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Bamboo as a cost-effective feedstock for production of low carbon transportation fuels

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Phyllostachys nuda (bamboo) was evaluated for biofuel production using hydrothermal liquefaction. The measured biocrude mass and carbon recovery were 35.6 wt% and 53.1 wt% at 300 °C and 10 min, conditions which correspond to a mild reaction kinetic severity factor of approximately 7 and without the addition of catalyst. Technoeconomic analysis projected an Nth-plant break-even selling price of 2.75 USD per gasoline gallon equivalent (gge). This is a plant-gate production cost and is appropriately compared with wholesale rather than retail distillate prices. Well-to-wheel analysis indicated that bamboo-derived biofuel emits 3.5 g CO₂-eq. MJ⁻¹, corresponding to a carbon abatement cost of 35.2 USD per ton CO₂ with the direct land-use change soil-carbon credit and 43.8 USD per ton CO₂ without it. A first-order scaling estimate suggests that, under the yield and conversion assumptions used here, bamboo HTL could supply an energy equivalent of current U.S. corn-ethanol output using roughly 13% of the corresponding cultivated land area, a theoretical potential rather than a demonstrated supply outcome. Under the modeled Nth-plant conditions, an HTL biorefinery using fast-growing bamboo shows substantial economic and environmental potential.

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Main

Fossil fuels provide over 80% of the world's energy, but their combustion significantly contributes to air pollution, climate change, and negative public health outcomes.¹ Although increasing global awareness of these issues has motivated a search for non-fossil energy sources, transportation sectors such as aviation, maritime shipping, and long-distance road travel remain highly dependent on fossil fuels.² In these industries, electrification remains either technologically impractical or economically challenging.² For this reason, energy-dense liquid fuels continue to be the most practical option for many transportation applications.

Among the options for low-carbon energy, liquid fuels produced from biomass have gained attention for their potential to reduce greenhouse gas emissions (GHGs) while remaining compatible with current fuel infrastructure.³ Lignocellulosic biomass, which includes non-edible agricultural residues, dedicated energy crops, and forestry byproducts, offers a renewable and abundant carbon source.⁴ In the United States alone, it is estimated that 615 million dry tons of biomass are produced annually.⁵ If harnessed efficiently, this supply could

offset as much as 15 percent of the nation's transportation energy demand.⁵ However, the potential of biomass-based fuels as a fossil fuel replacement depends on both conversion technology and the selection of feedstocks and previous efforts have failed to achieve economic competitiveness while retaining environmental benefits.

Corn stover, an agricultural residue widely available in the U.S., has been one of the most studied biomass sources for biofuel production.⁶ Yet its relatively modest yields and high ash content have created significant challenges for scaling up production.⁷ Alternative feedstocks such as switchgrass have been explored, but these offer only incremental improvements in performance relative to corn stover, particularly in ash content and growth rate.⁸ These limitations highlight the importance of identifying and evaluating less conventional biomass sources that may offer superior attributes for fuel production.

Bamboo has emerged as a strong candidate due to its rapid growth, high productivity per unit area, and low input requirements.⁹ Some bamboo species reach their full height within a few months and mature within four years.¹⁰ Bamboo's deep root systems improve soil stability, promote subsurface carbon sequestration, and support water conservation.¹¹ It can also be grown on marginal or degraded land, reducing competition with food crops and offering economic opportunities for rural communities.¹² Critically, bamboo also possesses an exceptionally low ash content compared with most lignocellulosic feedstocks, which minimizes inorganic fouling and catalyst

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poisoning during thermochemical conversion and improves the quality of the resulting biocrude. Furthermore, the presence of ash complicates thermochemical conversion to products, with frequently reported adverse effects on yields.^{13–15} The characteristics of fast growth, low fertilizer and water use, and low ash content make bamboo stand out as a promising source of biomass that can achieve economic competitiveness that has not been obtained with other feedstocks. Unfortunately, despite these advantages, bamboo remains largely underexplored as a feedstock for liquid fuel production, especially in thermochemical conversion processes such as hydrothermal liquefaction (HTL).

HTL is a promising chemical conversion process that transforms wet biomass into biocrude using hot, pressurized water at subcritical or supercritical conditions (250–400 °C, 50–250 bar).¹⁶ Unlike pyrolysis, HTL does not require the biomass to be dried before processing, which lowers energy consumption.¹⁷ HTL biocrude has a higher heating value, lower oxygen content, and improved storage stability compared with pyrolysis oil.¹⁸ HTL also performs well with feedstocks that have high lignin content, converting lignin into valuable phenolic compounds.¹⁹ Although HTL has been applied to various feedstocks, including algae, agricultural waste, and forest residues, its application to bamboo, and the role of ash in determining biocrude yield, has not been systematically investigated.

This study aims to evaluate the potential of *Phyllostachys nuda* (*P. nuda*), a minimally invasive bamboo species known for its adaptability to the southeastern United States, as a feedstock for HTL.²⁰ *P. nuda* samples were harvested and analyzed for key properties governing bioenergy performance. HTL conversion was evaluated at different conditions, with the resulting biocrude analyzed for energy content, elemental composition, and molecular composition. Biocrude yields measured at varying reaction temperatures and residence times are used to determine sensitivity to operating conditions. These data are used to assess process economics and CO₂ emissions to evaluate the feasibility of using bamboo-based HTL for sustainable biofuel production. This research contributes to ongoing efforts in identifying effective, renewable feedstocks for advanced liquid fuel production. The contribution of this work is twofold. First, to our knowledge, it provides the first integrated assessment of *P. nuda* as an HTL feedstock combining bench-scale experiments, techno-economic analysis, and life-cycle assessment under consistent system boundaries. Second, it establishes the naturally low ash content of bamboo as a genuine feedstock advantage rather than an incidental property, since ash is widely reported to suppress biocrude yield and to complicate thermochemical conversion.

Results

Bamboo characterization shows superior feedstock properties

The suitability of *P. nuda* as a bioenergy crop was assessed based on key agricultural and compositional attributes. Bamboo was selected for its rapid growth, adaptability to marginal lands, low ash content and compatibility with existing fuel infrastructure.²¹ These attributes are particularly important for

Table 1 Key characteristics and growth parameters of representative bioenergy feedstocks^a

Biomass	Growth rate (ton ha ⁻¹ year ⁻¹)	Dry matter (%)	Ash content (%)	Cellulose content (%)	Hemicellulose content (%)	Lignin content (%)	Biomass availability (M ton year ⁻¹)	Source
Bamboo	22–44	61	0–1	40.9	20.3	26.6	16.1	This study, 21
Corn stover	3.9–7.2	52	4.8–7.3	36.5	22.9	14.0	2.5	24, 26 and 29
Switch grass	9.1–12.6	43	2.2–11.9	36.6	21.0	16.3	6.6	8, 25 and 30

^a Assumes a circular plantation with radius of 30 miles and based on lowest published values of biomass growth rate for biomass availability.

sustainable large-scale biofuel production.²² Of the more than 1500 species of bamboo that have been identified worldwide,²³ *P. nuda* was specifically selected as it is suitable for growth in southeastern U.S. and is minimally invasive, in contrast to the general reputation of bamboo.²⁰

Table 1 presents the agricultural and biochemical characteristics of *P. nuda* in comparison with corn stover and switchgrass. The bamboo growth rate (22–44 tons per hectare per year) is at least three times that of corn stover and at least twice that of switchgrass.^{24–26} Based on the lowest growth rate (Table 1), an idealized circular *P. nuda* plantation within 30-mile radius corresponds to an estimated 16.1 million dry tons of biomass per year. This is higher per unit area than corn stover or switchgrass under the same assumptions, though the realized supply would depend on cultivation and harvesting build-out not demonstrated here. Ash content, a critical parameter for processing efficiency and waste generation, was less than 1% in bamboo, compared with 4.8–7.3% and 2.2–11.9% in corn stover and switchgrass.^{13,27} The low ash content reduces fouling and catalyst deactivation in thermochemical systems, improving process efficiency.¹³ *P. nuda* also exhibits a favorable biopolymer composition, including 40.9% cellulose, 20.3% hemicellulose, and 26.6% lignin. The lignocellulosic composition of bamboo aligns well with the requirements of HTL, particularly due to its substantial lignin content, which enhances energy density in the resulting biocrude.²⁸ Accordingly, the *P. nuda* used in this study exhibited favorable elemental composition, with carbon content of 44.7 wt%, hydrogen content of 5.9 wt%, nitrogen content of 0.4 wt%, and an oxygen content of 49 wt%, calculated by difference.

HTL optimization identifies 300 °C and 10 minutes as ideal conditions for bamboo

The data in Table 1 establish *P. nuda* as a promising bioenergy feedstock. To investigate its performance specifically as an HTL feedstock, *P. nuda* samples were treated under HTL conditions at 300–350 °C and at residence times of 0, 10, 20, and 40 minutes. These reaction conditions encompass the range at which biocrude yield attains maximum values and are industrially accessible in a scaled-up process.³¹ HTL produces several products, the most important of which is biocrude since it can be upgraded to produce transportation fuels. Accordingly, biocrude yield is the single most important variable determining economic viability. Hydrotreating of biocrude using commercial catalysts has recently been demonstrated by multiple >1000 hour trials.³² Similarly, various methods have been proposed for valorizing char, including as a soil amendment, energy storage material, or adsorbent.³³ No catalyst was used in the HTL experiments reported in this study. While catalysts can boost biocrude yields, addition of a catalyst adds cost and complexity to the process. Accordingly, achieving favorable biocrude yield without catalyst addition is highly desirable.

Fig. 1a shows the distribution of the most important products (biocrude, and char), expressed as mass percentages relative to the dry biomass input. All yield values represent the average of two or more experiments with error bars representing

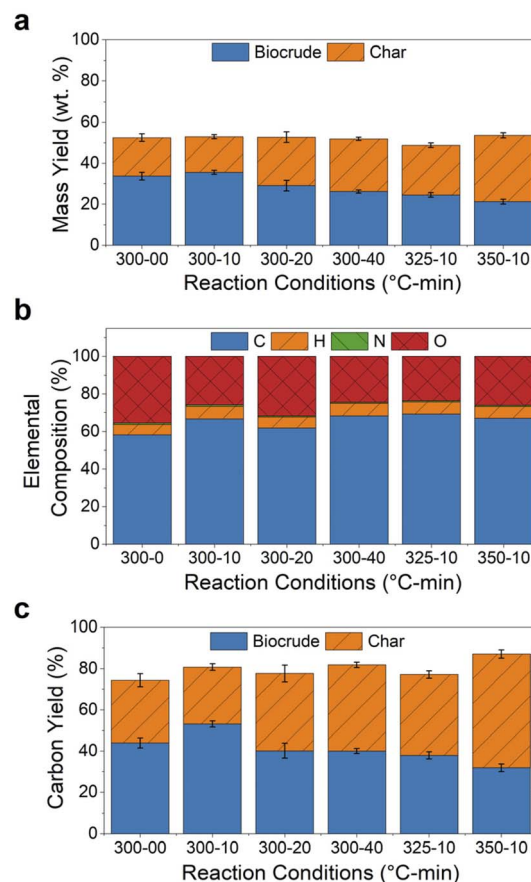


Fig. 1 (a) Product yields for biocrude and char at various reaction temperatures and residence times; (b) elemental composition (CHNO) of biocrude across tested conditions; (c) carbon distribution across biocrude and char phases for each set of HTL conditions.

the standard deviation (or range) of the measured values. Maximum biocrude yield was measured at 10 minutes, reaching a value of $35.6 \pm 1.0\%$. At a residence time of 0 minutes, defined as immediate quenching after reaching 300 °C, biocrude yield was slightly lower than observed at 10 minutes, while char yield was significantly higher indicating incomplete conversion. For residence times greater than 10 minutes, biocrude yield declined with increasing residence time while char production increased due to secondary reactions resulting in increasing molecular weight such as repolymerization.³⁴ HTL yields are sensitive to reaction temperature, and generally optimal at reaction temperatures near 300 °C. To evaluate the effect of temperature, reactions were conducted at 300, 325, and 350 °C using the previously identified optimal residence time of 10 minutes. As shown in Fig. 1a, biocrude yields were less at both 325 °C ($24.5 \pm 1.1\%$) and 350 °C ($21.2 \pm 1.2\%$) than at 300 °C,¹⁹ making 300 °C and 10 minutes the optimal reaction conditions for biocrude yield.

The conditions at which optimal biocrude yields are observed for bamboo are comparatively mild relative to HTL processing of other feeds, and the 10 minute reaction time is consistent with conversion in a compact volume when the reaction is performed in a flow reactor.³⁵ Continuous HTL has

now been reported for multiple feeds, including both woody and herbaceous biomass, meaning that employing similar continuous HTL processing of *P. nuda* and similar bamboo feeds should be readily feasible.³⁶ The low char yield observed for bamboo also should make continuous operation relatively easy to accomplish, since separation of char requires operation of hydrocyclones or other similar solids removal equipment that can be overwhelmed if char is the main product.

Biocrude quality impacts processability, with low oxygen and other heteroatom content especially desirable to minimize hydrogen consumption during hydrotreating. The elemental composition of biocrude samples produced under varying conditions was analyzed for carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) content. Fig. 1b shows carbon content across all samples ranging from 58.2 to 69.2 wt%, a significant increase in carbon content relative to the feed (see Table 1). Dehydration and decarboxylation reactions explain the observed increase in carbon and decrease in oxygen.³⁷ Biocrude produced at 300 °C and for 10 minutes exhibited a carbon content of 66.7 wt% and an oxygen content of 25.9 wt%, the most favorable composition observed for fuel production. In contrast, biocrude from the 0 minute condition had a lower carbon content of 58.2 wt% and higher oxygen content of 35.5 wt%, consistent with incomplete biopolymer conversion.³⁸ Nitrogen content was always <1%, consistent with the low nitrogen content of *P. nuda*. Low nitrogen content is highly desirable for biocrude hydrotreating since nitrogen compounds are difficult to convert into hydrocarbons and tend to poison hydrotreating catalysts.³⁹ In contrast with biocrude, char samples showed little variability in composition, averaging 72.7 ± 1.9 wt% carbon and 21.4 ± 2.0 wt% oxygen (SI Fig. S1).

Some of the carbon present in the bamboo feed exits the reactor in a water-soluble form known as the aqueous phase. To better understand the water-soluble carbon product, the aqueous phase from each experiment was analyzed for total organic carbon (TOC). At the optimal condition of 300 °C and 10 minutes, TOC in the aqueous phase measured 32.4 ± 2.3 g L⁻¹. All the mass and carbon values for the different phases at all conditions considered were reported in the SI (Tables S1 and S2). At higher temperatures or longer residence times, TOC concentrations decreased relative to the value observed at optimal conditions for biocrude production, indicating that more aggressive conditions led to greater decomposition or conversion of water-soluble organics into gaseous products or char. This trend establishes that mild reaction conditions favor the formation and retention of organic compounds in the aqueous phase, while harsher conditions break them down or shift carbon into other phases. These findings underscore a critical trade-off in HTL; while intermediate conditions like 300 °C and 10 minutes maximize biocrude yield and aqueous-phase carbon retention, pushing the system beyond this point can reduce the availability of recoverable organics in the aqueous phase. Although this carbon is not incorporated into the primary fuel product, it may still present opportunities for valorization through catalytic upgrading or biochemical conversion pathways.

Using measured product yields and elemental compositions, total carbon distribution across all product phases was calculated. Fig. 1c shows that the highest carbon recovery in biocrude was 53.1 ± 1.5 wt%, observed at 300 °C and 10 minutes. Biocrude and char yields were determined gravimetrically and subsequently analyzed for carbon and hydrogen content. Their combined carbon yields ($80.7 \pm 2.2\%$ at 300 °C and 10 min) are reproducible to within 5%. The aqueous and gas yields were estimated from TOC and by gravimetric difference, respectively, and are not provided in Fig. 1. The complete phase-by-phase organic and carbon yield distributions, including these estimated terms, are provided in SI Table S1. The organic yields in SI Table S1 are reported on a dry-feedstock basis and are not a closed mass balance, since water of reaction is a major HTL product that cannot be distinguished from the reaction solvent. Total system mass closure was verified independently by reactor mass measurement, as described in the Methods. All conclusions reported in this study rely on the direct measurement of biocrude and char carbon yields, which were highly reproducible. The optimal biocrude yield observed for bamboo compares favorably with those reported for corn stover and switchgrass, which typically range from 11–35% and often require alkaline catalysts to reach the higher end of this range of yields.⁴⁰

The low ash content of bamboo is expected to contribute to this yield advantage. Alkali and alkaline-earth species solubilized from ash are known to catalyze base-promoted reactions of carbohydrate-derived intermediates, including retro-aldol fragmentation and condensation pathways. That diversion takes reactive intermediates away from the biocrude fraction toward the aqueous-phase and char products. This pathway competition is the primary mechanism by which ash lowers true biocrude yield. A second, distinct effect must be considered when interpreting high-ash feeds, since silica-rich inorganic material can co-extract into the solvent fraction and inflate the apparent biocrude yield, so that part of a reported high-ash yield reflects co-extracted inorganics rather than organic product. Ash therefore influences HTL biocrude through more than one mechanism, namely alkali-catalyzed pathway competition that suppresses true biocrude yield and co-extraction that inflates apparent yield. The naturally low ash content of *P. nuda* is a genuine feedstock advantage that yields a biocrude fraction reflecting organic products rather than solubilized or co-extracted inorganic material.

The role of ash during HTL is incompletely understood, with only a handful of studies explicitly targeting it.^{41,42} These reports indicate a complex role of ash during HTL, with increases in biocrude sometimes reported and decreases in others.⁴³ Interestingly, machine learning studies on HTL report that biocrude yield is governed primarily by lipid content, with secondary contributions from protein and cellulose, whereas ash ranks among the least important features for yield prediction.⁴⁴ The low feature importance assigned to ash is best interpreted not as evidence that ash is unimportant, but a consequence of the conflicting effects noted above, since a model trained across feedstocks in which ash both increases and decreases biocrude yield will average these opposing contributions toward negligible global importance. Ash is moreover not itself a carbon

precursor to biocrude, so any influence it exerts on yield must be catalytic rather than compositional. Some insight can be gathered from comparison with the pyrolysis literature. The effect of ash on pyrolysis conversion of biomass has been much more thoroughly studied than for HTL, and under pyrolysis conditions the effects of ash are nearly always to decrease biocrude yields.¹³ The mechanism proposed for the effect of ash on pyrolysis is catalysis of the primary decomposition pathways by the alkali and alkaline earth metals (AAEMs) that constitute most of biomass ash, principally K, Na, Ca, and Mg. In the absence of AAEMs, cellulose decomposes largely by depolymerization to levoglucosan and related anhydrosugars, which are condensable and report to the biocrude. AAEMs suppress this depolymerization route and instead promote scission of the pyranose ring through dehydration, enol-keto tautomerization, and retro-aldol fragmentation, generating light oxygenates and permanent gases in place of condensable biocrude precursors. Individual AAEMs contribute in distinct ways, with potassium favoring formation of low molecular weight compounds, and gaseous species, magnesium promoting dehydration, and calcium and magnesium oxides upgrading volatiles by deoxygenation and deacidification. AAEMs additionally catalyze secondary cracking of primary volatiles and promote cross-linking reactions that favor char formation, so that the net effect is a shift of decomposition to lower temperatures with increased char and gas yields at the expense of biocrude.¹⁵ While pyrolysis and HTL occur under distinct thermodynamic conditions from one another, the effect of ash during pyrolysis must primarily occur in the biomass phase, which is comparable in density to the condensed phase present during HTL. Accordingly, the primary effect of ash during HTL and pyrolysis may be similar to one another. During HTL, the primary decomposition products enter the liquid phase where they continue to interact with solubilized ash components. This additional aspect of ash-biocrude interaction during HTL complicates the effect of ash on biocrude yields obtained by HTL compared with pyrolysis, and likely explains the conflicting results reported in the literature. The present work indicates that part of this conflict is apparent rather than real, since silica-rich inorganic material can co-extract into the solvent fraction and inflate the measured biocrude yield of high-ash feeds, so that reports of ash increasing biocrude yield may partly reflect co-extracted inorganics rather than increased organic product. The present study shows that HTL conversion of low ash feeds, including bamboo, offers a reliable path to obtaining high biocrude yields without the need for costly and energy intensive ash removal and while minimizing variability arising from spatial or temporal differences in ash content of the feed.²⁶ Further, ash can accumulate in reactor and heat exchanger internals, reducing their efficiency and leading to plugging, or deactivating downstream catalysts.^{14,31} These considerations strongly recommend low ash feeds as ideal for HTL, even if under some conditions ash can increase HTL biocrude yields.⁴⁵

To better evaluate sensitivity to conditions, the kinetic severity factor (KSF) was calculated for the different reaction times and temperatures. KSF compresses varying reaction time and temperature into a single value to allow intercomparison

between different conditions; in this study, KSF values ranged from 6.25 at 300 °C and 0 minutes to 8.5 at 350 °C and 10 minutes and used to correlate measured biocrude and char carbon yields. Fig. S2 summarizes the KSF analysis, showing that biocrude yield achieves a maximum value at KSF of approximately 7, with char yield remaining stable up to that point and then increasing at higher severities. This condition represents an optimal severity threshold at which biomass depolymerization to biocrude is maximized while secondary repolymerization reactions leading to char formation remain suppressed. The broad maximum in biocrude yield with respect to KSF informs scaleup and commercialization, showing that modest variation from optimal conditions can easily be tolerated. Similarly, the molecular composition of the biocrude was analyzed using mass spectrometry and infrared spectroscopy. These findings are summarized in the SI as Fig. S3(a) and S9(a). Overall, the composition of the bamboo-derived biocrude is consistent with previous reports, especially with the abundance of phenolic compounds which can be hydrotreated into useful fuel components or recovered as chemicals.⁴⁶ Phenolic compounds are present in both the biocrude and aqueous phases, suggesting opportunities to increase biocrude yield by solvent extraction of the aqueous phase to recover additional phenolic compounds from it.¹⁸

Techno-economic analysis demonstrates financial viability

A techno-economic analysis (TEA) was conducted utilizing the optimal HTL conditions of 300 °C and 10 minutes and for bamboo plantation described in Fig. 2. Published biocrude yields were used for benchmarking bamboo against other feeds. Aside from biocrude yield and reaction conditions, most model inputs used in the technoeconomic analysis were adopted from a previous study reported by Pacific Northwest National Lab (PNNL) on the state of the technology for hydrothermal liquefaction of sewage sludge.³² More details are provided in the SI. Notable deviations from the PNNL study inputs were feedstock

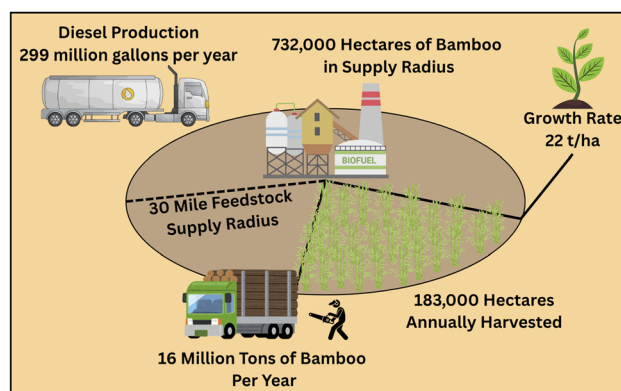


Fig. 2 Schematic representation of the conditions used for bamboo cultivation and conversion in the HTL biorefinery for a circular plantation with a 30 mile radius. The process assumes utilization of 25% of the available bamboo feedstock, representing a scale of 10 000 dry tons per day, following the same regional supply assumptions used for corn stover.⁵¹

cost and processing scale, both of which were set to values appropriate for bamboo and as shown in Fig. 2.

The economic analysis assumed a feedstock cost of 50 USD per dry ton of bamboo, sampled over 25 to 75 USD per dry ton in the Monte Carlo sensitivity analysis, and a processing capacity of 10 000 dry tons per day.⁴⁷ The feedstock costs are consistent with the ranges projected by the DOE Billion Ton update, and the scale of 10 000 dry tons per day is selected for consistency with similar TEA studies on biofuel production.^{5,48} The feedstock cost of 50 USD per dry ton is further informed by published techno-economic literature specifically examining the costs of establishing and operating bamboo plantations in the United States.⁴⁷ Published techno-economic studies on bamboo cultivation account for the full cost structure of domestic bamboo production, including plantation establishment, ongoing maintenance, mechanical harvesting, on-farm transport, land rent, and land remediation at end of life, all of which have been itemized and quantified in the U.S. context.⁴⁷ A cost of 50 USD per dry ton compares favorably with many conventional lignocellulosic feedstocks, supporting the economic competitiveness of bamboo as a bioenergy crop even before the productivity advantages described above are considered.⁵ The cost model follows Nth-plant conventions standard in bioenergy TEA literature, which assume a mature industry with established supply chains and financing, idealized long-run conditions rather than near-term commercial reality. In addition to the midpoint analysis, the robustness of the Nth-plant and other assumptions was subsequently evaluated by estimating fuel prices for several different realistic scenarios.

A first-of-a-kind (FOAK) facility would carry higher capital and financial costs than the Nth-plant basis assumes, and sustaining a 10 000 dry-ton-per-day feedstock supply would require collection-radius, transport and seasonal availability logistics not yet established at this scale. The base case is therefore a projection of long-term techno-economic potential, as is common practice in bioenergy economic analyses.⁴⁹ To bound the FOAK penalty, pioneer-plant capital premiums reported for first commercial deployments of process technologies typically span 1.5 to 3 times the corresponding Nth-plant estimate.⁵⁰ Such premiums are expressed here as a capital multiplier, defined as the ratio of assumed total capital investment to the Nth-plant value. A first commercial facility would also be built well below mature-industry scale, and the FOAK penalty is therefore evaluated at 1000 dry tons per day rather than at the base-case scale. At that scale the Nth-plant MFSP is 3.03 USD per gge, the increase from 2.75 USD per gge reflecting the loss of scale economy alone. Applying a capital multiplier of 2.0 as an illustrative midpoint at 1000 dry tons per day and re-solving the discounted cash flow for a net present value of zero, projects a FOAK MFSP of 3.58 USD per gge. This estimate holds financing terms and the availability factor at their Nth-plant values; a first commercial facility would in practice also carry a higher cost of capital and lower early-year availability, so 3.58 USD per gge is a realistic lower bound on FOAK cost. The Nth-plant and FOAK values bracket the range within which a commercial facility would operate as the technology matures.

Capital cost is the largest single input to the projected MFSP, and its influence was evaluated by re-solving the discounted cash flow at fixed capital multiples rather than by sampling. The response is linear; each unit increase in the capital multiplier shifting MFSP by 0.55 USD per gge at the 1000 dry ton per day scale. Over a factored-estimate accuracy range of 0.8 to 1.5 times the Nth-plant estimate, MFSP therefore ranges from 2.92 to 3.30 USD per gge. Separately from estimate uncertainty and reflecting real cost escalation rather than error in the Nth-plant figure, the pioneer-plant premiums of 2.0 to 3.0 reported for first commercial deployments place MFSP at 3.58 to 4.13 USD per gge. Across these capital multiplier ranges, capital exerts a larger influence on MFSP than either feedstock cost or biocrude yield.

The assumed processing scale corresponds to harvesting approximately 25% of a circular plantation within a 30-mile radius, representing 183 000 hectares out of a total 730 000 hectares theoretically available for cultivation. The 25% harvesting rate is based on a four-year growth rate cycle for *P. nuda*, in which one-quarter of the plantation reaches maturity annually. For comparison, the same land area would support approximately 1000 dry tons per day of corn stover, reflecting both its lower yield and the fraction of residue that must remain on the field to maintain soil organic carbon. Processing 10 000 dry tons per day assumes the full build-out of bamboo cultivation and harvesting infrastructure across the modeled area. Encouragingly for long-term prospects, the scale corresponds to the lower end of the potential harvestable bamboo yield from this area based on values presented in Table 1, suggesting that even greater economies of scale may be achievable as the industry matures.

The feedstock cost, plant scale, and capital basis established above define the cost side of the analysis, while the conversion performance measured in this work defines the output side. Carrying the optimal biocrude yield of 35.6 wt%, obtained at 300 °C and 10 min and reported in Fig. 1, through the process model at the 10 000 dry ton per day scale illustrated in Fig. 2 gives a projected upgraded biocrude production rate of 299 million gallons gasoline equivalent (gge) per year. This output is the basis over which capital and operating costs are annualized, and it therefore converts the cost assumptions described above into a break-even fuel price. The upgraded biocrude production rate includes a hydrotreating step to reduce oxygen and heteroatom content.⁵² Operating costs were estimated at 0.1159 USD per kilogram of dry bamboo, the cost to upgrade the biocrude to biofuel was set to 1.10 USD per gge based on previous reports, and the total capital investment (TCI) was estimated to be 1.725 billion USD using standard engineering methods.⁵² For a 30 year plant life, the selling price required for a break-even investment, that is an investment corresponding to a net present value equal to zero, was estimated to be 2.75 USD per gge on the Nth-plant basis. This value is a plant-gate production cost, and the appropriate benchmark is therefore a wholesale rather than a retail price, since the latter additionally carries distribution, marketing, and federal and state fuel taxes. Fuel costs are reported per gasoline gallon equivalent, defined as 116 090 BTU (122.5 MJ) on a lower heating value basis, following

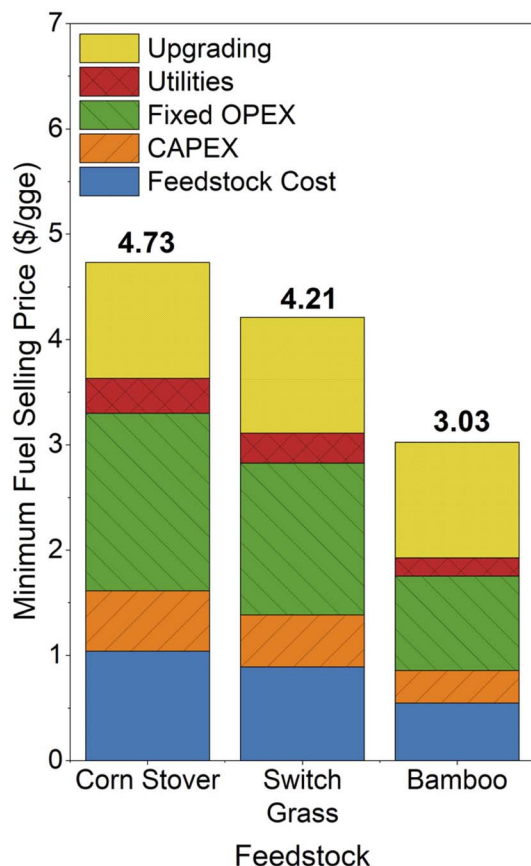


Fig. 3 MFSPs are shown at a common 1000 dry ton per day scale; feedstock cost 50 USD per dry ton; published biocrude yields used for corn stover (19 wt%) and switchgrass (22 wt%).

the convention used in bioenergy technoeconomic analysis.⁵³ The gge is an energy normalization and does not imply a gasoline product; the hydrotreated fuel is a distillate-range product evaluated against a petroleum diesel benchmark throughout the life-cycle analysis. Across the sampled input ranges, MFSP was most sensitive to feedstock cost and biocrude yield (SI Fig. 11).

To benchmark the economic performance of bamboo against other lignocellulosic feedstocks, additional TEA scenarios were evaluated using published biocrude yields within the same modeling framework.^{45,54,55} For this comparison, a processing capacity of 1000 dry tons per day was selected as commercially realistic and regionally deployable with conventional biomass supply chains. This scale aligns with typical feedstock aggregation limits, transportation logistics, and established technoeconomic assessments for agricultural and forestry residues, thereby enabling a meaningful and standardized comparison across feedstocks. Results are shown in Fig. 3, which presents the MFSPs for various feedstocks at a uniform processing scale of 1000 dry tons per day, with cost components split into the categories feedstock cost, capital expenditure (CAPEX), fixed operating expenses (OPEX), utilities, and upgrading. Bamboo is forecast to achieve a lower MFSP of approximately 3.03 USD per gge, compared to 4.21 USD per gge

for switchgrass and 4.73 USD per gge for corn stover. This difference is attributable to bamboo's higher biocrude yield (35.6 wt%), which results in greater fuel output per unit of feedstock than can be achieved for the other herbaceous feeds. In contrast, published values of corn stover and switchgrass biocrude yields are 19 wt% and 22 wt%, respectively, leading to less favorable cost projections as illustrated in Fig. 3.^{45,55} The economic findings shown in Fig. 3 indicated that, under identical scale constraints and the assumptions used here, bamboo achieves a lower projected MFSP than corn stover or switchgrass. This advantage is conditional on bamboo's higher biocrude yield being realized at scale and on the successful development of bamboo cultivation and supply logistics, which are well established for corn stover and switchgrass and must be developed for bamboo.⁴⁷ As explained previously, bamboo plantations offer an added benefit of intense productivity on compact cultivation areas that can supply exceptionally large biorefineries, thereby achieving favorable economies of scale albeit with added upfront costs and while maintaining manageable transportation and logistics costs. Accordingly, scope remains for improving the already favorable cost estimates shown in Fig. 3 by reaping the benefits of economies of scale made possible by bamboo but not by other feedstocks.

Life cycle assessment establishes bamboo biofuel as low carbon fuel

A life-cycle CO₂ emissions assessment was conducted for HTL-biofuel production from bamboo, switchgrass, and corn stover. The system boundary included all stages from cultivation to final combustion, and results were compared against conventional petroleum diesel.⁵⁶ Experimental yields were used for bamboo, while published literature values were used for switchgrass and corn stover.⁴⁹ Emission factors for feedstock production, transportation, and biocrude upgrading were sourced from peer-reviewed studies and the GREET 2023 model.⁵⁷ To ensure a consistent comparison with fossil fuel emissions, a full well-to-wheel approach was adopted. This framework accounts for the total GHG emissions associated with producing and combusting 1 MJ of liquid fuel in a light-duty diesel vehicle. Model structure and assumptions are detailed in the Methods section, and all input parameters are provided in SI Tables S3 and S4.

Combustion CO₂ was treated as biogenic and balanced against CO₂ uptake during growth, consistent with ISO-compliant LCA practice for bioenergy; the net GHG intensity is therefore reported as a reduction relative to the petroleum diesel baseline rather than as a neutrality claim on an absolute basis.⁵⁸ Direct land use change (dLUC) was explicitly modeled based on the specific prior land classification appropriate for each feedstock considered in the study, incorporating changes in soil organic carbon (SOC) associated with that land conversion.⁵⁹ The dLUC impact captures the net soil-carbon flux, the balance between CO₂ released and CO₂ sequestered when the prior land is converted to bamboo cultivation. For switchgrass and corn stover, dLUC reflects published values that capture conversion from conventional cropland, while for bamboo, the

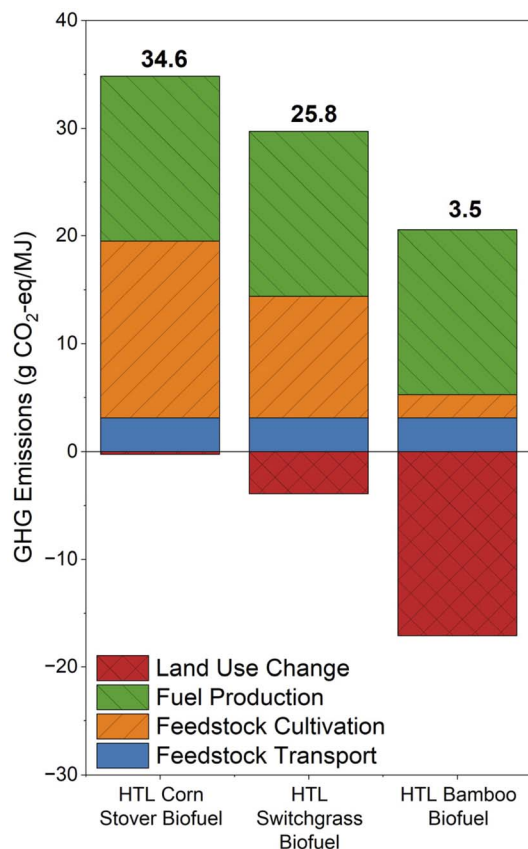


Fig. 4 GHG emissions that are associated with producing liquid fuels from different promising biomass feedstocks and fossil fuels (Unit: 1 MJ liquid fuel).

dLUC value used in this study corresponds to a shift from cultivated degraded land to bamboo plantations.^{60–62} SOC changes were input into the life-cycle model to quantify GHG emissions and removals associated with land conversion. For bamboo, SOC changes were derived from a 30 year field study comparing cultivated degraded land to bamboo plantations.⁶² The resulting dLUC factors represent the long-term soil carbon equilibrium over the crop lifecycle and were calculated in accordance with GREET land-use change framework guidelines.⁶³

The results of the comparative emissions analysis are presented in Fig. 4. The emissions resulting from combustion of conventional petroleum diesel are shown as a benchmark as 91 g CO₂-eq. MJ⁻¹.⁵⁶ The HTL biofuels were compared with this benchmark, demonstrating emission reductions in all cases. Bamboo-derived HTL diesel exhibited the lowest life cycle GHG intensity, at 3.5 g CO₂-eq. MJ⁻¹, representing a net reduction of 85.9 g CO₂-eq. MJ⁻¹ compared to petroleum diesel. This intensity depends on the dLUC soil-carbon credit the stage resolved contributions and the effect of removing the dLUC credit are reported in SI Table S3. Even with the dLUC credit removed entirely, the bamboo pathway yields 20.6 g CO₂-eq. MJ⁻¹, a 77% reduction relative to petroleum diesel and still below both switchgrass and corn stover, so the conclusion that bamboo HTL offers a large GHG reduction holds across the full

range of assumptions rather than depending on any single favorable choice. Fig. 4 shows that this favorable value is obtained due to the biogenic nature of bamboo combustion emissions, the modest emissions associated with processing, and the large negative dLUC associated with bamboo. In comparison, the emissions intensity for switchgrass-derived HTL diesel was 25.8 g CO₂-eq. MJ⁻¹, corresponding to a reduction of 65.2 g CO₂-eq. MJ⁻¹ relative to petroleum diesel.⁶³ Corn stover-derived fuel had the highest emissions among the three biofuels with a value of 34.6 g CO₂-eq. MJ⁻¹, yet still achieved a 56.4 g CO₂-eq. MJ⁻¹ reduction relative to petroleum diesel.⁶³

Direct numerical comparison with literature values is limited by differences in system boundaries, functional units, and allocation choices, so the comparison is indicative rather than definitive. Published life-cycle GHG intensities for HTL-derived liquid fuels nonetheless span a well-defined range, from net-negative values for waste-derived feedstocks carrying avoided burden credits to values approaching 60 g CO₂-eq. MJ⁻¹, with the spread reflecting feedstock, boundary, and co-product treatment.⁶⁴ For lignocellulosic feedstocks the reported values cluster more narrowly, with HTL of forest residues reported at 17 to 20.5 g CO₂-eq. MJ⁻¹ across three supply-chain configurations and HTL renewable diesel from a fermented agricultural effluent at 30.0 g CO₂-eq. MJ⁻¹.^{64,65} Against this range, the bamboo value obtained without any dLUC credit, 20.6 g CO₂-eq. MJ⁻¹, falls within the published lignocellulosic band. The base-case value of 3.5 g CO₂-eq. MJ⁻¹ lies below that band, and the difference is attributable specifically to the soil-carbon credit associated with establishing bamboo on cultivated degraded land, a benefit not shared by residue-based comparisons. Accordingly, a low carbon future for transportation fuels is possible using a combination of different feedstocks, with the largest reductions possible with energy crops like bamboo.

The final analysis in this study integrated economic performance with CO₂ emissions to determine the levelized cost of carbon abatement (LCCA). LCCA is the incremental cost incurred per ton of CO₂-equivalent emissions avoided, calculated as the difference in levelized product cost between the low-carbon pathway and its fossil benchmark divided by the difference in life-cycle emissions intensity between the two. Expressing the result on this basis places bamboo-derived fuel on a common footing with other carbon mitigation pathways, such as direct air capture, whose costs are conventionally reported per ton of CO₂ avoided. The LCCA was calculated using eqn (5) shown in the Methods, incorporating estimated capital and operating costs for bamboo-derived biofuel produced *via* HTL and including hydrotreating emissions.

Based on the findings of this study, the LCCA of bamboo-derived HTL biofuel was estimated at 35.2 USD per ton of CO₂ using the base-case net GHG intensity of 3.5 g CO₂-eq. MJ⁻¹. The dLUC soil-carbon credit appears in eqn (5a) only as the emissions difference in the denominator and leaves the cost difference in the numerator unchanged, so the corresponding value without the credit follows directly as 43.8 USD per ton of CO₂. Both values establish bamboo HTL biofuel as competitive relative to the other abatement pathways summarized in Table

Table 2 LCCA carbon aversion technology comparison between our study and conventional approaches

Process	LCCA (USD ton-CO ₂ ⁻¹)	Source
Bamboo HTL, with dLUC credit	35.2	This study
Bamboo HTL, without dLUC credit	43.8	This study
Direct air capture of CO ₂	200–300	68
Bioethanol produced from switchgrass	55–105	69
Hydrogen produced from water electrolysis	42–74	70
Photovoltaic panels	33–40	71

2. This metric is more commonly reported in the biofuel literature as a marginal abatement cost. Published values for HTL pathways span approximately 5 to 103 USD per ton of CO₂-equivalent for renewable diesel from swine manure, and reach negative values for sludge-derived fuels, with the low end reflecting avoided-burden credits for waste feedstocks.^{66,67} The bamboo estimate falls within that range without any avoided-waste credit, indicating that the yield and scale advantages of a purpose-grown feedstock can offset the counterfactual credit available to waste-derived pathways. For example, the LCCA value of bamboo biofuel is only 15% that of the median value reported for direct air capture (DAC). While comparison with DAC is especially favorable, the LCCA value estimated for bamboo-derived HTL biofuel is less than values reported for bioethanol from switchgrass and hydrogen produced by splitting water molecules using electricity, while being comparable to values reported for photovoltaics. Compared with bioethanol and hydrogen, HTL biofuel has potential as a drop-in fuel that can be used directly in existing internal combustion engines in any proportion. Compared with photovoltaics, HTL biofuel offsets emissions in the transportation sector, whereas photovoltaics is only appropriate for stationary power generation.

Discussion

This study evaluated the potential for using *P. nuda* as a feedstock for biofuel production using HTL. Biofuel precursor yields were measured at a range of reaction conditions, finding that 300 °C and 10 min residence time resulted in an optimal yield of 53.1% on a carbon basis, corresponding to an economically attractive selling price, estimated at 2.75 USD per gge, and a lower LCCA value than many popular options. The high growth rate of bamboo translates to greater fuel productivity per unit area than other second-generation crops under the assumptions used here. As an order-of-magnitude scaling calculation, assuming the lowest published bamboo yield (22 t ha⁻¹ year⁻¹), the measured biocrude yield (35.6 wt%), and current U.S. corn-ethanol land area within a 30-mile farm radius, bamboo HTL could supply an energy-equivalent volume using approximately 13% of that land area. This is a theoretical potential conditional on the stated assumptions, not a demonstrated supply or land-displacement outcome, and it excluded the cultivation, harvesting, and logistics infrastructure that large-scale bamboo supply would require. It should be noted that the analysis presented here does not include any economic incentives beyond the market value of the biofuel product, nor

does it include the ecosystem benefits of bamboo cultivation, which includes soil stabilization.¹¹

Beyond economics, HTL conversion of bamboo offers practical advantages. The resulting fuel drops into existing distribution and combustion systems. Its low water solubility minimizes pipeline and storage corrosion, a problem common to alcohol-based fuels. Additionally, unlike hydrogen, which requires entirely new infrastructure for storage, compression, and delivery, HTL biofuel can be handled using existing liquid fuel infrastructure, cutting a significant capital barrier to adoption. Unlike solar panels, which are tied to fixed locations and primarily used for stationary power, HTL biofuel can be used directly in mobile and distributed applications such as transportation fleets, construction machinery, aviation, agricultural equipment, sectors where electrification is still challenging. Altogether, bamboo-derived HTL fuel is not only economically practical, but also infrastructure compatible and technologically flexible. Collectively, these findings motivate future research, pilot-scale validation and technology development. Based on these considerations, bamboo conversion to renewable diesel may warrant consideration in future bioenergy policy discussions pending pilot- and commercial-scale validation.

Several limitations bound these conclusions. The experimental results derive from a single bamboo species and a single feedstock processed in a bench-scale batch reactor; performance at continuous, commercial scale remains to be demonstrated. The economic projections rest on Nth-plant assumptions of mature supply chains, established financing, and a 10 000 dry ton per day facility, none of which reflect FOAK costs or current commercial readiness. A first commercial facility, at an estimated 3.58 USD per gge, would not be cost-competitive with distillate on any price basis without incentives. The economic case advanced here is therefore that the mature-industry economics are attractive and that closing the FOAK gap is the development challenge, not that bamboo HTL is presently cheaper than fossil diesel. The life-cycle results depend on biogenic-carbon accounting, on a rain-fed cultivation assumption that is specific to the modeled growing region and would not transfer to arid-region cultivation, and on a dLUC soil-carbon credit specific to establishment on cultivated degraded land; when this credit is excluded the pathway yields 20.6 g CO₂-eq. MJ⁻¹, which remains a 77% reduction relative to petroleum diesel (SI Table S3). Finally, the carbon balance carries larger uncertainty in the estimated aqueous and gas fractions than in the directly measured biocrude and char

yields. These limitations should be addressed before the findings are extended beyond the conditions studied here.

Methods

Materials

Phyllostachys nuda (*P. nuda*) bamboo culms were donated by Avos Bioenergy and collected from a location near the Smithsonian National Zoo in Washington D.C. *P. nuda* was selected because of its high biomass yields, short growth rotations, and ability to be planted broadly. Samples were refrigerated prior to use. Bamboo culms were dried at 65 °C for 3 days to reduce residual moisture and then mechanically reduced using a high-energy planetary ball mill (Across International) to produce a fine powder with an average particle size of ~40 µm (SI Fig. S12 provides a map of the harvest location). Although planetary ball milling is considered an aggressive mechanical treatment due to the high shear and impact forces applied, the total specific energy input at this scale remains relatively low compared to thermal or chemical pretreatment methods, serving primarily to reduce particle size and enhance surface accessibility rather than induce substantial chemical modification of the biomass. Acetone (purity >99.5%, Sigma-Aldrich) was used as a solvent for cleaning and biocrude extraction. Deionized water (electrical resistivity >18.0 MΩ cm) was used to prepare the bamboo feedstock for HTL reactions. Nitrogen gas (purity >99.9%, Airgas) was used to pressurize the HTL reactor before each run. Helium (grade 5.0, Airgas) was used as a carrier gas for gas chromatography.

Hydrothermal liquefaction and product separation

HTL experiments were conducted in a 300 mL stainless-steel bench-top reactor (model 4841, Parr Instrument Co., Moline, IL) equipped with a magnetic stirring drive. In each experiment, 15 grams of bamboo were loaded into the reactor and combined with 85 grams of DI water for a solid loading of 15 wt%, consistent with the solid loading in previous batch HTL studies and at the upper concentration limit for generating a pumpable slurry for flow reactor systems.⁷² The reactor was sealed, purged with nitrogen in triplicate to remove residual oxygen, and then pressurized to 300 psi with nitrogen. The reactor was then heated with a heat-up time of approximately 30 minutes to the desired temperature using an external resistive heating jacket. Once the reaction temperature was reached, the reaction temperature was maintained at ±5 °C using an internal type T thermocouple for a desired residence time, at which point the reaction was quenched by placing the reactor in a water-ice bath. After quenching and depressurization, the reactor was opened, and the products were recovered. To ensure the reaction products were fully accounted for, the mass of the reactor and its contents was measured to within ±1.0 g before each experiment, after each experiment, and after venting the gas product formed during the experiment. Overall mass balance closure was confirmed to within ~12% across all runs.

After reaction, gas, biocrude, aqueous phase, and char yields were quantified. Gas yield was determined gravimetrically by

mass difference before and after venting the reactor. Solid and liquid products were removed and vacuum filtered (Whatman no. 1, 11 µm) to separate the aqueous phase from the solid and biocrude-containing fractions. The retained solid phase consisted of mineral and carbonaceous char with associated extractable organics. This solid was rinsed with acetone to recover solvent-soluble, char-associated organics, which were combined with the biocrude fraction and included in the reported biocrude yield. The remaining solvent-insoluble material was defined as char. Acetone was removed from the combined biocrude fractions using rotary evaporation at 40–50 °C under vacuum prior to weighing. The washed char was dried overnight at 60 °C, weighed, and stored for further analysis. No suspended solids passing through the filter were included in the reported char yield; any dissolved or fine particulate carbon remaining in the filtrate was accounted for within the aqueous phase.

The carbon mass balance, calculated from the gravimetric yields of biocrude, gas, aqueous, and char fractions multiplied by their respective elemental carbon contents, deviated by up to 30% from ideal closure across samples, consistent with previously reported uncertainties in HTL mass balance analyses.⁷³ Over- and under-recovery have distinct origins. Under-recovery is driven primarily by the gas yield, which is estimated by difference using a top-loading analytical balance, together with minor carbon losses retained in reactor fittings and the pressure transducer. Over-recovery, including the cases where total carbon exceeds 100% (SI Table S2), is driven primarily by the aqueous-phase term, which is estimated from TOC and is prone to overestimation; because biocrude and char carbon are measured by direct elemental analysis and reproduce to within ~5%, the deviation in either direction is confined to the two estimated fractions. Importantly, because prior HTL studies consistently report the gaseous phase to be predominantly CO₂, incomplete gas quantification is not expected to materially affect the comparative carbon distribution trends or the conclusions drawn in this work.⁷³

Experiments were performed at a series of pre-determined temperatures and reaction times. Kinetic severity factor (KSF) was calculated to quantify the intensity of the reaction conditions; KSF permits intercomparisons between experiments performed at different reaction temperatures and residence times, and is calculated as follows:

$$\text{KSF} = \log_{10} \left(\int_{t_0}^{t_f} e^{\frac{T(t)-100}{14.75}} dt \right) \quad (1)$$

where $T(t)$ represents temperature as a function of time and is integrated from the start time (t_0 in minutes) to the end of the reaction (t_f in minutes).⁷⁴

Characterization techniques

Product yields were determined based on gravimetric measurements on a dry biomass basis as shown in the following equations:

$$\text{Biocrude yield (wt\%)} = \frac{\text{biocrude mass (g)}}{\text{mass of dry biomass (g)}} \times 100 \quad (2a)$$

$$\text{Char yield (wt\%)} = \frac{\text{char mass (g)}}{\text{mass of dry biomass (g)}} \times 100 \quad (2b)$$

$$\text{Gas yield (wt\%)} = \frac{\text{initial reactor content (g)} - \text{final degassed reactor content (g)}}{\text{mass of dry biomass (g)}} \times 100 \quad (2c)$$

All HTL runs were performed in duplicate. Gravimetric product yields agreed with one another to within $\pm 5\%$, and the biocrude and char carbon yields determined by elemental analysis agreed to within $\sim 5\%$.

Moisture content of the biocrude was determined by Karl-Fischer (KF) Coulometric titration using a Mettler-Toledo DL32 Karl-Fischer Coulometer (Mettler-Toledo, LLC, Columbus, OH). Biocrude was dissolved in HPLC grade methanol (1 : 10, wt to vol ratio; Fischer Scientific, Canada) to prepare the solutions for moisture analysis. The moisture content of bamboo was measured by comparing the weight before and after placing the bamboo fibers in an oven held at 65 °C for 72 hours. Higher heating values (HHVs) of the biocrude products were measured using a semi-micro calorimeter (25 720, Parr, Moline, IL). The instrument was calibrated using the average combustion of five benzoic acid tablets. The CHNO composition of the HTL biocrude product, and HTL solid product char were analyzed at an external analytical laboratory (Midwest Micro Lab, Indianapolis, IN). Carbon, hydrogen, and nitrogen contents were directly measured by analysis of sample combustion gases. Oxygen was calculated by the weight percent difference.

$$\text{O (wt\%)} = 100 - [\text{C (wt\%)} + \text{H (wt\%)} + \text{N (wt\%)} + \text{ash (wt\%)}] \quad (3)$$

The total organic carbon (TOC) of HTL aqueous samples were measured using a TOC analyzer (Shimadzu Co., Kyoto, Japan). Samples were diluted and acidified using HCl (1 μL of 6 M acid in 1 mL of the product) prior to analysis. All measurements were conducted in at least duplicates.

The chemical composition of the volatile fraction of biocrude phase was analyzed using gas chromatograph mass spectrometer (GCMS) consisting of a GC-2010 Plus gas chromatograph, a QP2010 SE mass spectrometer, and an AOC-20i autoinjector (Shimadzu Co., Kyoto, Japan). Product identification was based on spectral matching with standards contained in the National Institute of Standards and Technology mass spectra database. The following criteria were used to verify a match: (1) >90% agreement between the experimental spectrum and the standard; (2) chemically plausible (*i.e.*, confirmed matches contained only C, O, H, or N atoms); (3) elution time reconciliation (*i.e.*, retention times were required to follow trends expected based on relative volatility). The biocrude and

char products infrared spectra were measured using a Fourier Transform Infrared (FTIR, PerkinElmer, model Spectrum Two) spectrometer equipped with an attenuated total reflectance (ATR) stage to identify functional groups. Additional GCMS and FTIR characterization method details are provided in the SI.

Technoeconomic analysis

Process simulations were performed as part of a techno-economic analysis to evaluate fuel production *via* HTL of bamboo sourced from a biomass cultivation farm. The process included feedstock pre-heating, reaction during HTL, product recovery, and biocrude hydrotreating. The model was adapted from a previously published economic study of HTL, originally designed for sewage sludge, and was modified using experimental data generated from bench-scale HTL testing of bamboo waste streams.⁵² The model basis was updated to 2024 dollars using the Chemical Engineering Plant Cost Index (CEPCI), the Bureau of Labor Statistics labor index, and relevant commodity cost factors.^{75,76} A base-case scenario was established that assumed an HTL facility processing 10 000 dry metric tons of bamboo per day, producing 23 807 barrels per stream day (BPSD) of biocrude prior to upgrading. Biocrude yield was used as a key input to determine the minimum fuel selling price (MFSP), that is the fuel selling price at which the net present value on a 30 year investment is zero. The interest rate of return was assumed to be 10% based on a similar techno-economic analysis.⁴⁸

The economic assessment is divided into two main components: (1) a market-based analysis of capital and operating expenditures, and (2) a Monte Carlo sensitivity analysis (@Risk, Palisade) in which uniform distributions were assigned to each of eight key inputs over the ranges in SI Table S5 and sampled across 10 000 iterations. Capital cost was not included in the sampled set. Its influence on MFSP is instead evaluated deterministically, since annualized capital enters the break-even calculation linearly under the discounted cash flow structure used here and therefore does not require sampling. The resulting capital sensitivity is reported in the technoeconomic results. A discounted cashflow rate of return analysis was performed, assuming a plant payoff period to be across 30 years with an annual availability factor of 90%, including an 8% annual interest loan with a payback time of 10 years. Capital and operating cost references were taken from the 2016 PNNL HTL study and scaled to the target plant size of 10 000 dry tons per day of bamboo, accounting for the total plant load (including biomass, water, and other components).⁵² Costs were updated to 2024 using appropriate cost indices and a scaling factor with an exponent of $b = 0.6$ was used to adjust for scale, as shown below:⁷⁷

$$\text{Cost}_{\text{ref plant 2016}} = \text{Cost}_{\text{ref year}} \left(\frac{\text{Cost} - \text{index}_{2016}}{\text{Cost} - \text{index}_{\text{ref year}}} \right) \quad (4a)$$

$$\text{Cost}_{\text{plant}} = \text{Cost}_{\text{ref plant 2016}} \left(\frac{\text{Plant capacity}}{\text{Ref plant capacity}} \right)^b \quad (4b)$$

LCA methodology

The environmental impact assessment was conducted by performing a life cycle assessment in GREET 2023 model software developed by Argonne National Laboratory. The LCA was applied to evaluate the emission savings both from the production and end-use (combustion) stages of diesel compared to the fossil-based equivalent diesel. To compare these values with the conventional fossil fuel-based equivalent fuels, the emissions of the fossil-based fuels in the corresponding diesel engines are accounted for. The LCA framework was developed based on the steps of the ISO standard 14 040, including the goal and scope definition, the life cycle inventory analysis, the life cycle impact assessment, and the interpretation of the results. The analysis encompassed the full bamboo-to-fuel pathway, from cultivation through conversion and end-use combustion. The overarching objective was to estimate CO₂ emissions from the biofuel production process in comparison to conventional fossil fuel diesel. Experimental data were used for the mass flow rates of product streams. All other process input streams (raw materials and chemicals), output streams (main or co-products, byproducts and waste streams), and utility needs (electricity, fuels) were acquired from an earlier LCA study performed by PNNL on HTL.⁴⁹ Data for upstream process models, which represent processes which are outside of system boundaries and correspond to flows which supply the system streams with raw materials and energy (*e.g.*, such as electricity generation, natural gas, production of chemicals, *etc.*) or correspond to the way that waste streams are handled when leaving system boundaries such as average models for wastewater treatment, were obtained from GREET's

default databases and emission factors. The functional unit is 1 MJ of fuel combusted in a light-duty diesel vehicle, and the system boundary spans cultivation, feedstock transport, conversion and upgrading, and end-use combustion. Bamboo cultivation was modeled as rain-fed, consistent with the field study from which the soil organic carbon and yield data were taken and with commercial *Phyllostachys* cultivation in the southeastern U.S. climate zone, where growing-season precipitation is sufficient without supplemental irrigation. No irrigation water, pumping energy, or associated emissions are therefore included in the foreground inventory reported in SI Table S4. Stage resolved GHG contributions with their data sources (GREET 2023, PNNL, and Ecoinvent) are given in SI Table S3, and the bamboo foreground inventory is given in SI Table S4. All wastewater streams generated in the process were assumed to be treated by the same type of facility. The fuel production inventory was adapted from a single PNNL basis and applied per MJ of finished fuel without rescaling for feedstock throughput, so the same conversion burden is assigned to all three feedstocks. The heating and reactor duty components of that burden scale with the mass of biomass processed per unit of fuel produced, and therefore with the inverse of biocrude yield, whereas the hydrotreating component is approximately invariant per MJ of finished fuel. Holding the stage constant across feedstocks therefore understates the conversion burden for the lower-yield feedstocks. Correcting it would increase the switchgrass and corn stover intensities while leaving bamboo unchanged, so the simplification is conservative with respect to the comparison drawn here.

LCCA was calculated to evaluate the HTL process with bamboo feedstock on a cost-per-ton-avoided basis, using conventional fossil diesel as the reference system.⁷⁸ The calculation is given below:

$$\text{LCCA} = \frac{(\text{LCOF}_{\text{HTL}} - \text{LCOF}_{\text{Fossil Fuel Reference}})}{(\text{CO}_2 \text{ Emissions Fossil Fuel Reference} - \text{CO}_2 \text{ Emissions HTL Fuel})} \quad (5a)$$

$$\text{LCOF}_{\text{HTL}} = \frac{\text{Annualized CAPEX} + \text{Annual OPEX} + \text{Feedstock Cost} - \text{Byproducts}}{\text{Annual Fuel Energy Output}} \quad (5b)$$

$$\text{LCOF}_{\text{Fossil Fuel Reference}} = \frac{\text{Diesel Wholesale Price}(\text{Crude Oil Fraction} + \text{Refining Fraction})}{\text{Energy output}} \quad (5c)$$

The net GHG intensity depends on the dLUC soil-carbon credit, which carries inherent uncertainty. To bound its influence, the dLUC credit varied from its base-case value ($-17.1 \text{ g CO}_2 \text{ MJ}^{-1}$) to zero, the conservative case in which no dLUC credit is taken. The resulting net GHG intensities ($3.5 \text{ g CO}_2\text{-eq. MJ}^{-1}$ with the credit and $20.6 \text{ g CO}_2\text{-eq. MJ}^{-1}$ without it) are reported in SI Table S3. The conversion-stage inventory is also applied uniformly across feedstocks rather than scaled to biocrude yield, which understates the burden for switchgrass and corn stover and therefore makes the reported advantage for bamboo a lower bound.

Author contributions

Timothy M. Woodard: conceptualization, design, and execution of bamboo HTL experiments – characterization of char and biocrude phases; technoeconomic analysis; lifecycle assessment; original manuscript writing and revisions. Michael T. Timko: supervision; writing – manuscript revisions. Charles M. Cai: Manuscript feedback. James Walters: feedstock selection, methodology, and conceptualization.

Conflicts of interest

MTT has partial ownership of River Otter, a company commercializing HTL for organic waste processing. JW is the founder of Avos Bioenergy, a company aiming to commercialize bamboo-derived biofuels.

Data availability

The data supporting this article are included in the supplementary information (SI). Supplementary information: Fig. S1–S12, Tables S1–S5, additional experimental details, experimental measurements of yield, inputs to the TEA and LCA, and related information. See DOI: <https://doi.org/10.1039/d6se00296j>.

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