracturing thresholds—are effective in protecting Underground Sources of Drinking Water. Proper well construction, integrity testing, and adherence to regulatory standards are critical components in ensuring the safety and efficacy of these injection operations [38–40].

The study also includes the pioneer plant and learning rate analysis. Pioneer plant analysis [41] estimates the cost ratio of a first-of-a-kind facility to a mature Nth plant design. It was developed based on industrial statistical data for chemical facilities and reflects improvement in the process design. Learning rates capture decreases in capital costs due to manufacturing advances [42]. It was developed as a way to measure cost reductions over time based on the number of units produced. A combination of pioneer plant analysis and learning rates could capture the potential cost decreases of pyrolysis units by addressing both process design development and manufacturing advances [43].

1.6. Scope and organization of the paper

In this study, we conduct a comprehensive techno-economic analysis (TEA) encompassing feedstock collection and delivery, pyrolysis costs, bio-oil transportation, utilities, and other operational expenses. Additionally, we perform a life cycle assessment (LCA) to estimate the system's net carbon emissions, accounting for carbon removal from bio-oil and carbon sequestration. A sensitivity analysis is also carried out to identify critical factors in decision-making and to gauge uncertainty. Moreover, the study includes pioneer plant and learning rate analysis to measure the reduction in capital cost based on the deployed capacity. The following sections provide detailed methodology and results: the methodology section outlines the process design approach and TEA assumptions, while the results section presents the study's preliminary findings.

2. Methods

2.1. Process design

The proposed system centers around a network of several biomass pyrolysis biorefineries, as illustrated in Fig. 2. These facilities convert biomass into bio-oil, which is then transported to a central terminal for storage and potential upgrading. The terminal acts as a hub for bio-oil management, facilitating its transport via truck, rail, or pipeline to designated carbon storage sites. The modeled system consists of mobile small-scale biomass pyrolysis units designed for bio-oil production. These units, specifically tailored for corn stover sourced from the U.S. Midwest, have a processing capacity of 10 tons per day. To achieve a larger-scale operation, the system employs a network of two hundred mobile pyrolysis units, collectively processing approximately 2,000 tons of biomass daily.

2.2. Feedstock selection

We modeled six feedstocks for this analysis: corn stover, clean pine, tulip poplar, hybrid poplar, switchgrass, and oriented strand board. These feedstocks were selected as part of a Pacific Northwest National Laboratory (PNNL) study [44]. They represent the most common biomass considered for bioenergy production.

2.3. Feedstock characterization

Corn stover is a cellulosic material composed of cellulose (36.5 %), hemicellulose (35.1 %), lignin (18.1 %), ash (10.3 %), and water (initially at 40 %) [45]. After harvest field drying, a secondary drying process is performed to achieve the target moisture content of 12 % for optimal pyrolysis. High moisture content in biomass increases the energy needed for drying and reduces bio-oil yield [22]. While field drying can reduce moisture to 25 %, it is unreliable due to weather and harvest schedules, and storage can reintroduce moisture. To potentially reduce natural gas consumption for drying, utilizing non-condensable gases (NCGs), a pyrolysis byproduct, as a heat source is explored. Furthermore, corn stover's significant ash content (assumed at 10.3 %) can cause fouling and corrosion in pyrolysis equipment. While mitigation strategies like passivation exist, they are not considered here. The ash, containing valuable plant nutrients, is assumed to be returned to the field with biochar after pyrolysis. Corn stover's collection cost are estimated at \$10- \$40/ton [46], with collection and stacking assumed for on-field mobile units (<100tons/day), and windrowing, baling and bale collection/stacking for larger (>100 tons/day) pyrolysis capacities. Nutrient removal costs are neglected due to nutrient return via biochar [47].

We assume that clean pine, tulip poplar, and hybrid poplar are all collected as waste residues. Clean pine is commonly grown in managed plantations. Composed of primarily cellulose (40–50 %), hemicellulose (25–35 %), and lignin (25–35 %). Its ash content (typically <1 %) is significantly lower than that of agricultural residues like corn stover (which can be >10 %). This lower ash content reduces the risk of fouling and corrosion in pyrolysis equipment. Extractives like resins and terpenes are also present, which can contribute to higher bio-oil yields but require downstream processing to remove any undesirable content. Further, the moisture content is higher (50 % or more) in a freshly cut pine and can be reduced to 15–20 % by air dying [48].

Tulip poplar is naturally found in the eastern US and grown in plantations. Hybrid poplars are short-rotation woody crops grown for the pulp and paper industries. Both have a high proportion of cellulose and a low proportion of lignin compared to other woody crops, making them more suitable for biofuel conversion [49]. Similar to pine, freshly cut poplar has high moisture content, so air-drying is common. Both

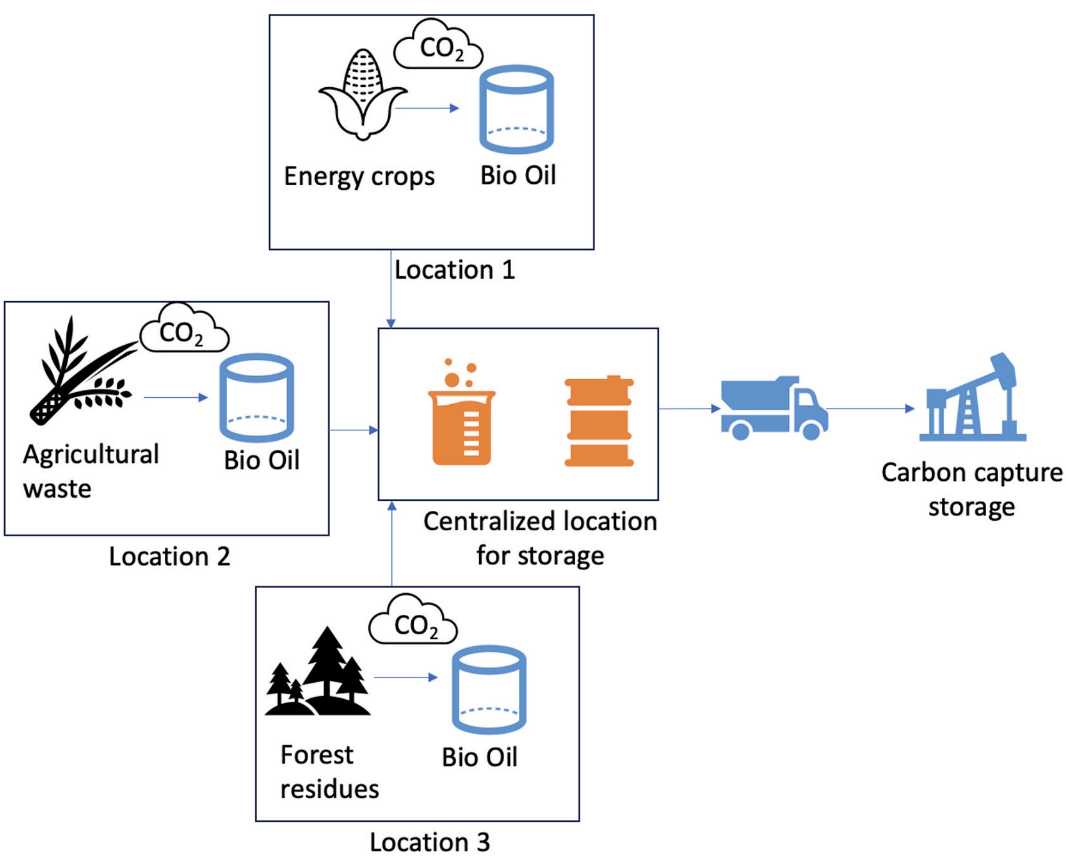

Fig. 2. Supply Chain of the Biomass Pyrolysis for Bio-oil Carbon Sequestration System.

feedstocks have been reported to have good bio-oil yields given their lower ash content.

Switchgrass is a perennial grass available across the US. It offers many ecological benefits, like improving erosion control and increasing soil organic carbon [50]. It is an attractive feedstock for bioenergy systems due to its adaptability to various weather and soil types. It has higher ash content (3.2–7 %) than woody biomass but generally less than corn stover [51]. The moisture content varies on harvesting time and field drying is a common practice. Oriented strand board is the last feedstock we considered. It is a type of engineered wood product employed in construction made from wood strands bonded with adhesives. We assume that oriented strand board is available as construction waste from demolition and other waste management activities. Typically, low moisture content is due to the manufacturing process, but the presence of adhesive can decompose into undesirable products and affect bio-oil quality.

The cellulose, hemicellulose, lignin, and ash content for these feedstocks are demonstrated in Table 2. In general, woody crops like clean pine and poplar have higher lignin content as reflected by their stronger structural properties. Feedstock prices were adjusted from the original study. The PNNL study focused on large-scale biorefinery operations processing thousands of tonnes per day. Since this study evaluates a small-scale operation, we adjusted the corn stover price to a baseline value of $30/Mt. The prices for other feedstocks were adjusted by the same factor to maintain the same relative difference in price.

2.4. Pyrolysis modeling

Feedstock composition significantly impacts pyrolysis performance [52]. Consequently, various modeling approaches, including empirical, kinetic, and even machine learning-based models, have been developed to predict biomass pyrolysis performance. This study utilizes the Kriging machine learning model, as described by Ganguly et al. [53] and Olafasakin et al. [54] which is well suited for predicting spatially and temporally correlated data. This Kriging model is informed by kinetic models to predict pyrolysis yields for multiple products simultaneously, including levoglucosan, phenols, biochar, kerosene, diesel, high and low naphtha, and others. To provide the underlying basis for the machine learning predictions, we employ the approach of Ranzi et al [55]. This kinetic model uses feedstock compositions (mass fractions of cellulose, hemicellulose, lignin, and extractives) and process conditions (temperature and heating rate) as inputs. The model outputs include the detailed composition of gas, tar, biochar, and other solid residue products, accounting for both primary solid phase and secondary gas phase reactions. Grounding the machine learning predictions in this detailed kinetic model ensures they are based on fundamental chemical principles. Once trained, the machine learning model can provide rapid predictions, obviating the need for complex kinetic calculations.

Table 2
Feedstock composition and prices (Adapted from Meyer et al. [44]).

Feedstock	Cellulose (wt. %)	Hemicellulose (wt. %)	Lignin (wt. %)	Ash (wt. %)	Price ($/Mt)
Clean Pine	0.365	0.351	0.188	0.19	$ 38.12
Tulip Poplar	0.463	0.249	0.244	0.044	$ 38.12
Hybrid Poplar	0.463	0.249	0.244	0.044	$ 38.12
Corn Stover	0.390	0.258	0.143	0.211	$ 30.00
Switchgrass	0.370	0.274	0.130	0.226	$ 30.50
Oriented Strand Board	0.5	0.05	0.4	0.05	$ 22.47

2.5. Overall process flow

Fig. 3 illustrates the overall process flow, divided into four key stages: 1) feedstock handling and pretreatment, 2) pyrolysis, 3) bio-oil recovery, and 4) heat recovery and gas recycling. The pyrolysis facility is designed as an "Nth plant" biorefinery, converting 10 metric tons per day (MTPD) of feedstock biomass into biochar and bio-oil. The N^{th} plant assumption indicates that the technology is mature and reliable, with major engineering and technical details having been addressed. This approach avoids the high costs associated with developing entirely new technologies ("pioneer plants"). The study incorporates a combined approach using pioneer plant analysis and learning rates to estimate potential cost reductions for future deployments. Pioneer plant analysis considers the cost premium associated with a first-of-its-kind facility compared to a mature Nth plant design. Learning rates account for cost reductions achieved through manufacturing advancements as the number of units produced increases. Together, these analyses provide a more realistic projection of future pyrolysis unit costs by capturing improvements in both process design and manufacturing efficiency.

2.6. Process stages

2.6.1. Feedstock collection and pretreatment

Key assumptions for each process stage are defined as per the base case of corn stover below:

Biomass collection and storage: Supplying the 12.5-ton-per-day (on a wet basis) pyrolysis unit with corn stover involves collection directly from the field, drying, and storage in a designated bin before processing. While the model uses a bin for storage, real-world applications might utilize an open concrete pad, or a designated field area covered by an optional tarp. To minimize spoilage, the system prioritizes using older stover first (First-In-First-Out method). Storage duration can vary between 1 and 6 months, with an additional buffer of 1 to 3 years' worth of stover kept on hand.

Stover availability is promising. Considering the average Illinois farm size of 375 acres [56] and a corn yield of 214 bushels per acre [57], we can estimate a corn stover yield of roughly 5.4 tons per acre annually (assuming stover yield matches corn yield by weight). Furthermore, the USDA billion-ton report suggests that 30 % to 70 % of corn stover can be sustainably collected without harming corn production or increasing erosion [58]. This translates to a potential range of 1.62 to 3.78 tons of stover available per acre.

Storage requirements depend on the stover quantity and storage practice. The most common practice is to bale the material and stack it either on the field or at a dedicated storage location. For long-term storage, the bales can be covered or wrapped. If the stover is used immediately, it may be set aside at the farm edge for the pyrolyzer unit to process on-site. Using common square bale dimensions (3ft x 4ft x 8ft) and assuming no stacking, storing 1400 tons would necessitate approximately 5.7 acres of land, or roughly 1.5 % of an average farm. This calculation does not take into account natural deterioration (10–30 % weight loss) or potential losses due to weather or human activity [46].

For larger pyrolysis units (100 tpd or more), stover collection extends beyond a single farm. Here, the stover is collected and transported to the central pyrolysis location, with the transport distance determined by the area of land needed to cultivate the required biomass feedstock. This can be calculated using the following equation [59]:

$$\boldsymbol{transport}_{distance} = \boldsymbol{\tau} \times \sqrt{\frac{\boldsymbol{biomass}_{year}}{\boldsymbol{\pi} \times \boldsymbol{biomass}_{yield} \times \boldsymbol{f}}}$$

where τ is the tortuosity factor (1.5) that accounts for the ratio between road network distances and straight-line travel, and f is the land or farmer participation factor (60 %) to adjust for the percentage of land that will agree to provide corn stover.

Grinding and Screening: The biomass undergoes size reduction in a

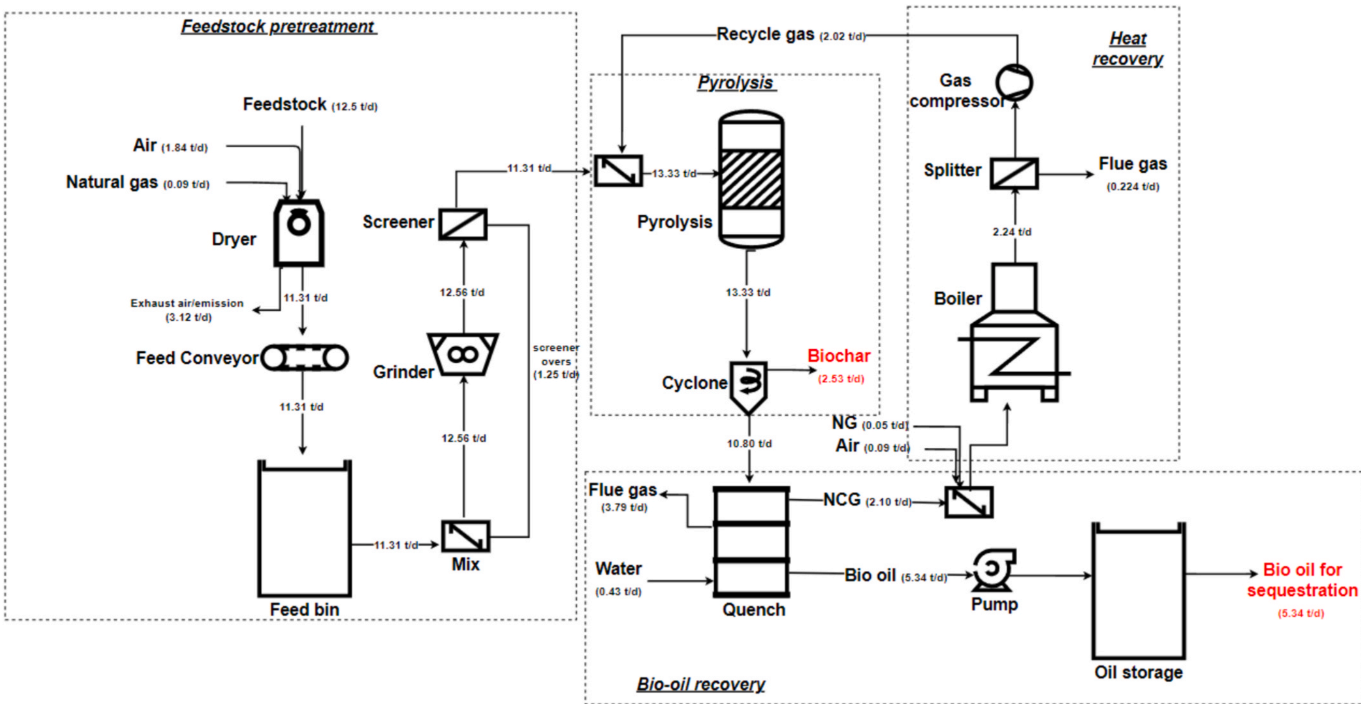

Fig. 3. Overall simplified process diagram for various feedstock fast pyrolysis to bio-oil and biochar.

grinder to increase its surface area for efficient pyrolysis. This grinding process aims for a final particle size of around 10 mm (mm) in diameter. Following grinding, a screening step separates the biomass. Here, approximately 90 % of the material progresses to the next stage, while the remaining 10 % consists of oversized particles. These overs are recycled back to the grinder to achieve the desired size, forming a closed-loop system that ensures complete utilization of the biomass feedstock. The grinder's energy consumption ranges between 50 and 100 kWh per ton of biomass.

Hammer mills are a well-established technology for biomass size reduction. A study by the Idaho National Laboratory [60] demonstrated that hammer mills equipped with a 2-inch square screen can achieve a single-pass grinding efficiency exceeding 87 %, reducing particles to less than 0.5 in. (12.7 mm). However, selecting the optimal screen size involves a trade-off. While a smaller screen can achieve the desired size in a single pass (higher efficiency), it may also increase grinding costs. These cost considerations are not currently factored into this model.

Key assumptions for each process stage—biomass collection and storage, grinding and screening—are defined as per the base case of corn stover described below, and are applied similarly to the other four feedstocks (clean pine, tulip poplar, hybrid poplar, oriented strand board and switchgrass). The logistics and handling of switchgrass are particularly similar to those of corn stover. While minor differences exist in the logistics of handling woody crops like clean pine, tulip poplar, and hybrid poplar, further details regarding these variations can be found in Thompson et al. (2017) [61].

2.6.2. Pyrolysis

Following drying, the biomass is mixed before entering the pyrolysis reactor. Inside the reactor, the biomass undergoes thermal treatment at approximately 500 °C in an inert environment fluidized with combustion gases derived from burning non-condensable gases (NCG) produced during the process itself. This pyrolysis process converts the biomass into various products, with expected yields of 28.8 % biochar, 39.7 % light bio-oils, 19.2 % heavy bio-oils, and 17.6 % non-condensable gases (as shown in Table 3). These yield estimates are based on experimental work by Polin et al. [62]. The machine learning model predicted

Table 3
Corn stover autothermal pyrolysis chemical formula, and yields for biochar, heavy ends, light ends, and NCG (Adapted from [62]).

Compounds	Chemical Formula	Pyrolysis yield
Cellulose	C6H10O5	–
Lignin	C9H10O3	–
Hemicellulose	C5H8O4	–
Biochar	C5.12Si0.642	0.201
Heavy ends	C5.2H5.98N0.14S0.001O1.9	0.192
Light ends	C1.76H3.52N0.092S0.002O4.62	0.406
CO_2	CO_2	0.118
CO	CO	0.058
CH_4	CH_4	0.01

pyrolysis yields for other feedstocks.

Gas Handling and Recycling: The non-condensable gas (NCG) stream exiting the flash tank is not discarded but utilized for heat generation. It's mixed with combustion air and burned in a furnace. The flue gas from this furnace passes through a cyclone filter to prevent solid particles and impurities from accumulating in the pyrolysis reactor. The remaining hot gas is then recycled back to the pyrolysis mixer using a compressor. This recycled gas provides heat and helps maintain the desired temperature within the reactor.

2.6.3. Separation

Biochar and Ash Separation: The output from the pyrolysis reactor travels to a two-stage cyclone for efficient biochar separation. The first stage, a high-volume cyclone, captures roughly 90 % of the biochar and ash from the vapor phase. A subsequent high-precision cyclone refines the separation, achieving a final biochar and ash recovery rate of 99 %. The separated biochar finds application in agriculture and is sold for $100 per ton, with a handling fee of $50 per ton factored into the price [63].

Bio-Oil Separation and Storage: After exiting the cyclone, the vapors travel to a quenching unit for rapid cooling. This cooled vapor stream then enters a flash tank, where bio-oil condenses and separates from the non-condensable gas phase. The bio-oil is subsequently pumped into a dedicated storage tank for accumulation.

2.6.4. Bio-oil transportation

Transportation of the bio-oil to a central collection point, located between 30 and 90 miles away, is achieved via trucks. The estimated bio-oil delivery cost is \$0.12 per ton per mile, factoring in a flatbed truck weight limit of 21.8 tons and a cost of \$2.60 per mile (detailed analysis in the TEA section).

Transportation costs are based on research by the American Transportation Research Institute (ATRI) [64]. The average industry respondent reported a flatbed transportation cost of \$2.604 per mile. The average flatbed trailer capacity is 21.8 tons (48000 lb) and 57.8 m^3 (2040 ft^3). The as-received density of corn stover (our base case) is 50 kg per m^3 [65]. The density of bio-oil is assumed as 1200 kg per m^3 [66]. When transporting biomass, the flatbed truck is limited by volume and can carry up to 2.8 tons. When transporting bio-oil, the flatbed truck is weight-limited and can carry 21.8 tons. Thus, the biomass delivery cost is \$0.90 per ton per mile, and the bio-oil delivery cost is \$0.12 per ton per mile.

The estimated bio-oil delivery cost of \$0.082 per ton per mile factors in the density difference between bio-oil and corn stover. While nominal loading and unloading costs are included, this does not account for potential variations in equipment needs. For biomass collection, existing farm equipment might suffice for handling, keeping costs low. Bio-oil could also be loaded into the truck at minimal cost. However, the use of flatbed containers necessitates additional considerations. These containers may require specific materials to resist corrosion and clogging, potentially impacting costs related to maintenance and cleaning.

2.6.5. Bio-oil injection (well plugging)

Bio-oil is assumed to be sequestered in a well-site at cost. The LCA methodology follows the ISO 14040/14044 standard approach. The analysis employs OpenLCA and the EcoInvent 3.7 database to gather the environmental impact factors of the process using the U.S. TRACI impact assessment method. The functional unit for the analysis is 1 kg of bio-oil. We employ a mass basis, instead of an energy or economic basis, for the functional unit because the primary product will not be combusted or sold for energy applications. This functional unit is comparable to those reported in the literature [67]. The system boundary ranges from cradle-to-grave. It starts with the feedstock production to the oil injection at the well closure site. More details under the LCA section below.

2.7. Techno-economic analysis (TEA)

TEA examines the economic feasibility of the pyrolysis biorefinery network. It considers various cost factors, including employee salaries, feedstock collection and delivery, bio-oil transportation, utility costs, and other operational expenses. This analysis is then compared to a 2015 National Renewable Energy Laboratory (NREL) report to identify cost variations across different operational sections [26]. Ultimately, the TEA determines the minimum selling price (MSP) for the produced bio-oil, a critical indicator of the project's commercial viability. At a 0 % internal rate of return (IRR), the MSP is equal to the production cost.

Table 4
Material and utility price assumptions.

Item	Price (\$/unit)	Source
Biomass collection cost	(\$10 – \$40) per ton	[46,68]
Biomass delivery cost	\$0.90 per ton per mile	[64,69]
Bio-oil delivery cost	\$0.12 per ton per mile	[64]
Natural gas	\$3.0 per MMbtu	[70]
Electricity	\$0.065 per kWh	[70]
Water	\$0.0005 per kg	[71]
Solids/biochar handling	\$50 per ton	[63]
Bio-oil (well cement)	\$0	NA
Biochar price	\$100 per ton	[72]

Key TEA assumptions include material and utility prices, equipment costs, and financing terms. Table 4 details the assumed values for materials and utilities. Biomass collection costs vary depending on plant capacity. Plants below 100 tons per day incur a cost of \$10 per ton, while larger facilities pay \$40 per ton to account for additional logistic costs. This cost incorporates harvesting, farm-side collection, and truck loading.

Natural gas and electricity prices are based on historical U.S. averages for industrial prices. Water prices are for processed water use. Solid handling costs are primarily for biochar storage. Biochar is assumed to be valued at \$100/ton for agricultural market applications [72].

Table 5 details the financial assumptions for this project, which are aligned with Department of Energy (DOE) biorefinery assessment guidelines. We target a 0 % internal rate of return (IRR) and explore higher IRRs (10–40 %) typically associated with novel technologies. The analysis assumes a 21 % income tax rate and operation for 333 days per year. Financing involves a 40 % equity share and a 7 % loan rate over 10 years. Additional factors like labor benefits, property taxes, insurance, supplies, maintenance, and administration are consistent with standard DOE TEA reports [7,22]. The fringe and supplies costs are labor percentages, whereas all other costs are capital costs percentages.

2.8. Lifecycle assessment (LCA) and marginal abatement cost (MAC)

Table 6 shows the global warming potential (GWP) factors for feedstock and key resources. A complete inventory table containing other environmental impact categories is provided in the Supplementary Information **(SI), Table S1**.

The Marginal Abatement Cost (MAC) is the primary metric for this study. The MAC is the minimum carbon revenue required for the process to break even. It is calculated as the production cost ratio to the net carbon removed. It is a common metric for comparing carbon removal technologies [73].

2.9. Pioneer cost growth, learning rate, and economies of number analysis

Following the methodology outlined by Wright et al. [22], we conduct a cost analysis for this pioneering pyrolysis plant. This analysis considers two key factors: plant performance and cost growth.

Plant Performance: The plant performance is a factor applied to the operating costs, and it depends on the number of new steps, unknown mass balance equations, solids use, and waste disposal. For example,

Table 5
Financial and Lifetime Operation Assumptions (Adapted from [26]).

Item	Value
Internal Rate of Return	0 %
Duration	(2018, 2038)
Depreciation	7-year MACRS schedule
Income tax	21 %
Operating days	333 days/year
LANG factor	2.5
Construction schedule	2 years (40 % year 1, 60 % year 2)
WC over FCI	5 %
Labor Cost	
Fringe benefits	40 %
Supplies	20 %
Capital Cost	
Property tax	0.10 %
Property insurance	0.50 %
Maintenance	0.30 %
Administration	0.50 %
Finance fraction	40 %
Finance years	10 years
Finance interest	7 %

Table 6
Global Warming Potential Lifecycle Inventory Table for feedstock and resources (see SI for other factors).

	Global warming (kg $CO_{2\text{-eq}}$)	Unit	EcoInvent Provider
Clean Pine	1.72E-02	kg	bark chips, wet, measured as dry mass to generic market for residual hardwood, wet | residual softwood, wet | APOS, U
Tulip Poplar	3.69E-02	kg	bark chips, wet, measured as dry mass to generic market for residual hardwood, wet | residual hardwood, wet | APOS, U
Hybrid Poplar	3.69E-02	kg	bark chips, wet, measured as dry mass to generic market for residual hardwood, wet | residual hardwood, wet | APOS, U
Corn Stover	1.08E-01	kg	maize silage production | maize silage | APOS, U
Switchgrass	3.78E-01	kg	alfalfa/grass silage production | alfalfa-grass silage | APOS, U
Oriented Strand Board	2.34E-02	kg	oriented strand board production | residual wood, dry | APOS, U
natural gas, high pressure	8.59E-01	m^3	natural gas, high pressure
electricity, high voltage	1.14E-01	MJ	electricity, high voltage
bundle, energy wood, measured as dry mass	5.19E-02	kg	bundle, energy wood, measured as dry mass
heat, air–water heat pump 10 kW	8.45E-02	MJ	heat, air–water heat pump 10 kW
electricity, high voltage	1.66E-01	MJ	electricity, high voltage
transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100 %	1.20E-01	t*km	transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100 %
heat, district or industrial, natural gas	7.39E-02	MJ	heat, district or industrial, natural gas
transport, tractor and trailer, agricultural	3.64E-01	t*km	transport, tractor and trailer, agricultural
natural gas, high pressure	8.59E-01	m^3	natural gas, high pressure
dryer	2.03E + 02	Item (s)	dryer
charcoal	1.31E + 00	kg	charcoal
deep well closure	1.60E + 00	m	deep well closure

power plants are mature technologies, and their design can be accomplished with significant accuracy. If we add a pyrolysis unit to process a portion of the feedstock, the mass balances around the pyrolysis unit would be considered unknown or uncertain relative to the power plant's significant empirical data. We have assumed that essentially all pyrolysis biorefinery process steps are novel, including the pyrolysis reactor, bio-oil recovery, and biochar handling. We consider that all mass balance equations are accounted for. Solid is a binary factor indicating that solids are present in the process. The waste factor represents our current understanding of the waste management practices needed by the facility. We have conservatively selected values resulting in a plant performance factor of 22.3 %. This means that the facility operates at 22.3 % of its full capacity in its first year, and its operating capacity increases by 22.3 % every year until it reaches its full capacity.

Cost Growth: Cost growth estimates the capital investment for a pioneer plant based on a Nth plant design. The cost growth calculation considers the percentage of new operations, the presence of impurities, the process complexity, the inclusiveness of the design, and the level of the project definition. Based on conservative assumptions, we employ a cost growth factor of 29 %. This means that the Nth plant costs are 29 % of the pioneer plant costs.

Additionally, we include an Economies of Number analysis based on the model by Wright, from Weiss et al. [74]. The Wright model has been improved by various studies, but it provides a reasonable estimate for learning rate impacts [43]. The Wright model calculates the capital cost of a future unit as a function of the original capital cost, the number of manufactured units, and the learning rate (LR):

$$C_t(M_t) = C_0 M_t^{\log_2(1-LR)}$$

Economies-of-numbers is an alternative to economies-of-scale that can enable technological cost savings through mass production and rapid iteration. Compared to economies-of-scale, which leverage large plant capacities, economies-of-numbers benefit from building many small units. Power plants and vehicle engines offer a classic example. Both rely on combustion and power cycles, but they apply the cycle at different scales and are now significantly cheaper than decades ago. Pyrolysis and direct air capture systems share a similar analogy.

Fasihi et al. [75] recently reviewed the learning rates of direct air capture systems. Their analysis compared various DAC configurations, including high and low-temperature designs. They projected that DAC capital costs would decrease from \$815 to \$84/t CO_2 through scale-up and technological advances between 2020 and 2050. The levelized cost of decarbonization (LCOD) for these scenarios ranged from \$289 to \$32/t CO_2 depending on various colocation scenarios that reduce heating costs. A National Academies of Science Engineering and Medicine report estimated DAC carbon removal costs to range from \$89 to \$420/t CO_2 [5].

In this study, we compare the impact of economies of scale and learning rates on the scale-out of DAC and pyrolysis systems. The baseline assumptions are provided in Table 7. The DAC assumptions are adapted from Fasihi et al. [75]. The pyrolysis systems are from Ganguly et al. for the 250 tpd system [7] and this study (10 tpd).

3. Results

The simulated pyrolysis facility efficiently generates 5.3 tons per day of bio-oil and 2.5 tons per day of biochar from 10 dry tons per day of corn stover. These results are similar to those reported in previous experimental [62] and simulation studies [7]. The material and energy flow data, process block diagram, and equipment design parameters are provided in the SI. Additional data is publicly available at the Github repository (https://github.com/markjet7/pyrolysis_wells.git).

The base case capital cost is estimated at \$1.28 million or \$128,000 per ton per day of feedstock capacity (\$241,000 per ton per day of bio-oil output capacity). The base case bio-oil minimum selling price is \$175 per ton at a 10 % IRR. The base case carbon abatement cost is \$83.6 per ton of CO_2 or \$152 per ton of CO_2 when not considering biochar carbon sequestration.

3.1. Capital costs

The estimated capital cost for the basecase scenario is \$128,000 per ton per day of feedstock capacity. Capital cost estimates range from \$13,000 to \$440,000 per ton per day of feedstock capacity. The lower estimate is for a facility with a 20 % learning rate after 1000 manufactured units based on an N^{th} plant design. The higher estimate is for a pioneer plant. We also compare our estimates to those published in the literature and normalized them to 10 tons per day and a \$2021 basis, as displayed in Fig. 4.

The study by Kim et al. [76] investigated the operation of a mobile pyrolysis unit. The high cost is due to a size mismatch between the pretreatment (grinding, drying, and handling) units and the pyrolysis reactor. During operation, the pyrolysis unit had a smaller throughput than expected, resulting in a high normalized cost. The Sandia study [77] modeled a single auger pyrolysis reactor for biochar production from forest residues. Their system does not include gas recycling or heat

Table 7
Economies of scale and learning comparison for direct air capture (DAC) and pyrolysis systems.

System	Capacity (Mt CO_2/year)	Capital Cost ($MM ($/t CO_2/year))	Operating Cost	Learning Rate (%)	Electric Use (kWh/t CO_2)	Heat Use (MJ/t CO_2)
LT DAC	473	730	250	4 %	250	6300
HT DAC	473	815	250	4 %	250	6300
Pyrolysis (250 tpd, 0 % LR)	50,325	$11 ($218)	$3.00	0 %	82	0.6
Pyrolysis (250 tpd, 5 % LR)	50,325	$11 ($218)	$3.00	5 %	82	0.6
Pyrolysis (10 tpd, 0 % LR)	2,000	$1.30	$0.12	0 %	NA	0.6
Pyrolysis (10 tpd, 20 % LR)	2,000	$1.30	$0.12	20 %	NA	0.6

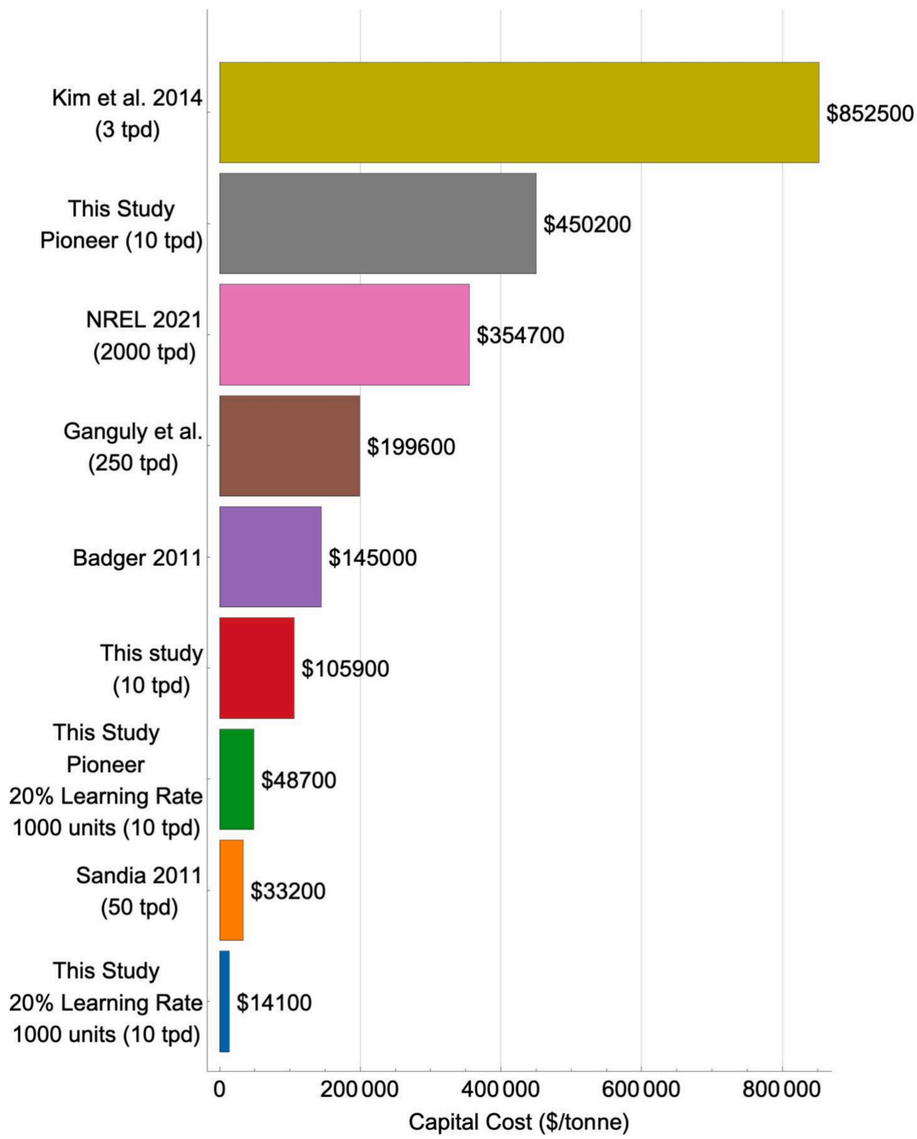

Fig. 4. Comparison of Pyrolysis Biorefinery Normalized Capital Costs Scaled to 10 tons per day of Biomass Capacity.

recovery units and has minimal pretreatment units.

3.2. Operating costs

Fig. 5 shows a comparison of the bio-oil production costs for the basecase (corn stover as feedstock), pioneer, and learning rate scenarios. A 20 % learning rate reduces the cost to about $168.67 per ton from a basecase of $220. The highest cost estimate, based on a pioneer plant analysis is about $531 per ton. Most of the cost differences are due to changes in the capital costs, as shown by the greater ROI. The primary operating cost is biomass purchase and collection at $87.4 per ton of bio-oil. Bio-oil delivery costs $3.1 per ton.

Fig. 6 shows a comparison of the MAC for the basecase, pioneer, and learning rate scenarios. As with the cost, the learning rate scenario has the lowest MAC of $146.8 per ton of CO_2 removed. The pioneer plant has a MAC of $328.8.

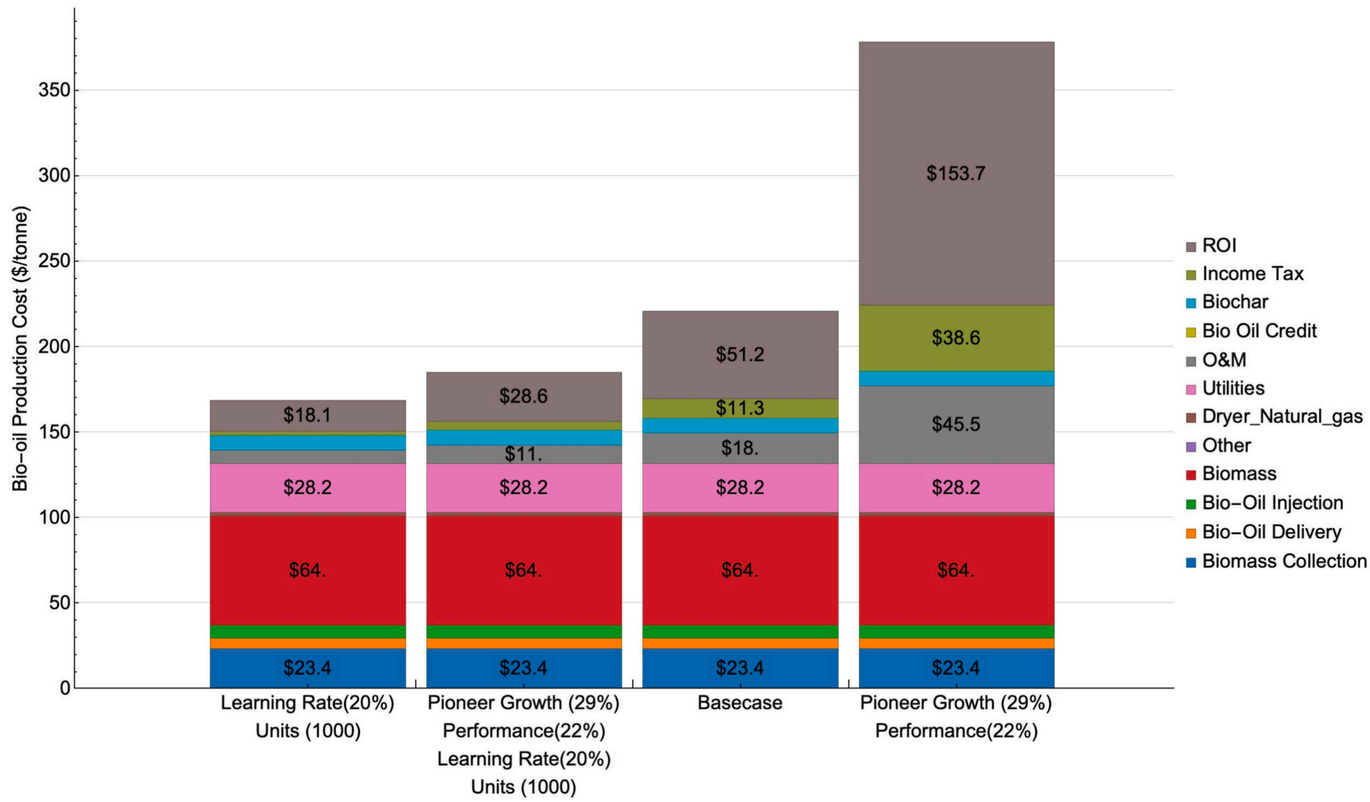

Fig. 5. Comparison of Bio-oil Production Costs ($/tonne) based on Learning Rate, Pioneer and Performance Growth.

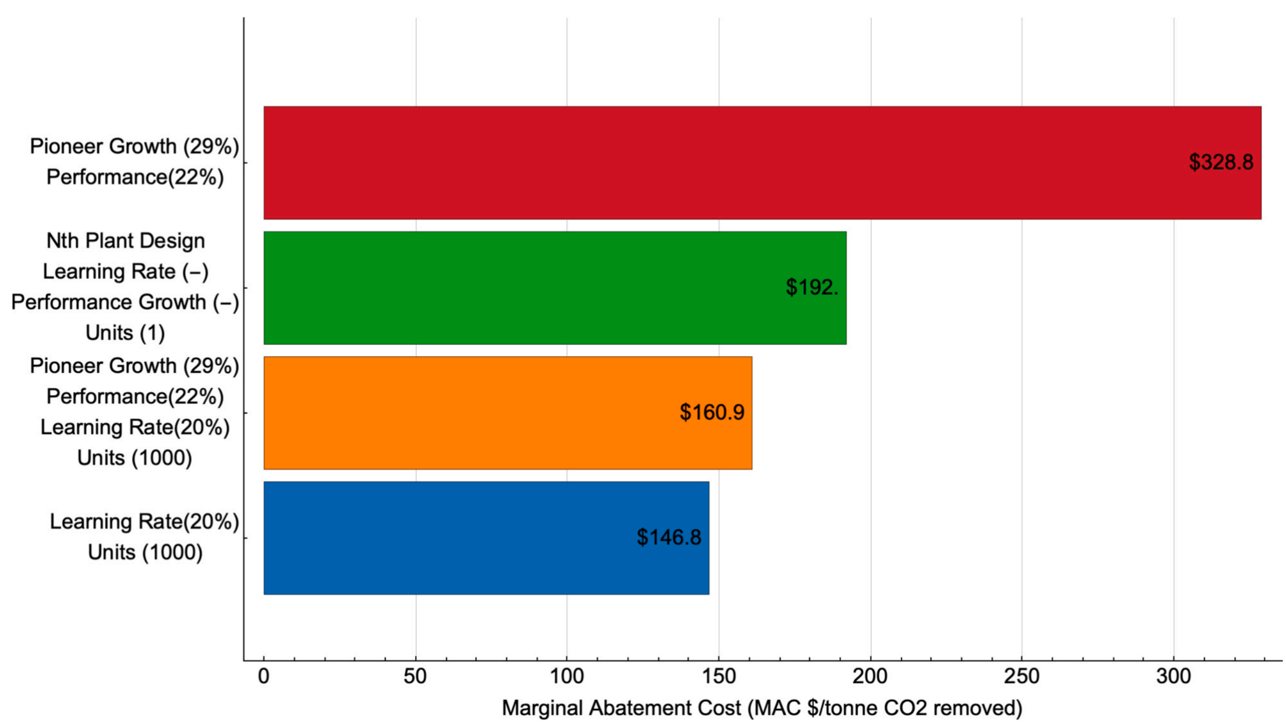

Fig. 6. Comparison of Marginal Abatement Costs for Base case (Nth Plant Design), Pioneer, and Learning Rate Scenarios.

3.3. Lifecycle analysis

The findings from the lifecycle greenhouse gas analysis are illustrated in Fig. 7. Corn stover (CS) captures about 2.20 (1.16 t CO_2e/t CS) t CO_2e/t BO during its growth phase. The carbon burden of corn stover from corn production is 0.2 (0.11) t CO_2e/t BO. Farm machinery emissions are estimated at 0.02 (0.01) t CO_2e/t BO. The pyrolysis step results in emissions of 0.04 and 0.18 tCO_2e/t BO (0.02, 0.1) from power and heat consumption, respectively. Bio-oil transport yields emissions of 0.12 (0.06) t CO_2e/t BO. Finally, wells plugging involves various mixing

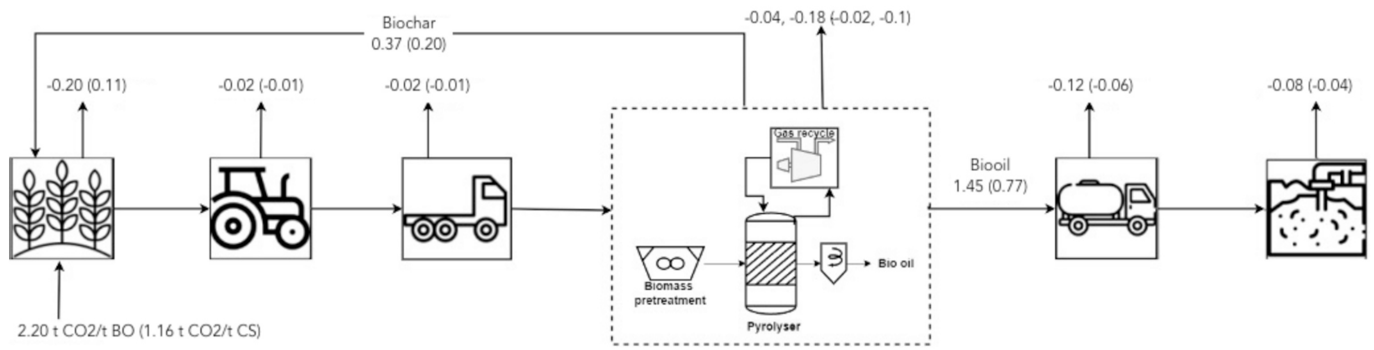

Fig. 7. Lifecycle greenhouse gas emissions of the pyrolysis to bio-oil well plugging system in t CO_2/t biooil (BO) or corn stover (CS) in parenthesis.

and heating processes that result in emissions of 0.08 (0.04) t CO_2e/t BO. From the original corn stover carbon of 2.20 (1.16) t CO_2e/t BO, about 1.45 (0.77) t CO_2e/t BO is sequestered. The business-as-usual approach for plugging wells is to use water and expensive cement binder materials. Thus, there is an argument that plugging emissions should be allocated to wells operations, but this will require further analysis and debate by LCA practitioners and policymakers. A more detailed breakdown of the supply chain costs and emissions is included in Fig. S2**.**

Fig. 8 shows the pyrolysis oil carbon footprint for the feedstock scenarios. The negative values represent carbon removals through bio oil well injection and biochar soil application. Carbon removals range between 1.7 and 2.1 kg CO_2/kg of oil. Carbon emissions range from 0.48 and 1.2 kg CO_2e/kg of oil. The woody feedstock scenarios have similar oil and char yields; thus, their carbon removal rates are similar. Corn stover and switchgrass yield lower bio-oil and char outputs. In most scenarios, utilities, oil transportation, and deep well closure are the primary emission sources. Feedstock production is a significant emission source for corn stover (0.20 kg CO_2/kg of oil) and switchgrass (0.72 kg CO_2/kg of oil). Net carbon footprints range from −0.62 to −1.55 kg CO_2/kg oil.

Switchgrass and corn stover have the most impact in other environmental categories, as shown in Fig. 9**.** Corn stover has the most impacts related to carcinogens, ecotoxicity, and non-carcinogenics. Switchgrass leads in other categories. The impacts of woody resources are typically less than 10 % of the leading crop scenario, except for ozone depletion and non-carcinogens, at about 20 %, and ecotoxicity, at about 42 %. These results are due to the differences between agriculture and forest management practices. They show that feedstock selection is an important criterion for sustainable carbon removal practices.

Fig. 10 presents the impact assessment results for all feedstocks, generated using OpenLCA. Emissions across various environmental categories are tracked to provide a comprehensive life cycle perspective. Climate change, quantified as kg CO_2 equivalent, reflects contributions to global warming. Feedstock production for switchgrass and corn stover shows the largest contribution to this impact, while woody crops contribute the least. Similarly, acidification (kg SO_2 equivalent) and eutrophication (assessing nutrient enrichment in aquatic systems) have feedstock production and oil transportation identified as the most significant contributors. Utilities are the primary contributors to ozone depletion and potential adverse effects on human health, with a similar percentage for all feedstock types.

Fig. 11 illustrates the carbon abatement cost for each feedstock type. Switchgrass exhibits the highest cost, primarily due to biomass collection and return on investment. Woody feedstocks show abatement costs around \$100/Mt CO_2, which could potentially decrease to approximately \$70/Mt CO_2 with the application of a learning factor.

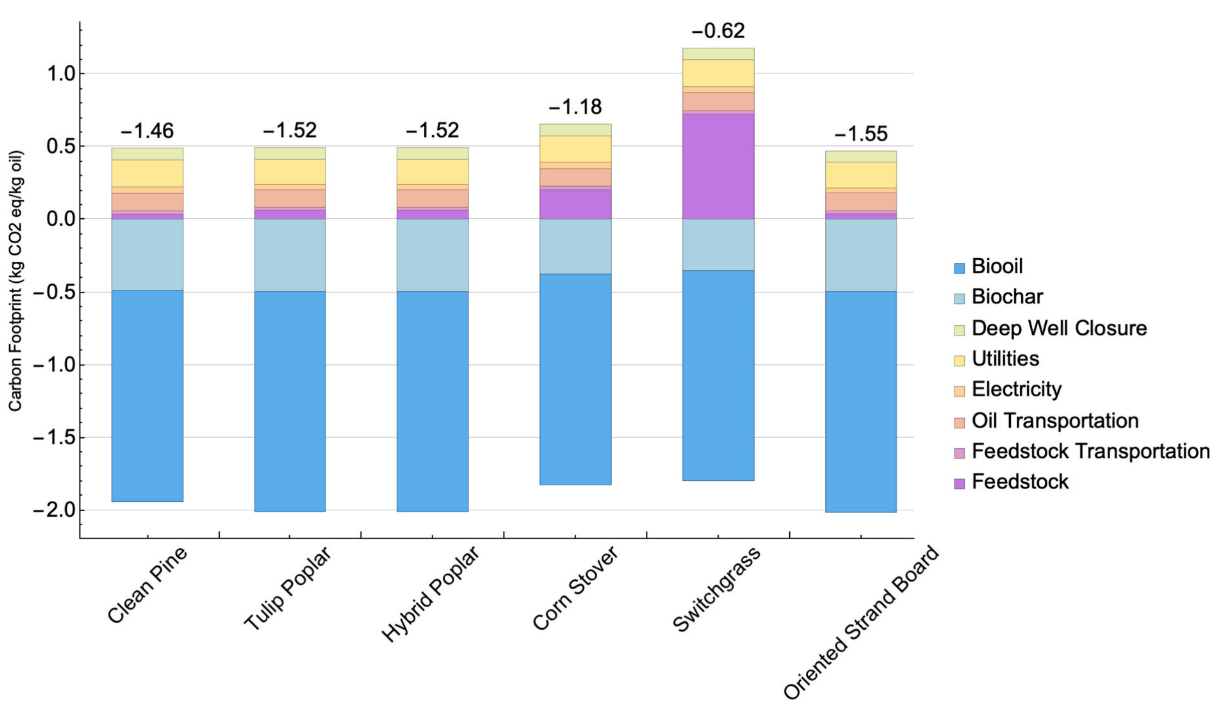

Fig. 8. Biomass fast pyrolysis for oil well injection lifecycle carbon footprint in kg CO_2eq/kg oil.

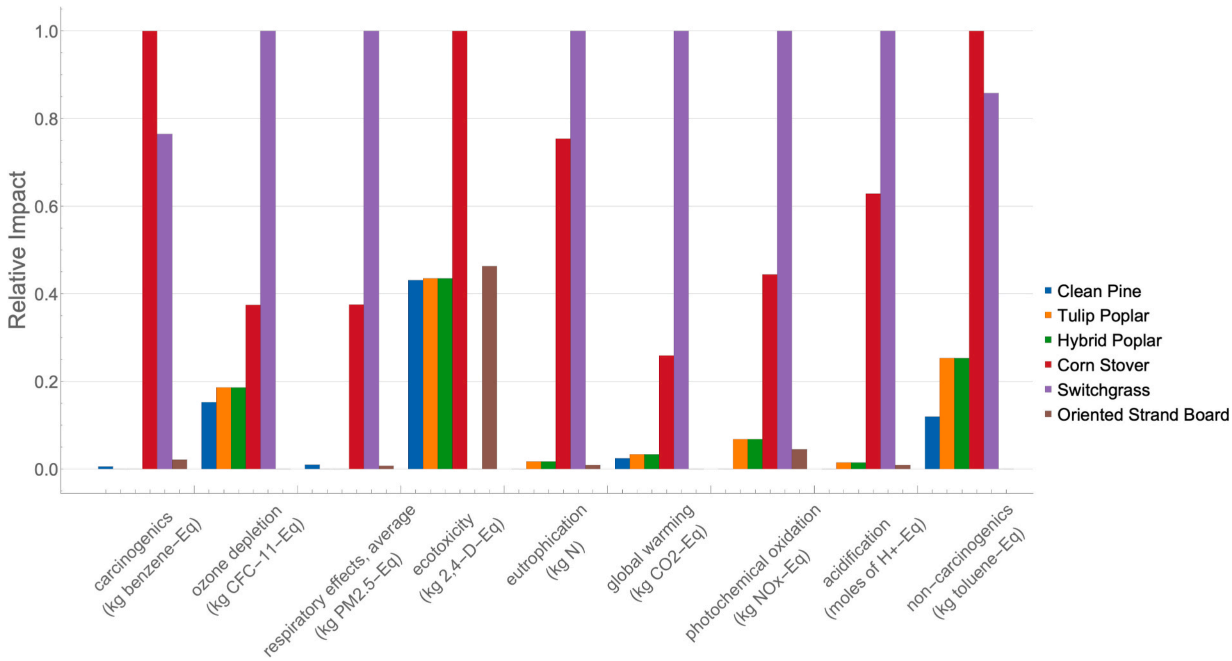

Fig. 9. Lifecycle environmental impacts relative to the maximum impact by feedstock.

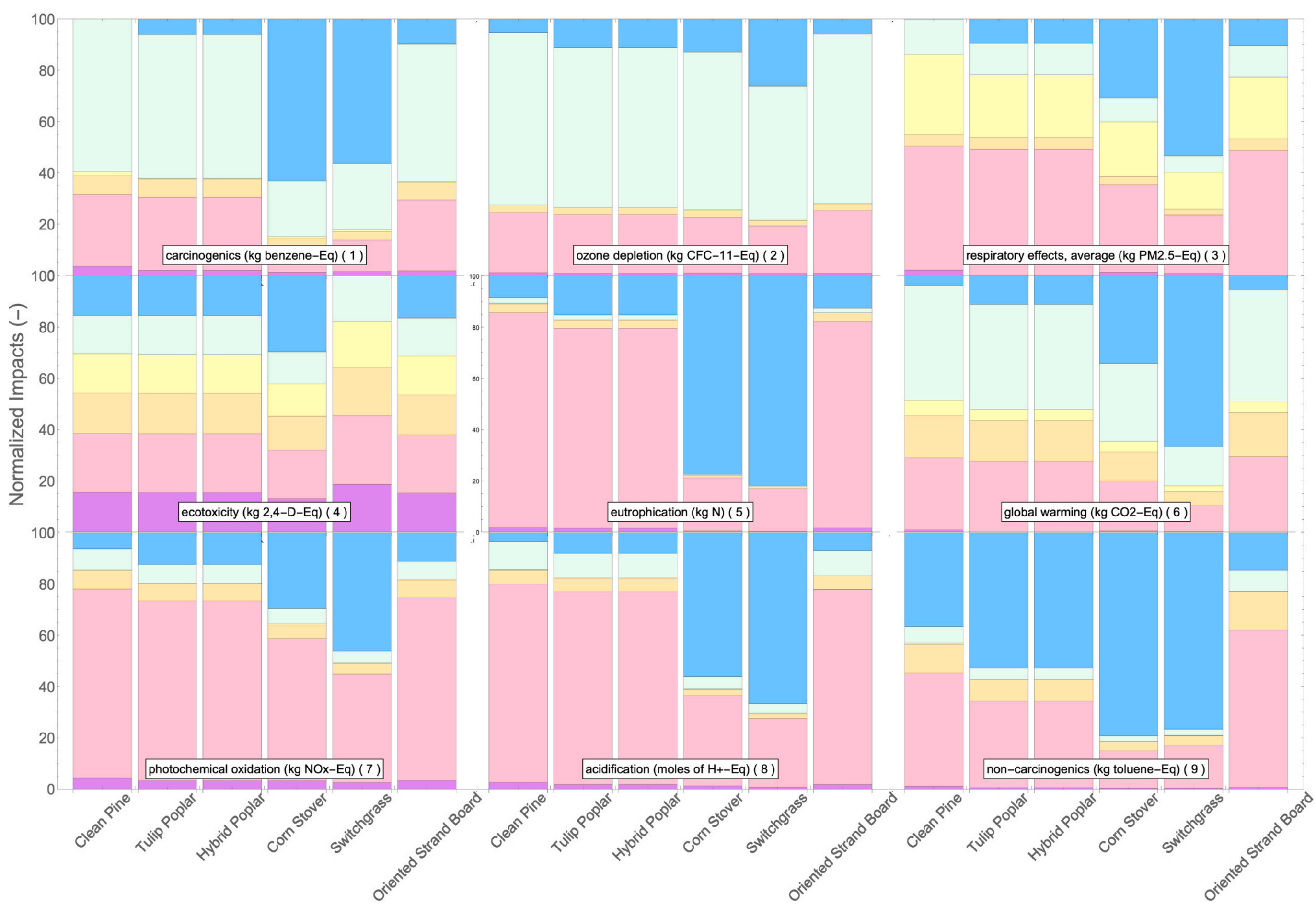

Fig. 10. Comparison of the normalized lifecycle environmental impacts for biomass fast pyrolysis oil for well injection applications.

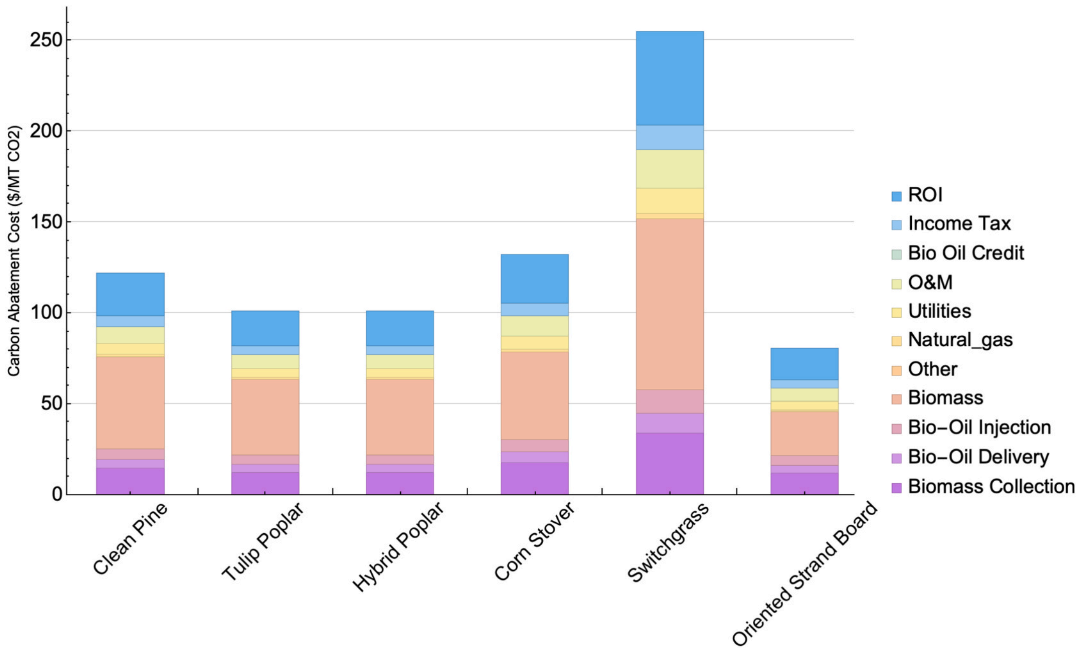

Fig. 11. Biomass fast pyrolysis for oil well injection lifecycle carbon footprint in kg CO_2eq/kg oil.

3.4. Sensitivity analysis

The production cost sensitivity analysis shown in Fig. 12 indicates that feedstock price and production factors have the largest impact on the MAC for most feedstock. Switchgrass has the greatest sensitivity to these parameters resulting in changes of more than \$50/MT CO_2. Oriented strand board has the lowest sensitivity. These results indicate the impacts of changes in single parameters. However, practical applications will experience changes to multiple parameters simultaneously, which could be evaluated using uncertainty analysis [78].

Small-scale pyrolysis systems can leverage economies of numbers as an alternative to economies of scale. As shown in Fig. 13, all proposed pyrolysis systems are more economical at scales below 6,000 Mt CO_2/year. At larger scales, DAC systems are competitive with pyrolysis systems at costs of about \$120/t CO_2. The uncertainty around these estimates is between −30 and 100 %. The small pyrolysis capacities allow them to reach large carbon removal capacities while avoiding the diseconomies of scale related to biomass and bio-oil transportation logistics. Investing in small units reduces investment risks during scale-out. However, building a mass-manufacturing facility to accelerate the benefits of mass production could require similar investment and risk as deploying a large centralized DAC facility, but this is a topic that is beyond the scope of this study.

3.5. Limitations of this study

The limitations of this study can be categorized into three types: technology readiness [79], modeling and parameter uncertainty [78], and scale-up and commercialization risk [80]. Pyrolysis systems have been commercialized for a variety of applications, including heat and power, asphalt production, and biochar production. However, pyrolysis systems for well-plugging systems are an emerging technology. Commercial systems are currently in operation, but it will take time for information on their performance to become available. TEA and LCA models and parameters are uncertain. Previous studies, including some by the authors [78], have attempted to characterize this uncertainty. In this study, there is significant uncertainty around the pyrolysis performance of the feedstocks, the TEA/LCA parameters, and changes during technology scale up. There is not sufficient data to, for example, compare the corn stover versus switchgrass pyrolysis uncertainty. The sensitivity analysis identified feedstock price and biochar carbon as key TEA/LCA parameters. There is no reliable market data on feedstock prices for all feedstock, and insufficient experimental data on how biochar carbon varies by feedstock for autothermal pyrolysis. Previous

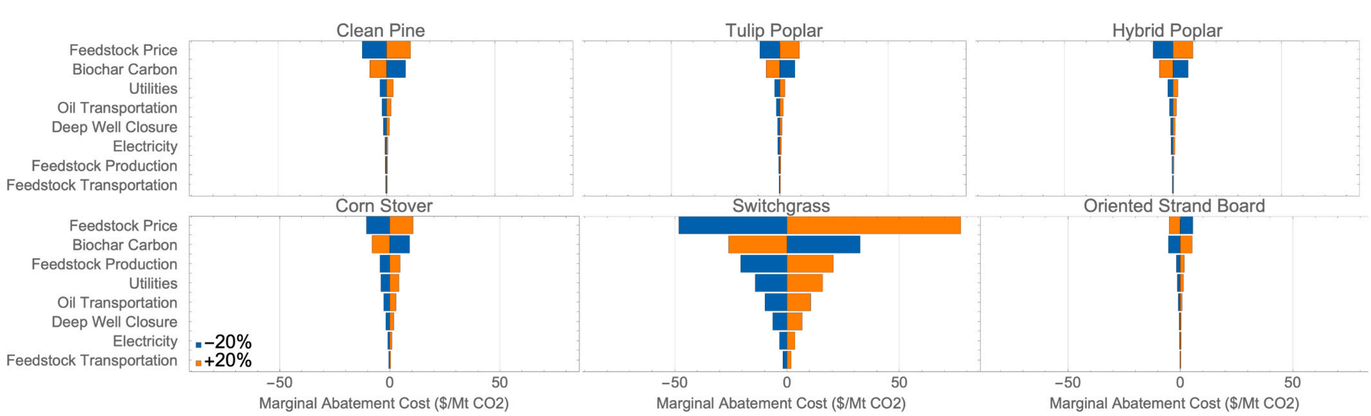

Fig. 12. Marginal Abatement Cost Sensitivity Analysis based on 20% Parameter Changes.

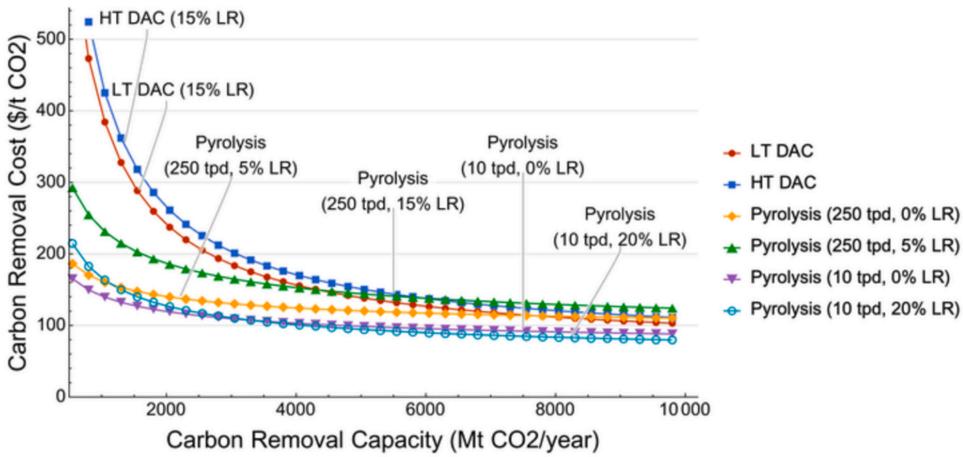

Fig. 13. Economies of scale and number comparison of direct air capture versus pyrolysis systems.

studies have discussed pyrolysis scale-up and commercialization risks [80–82]. There are technical, financial, and policy considerations to consider that are beyond the scope of this study. Infrastructure limitations, financial market instability, and carbon market incentives can significantly influence commercialization potential.

4. Discussion

4.1. Summary of key findings

This study explored the potential of biomass pyrolysis for capturing and storing atmospheric carbon dioxide, specifically in the United States. The study focused on six common biomass feedstocks: corn stover, switchgrass, clean pine, tulip poplar, hybrid poplar, and oriented strand board, supplied through a distributed network. Our analysis, encompassing process design, techno-economic assessment (TEA), and lifecycle assessment (LCA), suggests that this system presents a promising pathway for technically and economically viable carbon sequestration.

The proposed system utilizes a network of small-scale pyrolysis units strategically located near farms, processing biomass and generating bio-oil, biochar and gas. Using corn stover as a base case, the simulated facility efficiently generates 5.3 tons per day of bio-oil and 2.5 tons per day of biochar from 10 dry tons per day of feedstock. This yield is critical for the system's overall carbon balance and economic performance. The base case capital cost is estimated at $1.28 million, equivalent to $128,000 per ton per day of feedstock capacity ($241,000 per ton per day of bio-oil output capacity). This estimate aligns with the range reported in the literature but is influenced by system design choices. Capital cost estimates vary significantly, ranging from $13,000 (with a 20 % learning rate after manufacturing 1000 units, representing an Nth plant design) to $440,000 (for a pioneer plant). This wide range underscores the substantial impact of learning and economies of scale on capital expenditures. Our base case cost is lower than that reported by Kim et al. [76] for a mobile pyrolysis unit, likely due to their system's size mismatch between pretreatment and pyrolysis units, resulting in lower-than-expected throughput. Conversely, our estimate is higher than the Sandia study [77], which modeled a simpler system, which does not incorporate gas recycling, heat recovery, and extensive pretreatment.

This analysis highlights the critical role of learning rates and economies of numbers in improving the economic feasibility of small-scale pyrolysis systems. By incorporating pioneer plant and learning curve analysis, we demonstrate that capital and operating costs can decline substantially with increased unit deployment. Specifically, a 20 % learning rate reduces the minimum bio-oil selling price by ~23 % and cuts the marginal abatement cost nearly in half compared to a first-of-a-kind facility. These results support the case for distributed manufacturing and modular deployment strategies, where scaling through replication—rather than size—can drive down costs and enhance competitiveness, particularly in early markets where large-scale infrastructure is not yet viable.

The base case bio-oil minimum selling price is $175 per ton at a 10 % internal rate of return (IRR). The resulting base case carbon abatement cost (MAC) is $83.6 per ton of CO_2 when including biochar carbon sequestration and $152 per ton of CO_2 when excluding it. Applying a 20 % learning rate reduces the MAC to $146.8 per ton of CO_2 removed. These abatement costs fall within the range of proposed carbon credit prices, suggesting potential economic viability, especially with scale-up and learning. Operating costs are primarily driven by biomass purchase and collection ($87.4 per ton of bio-oil), with bio-oil delivery contributing minimally ($3.1 per ton), highlighting the importance of optimizing biomass supply chains.

The life-cycle analysis reveals that corn stover captures approximately 1.16 t CO_2e/t during its growth phase, contributing to a net carbon sequestration of about 0.61 t CO_2e/t after accounting for emissions from corn production, farm machinery, pyrolysis, bio-oil transport, and well plugging. Carbon removals from bio-oil well injection and biochar application range from 1.7 to 2.1 kg CO_2/kg of oil, with net carbon footprints ranging from −0.62 to −1.55 kg CO_2/kg oil. Feedstock production contributes significantly to emissions for corn stover (0.20 kg CO_2/kg of oil) and especially switchgrass (0.72 kg CO_2/kg of oil). Switchgrass also exhibits the highest carbon abatement cost among all feedstocks, whereas woody feedstocks, however, show lower abatement costs, around $100/Mt CO_2, potentially decreasing to $70Mt CO_2 with a learning factor. These differences underscore the importance of feedstock selection for sustainable carbon removal practices. Furthermore, switchgrass and corn stover show the greatest impacts in other environmental categories, such as carcinogens, eutrophication, and non-carcinogenic, while woody feedstocks generally show impacts less than 20 % of the leading crop scenario (except for non-carcinogens).

Sensitivity analysis confirms that feedstock price and production factors exert the largest influence on the MAC for most feedstocks. Importantly, this study demonstrates that small-scale, distributed pyrolysis systems can leverage economies of numbers as an alternative to economies of scale, proving more economical than larger systems at carbon removal scales below 6,000 Mt CO_2/year. At larger scales, direct air capture (DAC) becomes more competitive, with costs around $120/t CO_2. The distributed nature of small pyrolysis units allows them to achieve substantial overall carbon removal capacity while mitigating the diseconomies of scale associated with biomass and bio-oil transportation logistics. Investing in smaller units also reduces investment risks during scale-out. However, the potential investment and risk associated with building a mass-manufacturing facility to accelerate the benefits of mass production could be comparable to deploying a large centralized DAC facility. This trade-off requires further investigation but is beyond the scope of this study.

4.2. Implication of the findings

The bio-oil injection pathway presented in this study represents one embodiment of BiCRS and one of the leading Carbon Dioxide Removal (CDR) approaches. It has delivered over 8,000 tons and sold nearly 310,000 tons, according to carbon industry tracker [83]. Despite the market traction for bio-oil sequestration and other emerging CDR approaches, this pathway is still underrepresented in integrated assessment models and other economy decarbonization models, due to a lack of publicly available economic figures. The lack of representation of BiCRS in the literature has also created a blind spot for policymakers, as while voluntary buyers have realized the potential of this approach, key policies, such as the United States' 45Q tax credit, do not compensate for this form of CDR. Instead, this credit and other similar policies are structured around the sequestration of gaseous or supercritical carbon oxides, like those that would be produced from CCS, BECCS, or DAC. The foundational techno-economic analysis provided here will enable integrated assessment modelers and, subsequently, policymakers to have a more holistic view of the opportunity afforded by bio-oil sequestration as a carbon removal pathway.

4.3. Addressing scale-up challenges

Logistical complexities can arise due to feedstock variability complicating consistent supply chains, while bio-oil's instability during storage and transport-due to high acidity, water content, and susceptibility to phase separation-demands specialized handling. Existing road and rail infrastructure may face limitations in cost-effectively moving large volumes of bio-oil, as pipelines suitable for corrosive liquids are limited [84,85]. Integration with existing infrastructure for centralized storage terminals or injection into orphaned wells require rigorous well-integrity assessments, site-specific permitting, and adaptations to handle bio-oil's high density and low pH [86]. Further we see that operational efficiency depends on standardizing equipment and processes across small-scale units. Bio-oil's variable quality (e.g., oxygen content, heating value) necessitates strict quality control to ensure compatibility with storage and injection infrastructure. Automation and remote monitoring could mitigate inefficiencies in distributed systems. Finally, policy and regulatory gaps pose another scale-up challenge, including inconsistent carbon crediting frameworks for bio-oil sequestration, unclear permitting pathways for geological storage, and fragmented state-level CCS regulations. Stable long-term incentives and harmonized standards for bio-oil properties (e.g., pH, viscosity) are critical to attract investment.

4.4. Strengths and limitations of the study

The strengths of this study lie in its integrated approach, combining detailed process modeling, TEA, and LCA to provide a comprehensive evaluation of the proposed pathway. Furthermore, the focus on a distributed network of small-scale units addresses the logistical challenges associated with dispersed biomass resources. The exploration of bio-oil injection into orphaned wells presents a novel and potentially cost-effective carbon storage solution. However, this study has limitations. The economic and environmental assessments rely on certain assumptions, particularly regarding feedstock availability and costs, and the long-term behavior of bio-oil in subsurface environments requires further investigation. The logistical modeling of a large-scale distributed network was simplified and could benefit from more detailed analysis.

4.5. Conclusion

The techno-economic analysis and lifecycle assessment indicate that distributed biomass pyrolysis could be an economically feasible carbon removal approach given sufficient scale-up and manufacturing learning. The estimated marginal abatement costs are within the range of proposed carbon credit prices. There are still challenges related to scale-up, financing, permitting, and public acceptance that must be addressed. Overall, the study demonstrates the promise of bio-oil carbon removal and highlights areas for additional research to advance its commercialization. Sustainable biomass utilization requires careful planning to ensure responsible practices regarding soil health, land use, and environmental impacts. Further research on large-scale implementation, financing, permitting, and public acceptance can pave the way for broader adoption of this promising carbon capture technology.

5. Data statement

The code for this study is available online at the Github repository (https://github.com/markjet7/pyrolysis_wells.git).

CRediT authorship contribution statement

Pallavi Dubey: Writing – review & editing, Writing – original draft, Investigation. **Samirah Gnangbe:** Writing – original draft. **Mark Mba Wright:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Mark Mba Wright reports financial support was provided by Charm Industrial. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2025.119980.

Data availability

Data is provided in the supporting information and online code repository.

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