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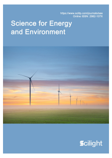

Article

Biomass Slow Pyrolysis Produces Stable Gaseous, Liquid and Solid Bio-Energy Carriers

Yitong Jiang [1], Debo Zhang [1], Xianfeng Fan [2], Tianwei Tan [3], Raf Dewil [4], Nick Sweygers [4] and Huili Zhang [3],*

[1] Beijing Advanced Innovation Centre for Soft Matter Science and Engineering, Beijing University of Chemical Technology, Beijing 100029, China
[2] Institute for Materials and Processes, School of Engineering, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JL, UK
[3] College of Life Science and Technology, Beijing University of Chemical Technology, Beijing 100029, China
[4] Chemical Engineering Department, KU Leuven, 3001 Leuven, Belgium
* Correspondence: zhhl@buct.edu.cn

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Abstract: Biomass is recognized as a renewable energy source with high potential. Its pyrolysis produces biogas, a storable bio-oil and char. Although bio-oil also contains a variety of C, H, O components; it also contains value-added chemicals such as levoglucosan. Pyrolysis proceeds at moderate temperatures (300 to 400 °C) temperatures in a slow mode, or at >> 500 °C is a fast mode. At low temperatures and long residence times, slow pyrolysis fosters the production of pyrolysis gas and biochar. At a very fast heating rate and a short residence time in the reactor, the pyrolysis mode changes to the so-called fast mode, where liquid pyrolysis products are higher than in slow pyrolysis mode. After condensation, a brown, acid, and low viscosity bio-oil is obtained. The research will assess the slow pyrolysis system, through its conversions, product distribution and process economics in view of a maximum gas and char production, both considered advantageous toward for energy-carrier storage and peak-time electricity generation.

Keywords: pyrolysis; biomass; reaction rate; energy storage; peak power generation

1. Introduction

The project aims to develop a flexible electricity-powered pyrolysis-based system for the production of storable bioenergy carriers; where the production of biogas and biochar offers distinct benefits for use as biofuel towards electricity grid stabilisation and a circular econoùy approach for the carbonaceous char residue. To achieve this objective, an innovative pyrolysis process will be developed, specifically targeting the use of biomass and biogenic waste. The technology will be demonstrated in a relevant environment and at a significant size (TRL 5).

The ongoing transition in electricity (power) production and use results in a high pressure on the existing power grids. The reasons are a shift from a centralized production in large scale power plants (such as coal-powered and nuclear plants) towards decentralized production, but also the growing application of intermittent major renewable power sources (solar, wind). Both issues require stabilization measures to avoid major grid stability problems and even black outs [1]. In those regions of a considerable wind and solar (photovoltaic) input, a significant pressure on the grid is expected, due to the intermittent nature of the of the outputs and the difficulty to rapidly control or predict the power generating yields. To avoid future blackouts in the EU, the study of grid balancing measures is a major concern [2]. To secure grid flexibility and stability, there is a general consensus that bioenergy can play a primary role as a stabilizing element in the renewable power supply system [3].

Integrating pyrolysis technology for balancing the grid will open up perspectives towards both mid-term and short-term balancing where the variability in load and variable generation is balanced by committing generation units to dispatch. Especially short-term measures need to be considered. All bioenergy carriers that are generated via the biomass pyrolysis process are perfectly suited for these types of grid balancing. The produced gas can be stored in the short term and utilized in a rapid response via internal combustion (IC) gas engines for short-term balancing. Given the higher energy density and ease of storage of possibly densified biochar, this bio-fuel product is extremely suitable for mid-term balancing. Biochar can additionally be used as a back-up to mitigate seasonal variations, since it is a type of biofuel that can be easily stored and utilized as a (co-)fuel in thermal power plants. The backup needed in winter also coincides with an increased heat demand, which is an ideal situation for combined heat and power, as envisaged by the concept.

A very important advantage of the proposed system in comparison with common pyrolysis reactors, is its electrical heating. This not only avoids diluting the gas/vapor phase with combustion gas if the heat of pyrolysis is supplied through combustion of char/biogas, but it moreover offers the opportunity to convert excess electricity from photovoltaic (PV) and wind to generate the storable energy carriers in a climate neutral and sustainable way. Also, in this way a grid balancing effect is created (equilibrating the grid in situations of excess power production). In this objective, the concept becomes a hybrid renewable energy concept.

Finally, the project aims to better understand the slow pyrolysis of biomass in general, with special emphasis on a high energy efficiency, reduced CAPEX/OPEX costs, and applicable from a small decentralized scale close to sufficient biomass resources, to a larger scale (close to power generation plants of larger scale, where biochar might alleviate the CO_2 burden of fossil fuel burning).

Although pyrolysis processes have been studied extensively in the literature, and some full-scale pyrolysis plants (mostly of the fast pyrolysis type) are already in operation worldwide, the specific utilization of this technology towards power grid stabilization poses specific challenges that will be addressed in the project through innovative targets.

2. Concept

As described in Figure 1, the overall concept underpinning the project is to bridge pyrolysis of biomass and the production of bioenergy carriers, used mainly to produce electricity (in-plant and by external power generating companies). Although the concept will partly build upon existing technologies and pilot-scale units, major modifications and innovations are required to meet the targets set by the project initiative.

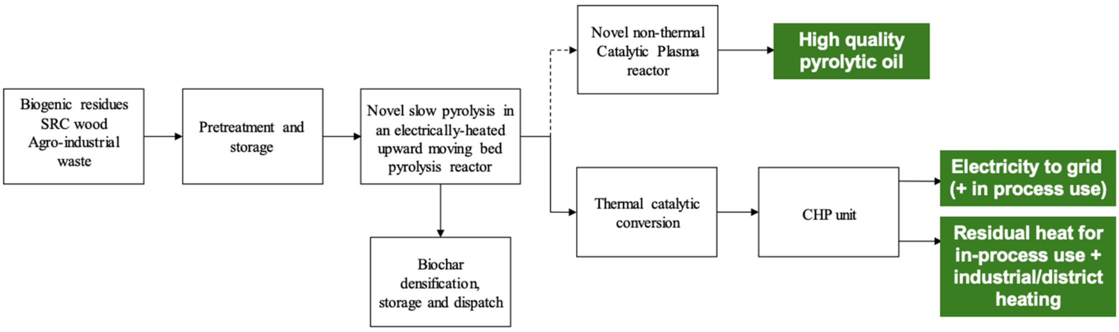

Figure 1. Review of the overall concept.

The resulting concept is a biomass-driven combined cycle featuring a small- to medium-scale biomass pyrolysis plant of the next generation. Six technology bricks are integrated to form the complete innovative system: the biomass preparation, the slow pyrolysis; the vapor/gas upgrading by either non-thermal plasma or thermal catalytic reforming reactors, the product storage, the CHP power generation unit, and the control and regulation system.

The main lay-out of the pilot process consists of (i) a pneumatic conveying of the milled feedstock to the feeding hopper, foreseen with N_2 blanketing and double gate valve; (ii) the vertical moving bed pyrolysis reactor (350–400 °C) with radially inserted electrical heating plates (Incoloy with tantalum heating elements embedded in ceramics); (iii) the char discharge conveying (to auger cooling and drums); (iv) the fractionating condenser for the pyrolysis oils with a top of condensed more volatile compounds, and a bottom of heavier compounds; (v) the connection of the pyrolysis gas to the outside gas storage (1 MPa) and 14.7 kW_{el} generator. In view of the intended cracking of pyrolysis oil into gaseous fuels, the oil cracking by reforming or NTP will be added.

The process concept is represented in Figures 2 and 3.

Figure 2. Photographic illustration of existing pilot-scale plant, by courtesy of Pyrum Innovations, Dillingen, Germany [4].

The layout illustrates the major process items that will be implemented.

(i) An Andritz shredding and sieving unit will be used [5].

(ii) Due to the high moisture content of most of the biomass species, a moving belt dryer with indirect hot water as heat transfer medium, will be added. Dried biomass (7.5 wt% H_2O) will be stored in a hopper.

(iii) The electrically heated updraft slow pyrolysis reactor will be including either a mechanical mixer (paddle mixer) or using locally fluidization of the bed material at various heights in the reactor (0.2 I.D., about 1.0 m effective reactor height). The location of the heating panels needs to be adapted to both the required axial and radial temperature gradients and the heat penetration in the biomass: the panels are currently interspaced at 40 to 60 mm, but need a closer spacing because of the low thermal conductivity of biomass particles. The heat input will be variable in function of the calorific requirements of the biomass and of the temperature gradient along the reaction path.

(iv) Instrumentation and controls will cater for the optimum operating conditions when using different biomass feedstock.

(v) Prior to further treatment of the pyrolysis vapors and gases, a high efficiency sintered metal fiber filter will be installed. The filtration mesh will be graded at 1 μm to 2 μm to guarantee a char removal to below 1 mg/Nm^3. The filter unit is executed as twin-assembly with N_2 back-pulsing: in the case of insufficient pulse jet cleaning (N_2) due to mesh clogging by the biochar or tars, a unit can be switched off-line, and filter candles can be thermally cleaned in a laboratory furnace.

(vi) If the non-thermal plasma treatment unit provides successful results at lab-scale, the fractionating conderser of pyrolytic oil will be maintained, however with an appropriate temperature gradient to match the boiling point profiles of the pyrolytic oil.

(vii) It is however expected that major economic and flexibility gains can be obtained by adding a Thermal Catalytic Reformer. This unit will be designed and manufactured on purpose.

(viii) Biochar will be discharged from the reactor, cooled in an indirect (H_2O) auger conveyer, and hopper-stored before further dispatching.

(ix) Minor modifications include the electrical circuit, the use of the H_2O flows in a residential or industrial thermal circuit, a genset capable of meeting the electricity production on a non-steady basis (major production in peak-hours demand time). The pyrolysis storage vessel (and compressor) will be designed and manufactured to enable storage at approximately 1 MPa.

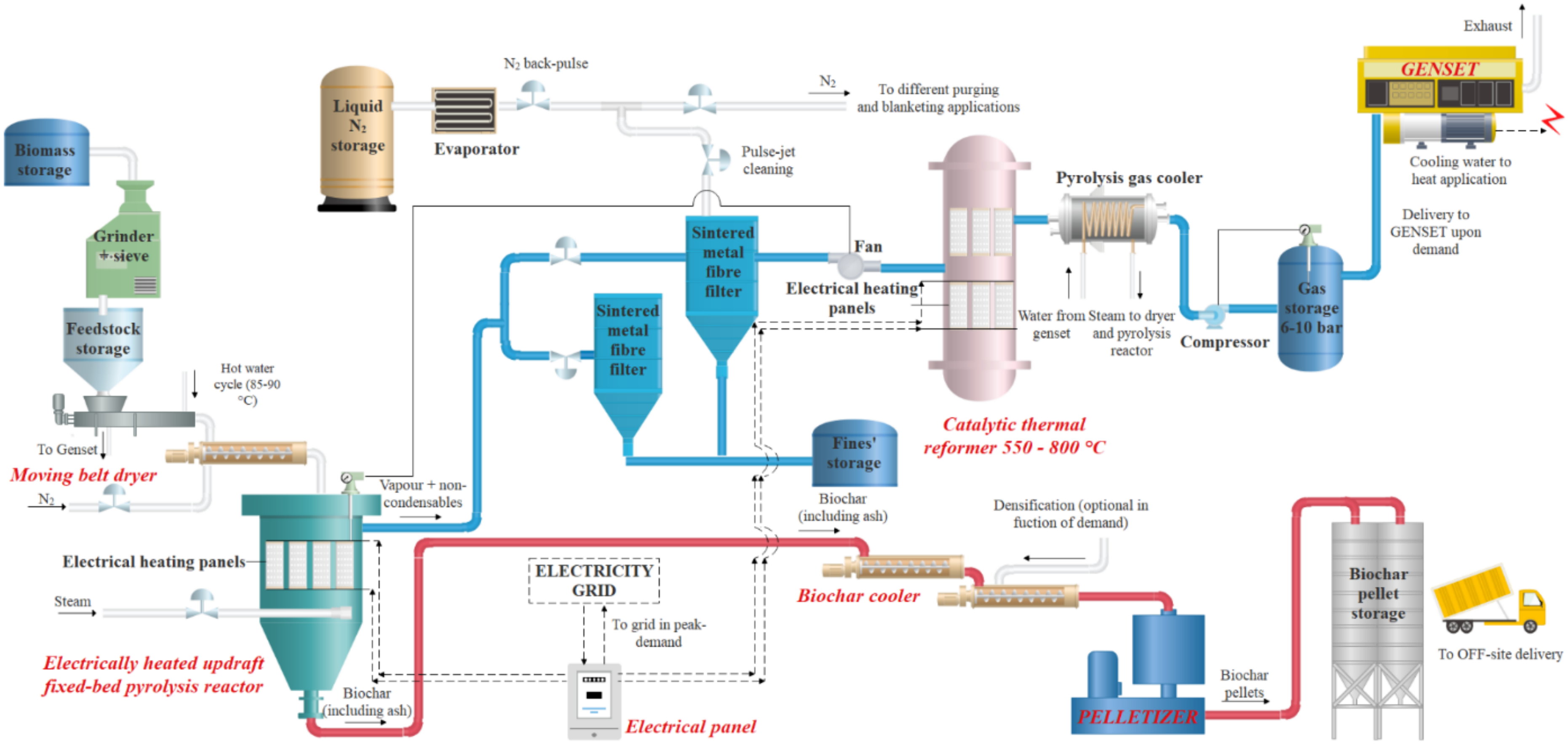

Figure 3. Proposed layout of the process.

(x) A biochar densification (pellets) will be added. As produced, biochar has a low density (150–300 kg/m^3) due to its high porosity. It moreover contains a wide range of particle sizes, due to fracturing in the pyrolysis reactor. To produce a dense, dust-free and stable biochar, densification is applied in the process. Pellet extrusion (radial extruder) are preferred to roll compaction or die compaction due to its suitability for products with less weight accuracy, high unit output and low unit value.

(xi) Biochar will be fed by a variable speed controlled screw feeder. Since the extrusion produces a substantial temperature rise, the biochar will be moistened before being fed. A densifying additive (e.g., molasses, starch, others) will also possibly be used. Pellet-mills are available in a wide capacity range from small-scale (e.g., Alexanderwerk Co.) to large-scale (Bepex, Sprout-Waldron, Simon, etc.). The size of the pellets will be controlled by the speed of the rotating scraper outside the die-cylinder. The roll speed and its distance to the die-ring will determine the pellet density, expected at 500 kg/m^3 to 700 kg/m^3 in case of the biochar.

3. State-of-the-Art of Pyrolysis

3.1. Progress of the Project beyond the Current State-of-the Art

Biomass feedstocks can be converted into energy, fuels and/or valuable chemicals through various thermochemical conversion processes, including pyrolysis, gasification and combustion [6–8]. Pyrolysis (fast pyrolysis and slow pyrolysis with the latter including torrefaction and carbonisation) is a promising approach to convert biomass into char, condensable volatiles (pyrolysis oil) and non-condensable gas (CO, CO_2, H_2, CH_4, etc.). It is carried out in a O_2 lean environment at temperatures of 200 °C to 750 °C [9–16]. Initially, mostly pyrolytic oils were the target product of pyrolysis, and numerous researchers have investigated this production mode, where biomass is heated at 10^3 K/s to 10^4 K/s. Fast pyrolysis has meanwhile seen its first commercial applications, some of them, however, dormant at present.

Within the applications of fast pyrolysis, mostly riser technology (VTT, BTG, Ensyn, among others, ablative (PyTec Germany, out of use), bubbling fluidized beds (Dynamotive, Canada, out of use), circulating fluidized beds (Fortum, Finland), rotating cone (BTG, Netherlands) and Auger reactors (Bioliq, Germany) have been built and are in operation. Most of these principles use fine biomass particles (hence requiring extensive grinding and sieving), high heating rates, and an external heat carrier (sand heated by biochar or gas combustion [17–21]).

Char production through biomass slow pyrolysis can be conducted in various reactors, including the screw reactor or microwave reactors or in the moving bed reactor developed by Pyrum Innovations, and to be further modified and upscaled in the present project. The moving bed Pyrum pyrolysis reactor has a number of advantages for producing char through biomass slow pyrolysis. For instance, the flow of biomass particles inside the reactor can be flexibly adjusted by manipulating the rotational speed (or frequency) of the mixing. In addition, biomass feedstocks with various particle shapes, sizes and morphological characteristics (from fine sawdust to lumpy, sticky and fibrous biomass particles can be processed.

Preliminary results of own and literature data are given in the Figure 4 below.

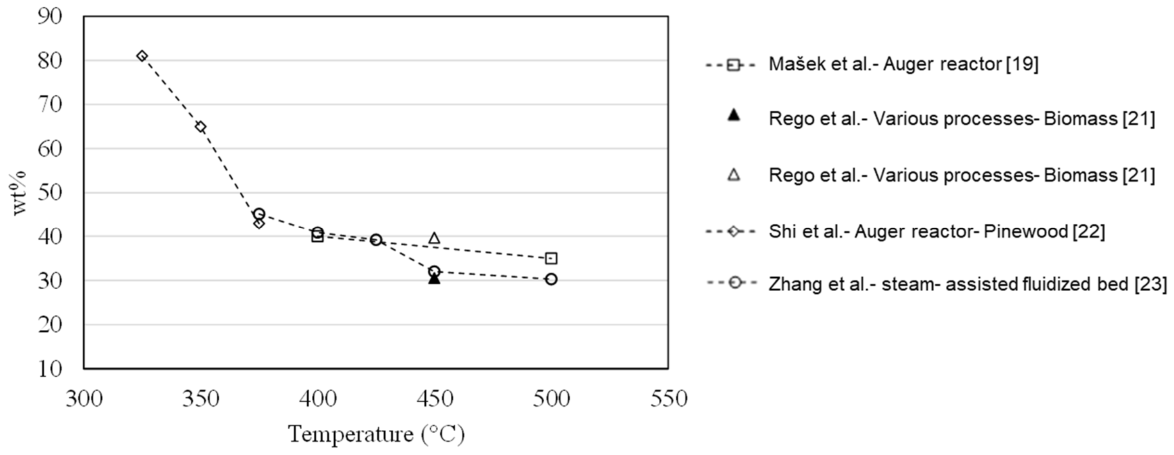

Figure 4. Biochar yield (wt% of dry biomass) by slow pyrolysis in function of operating temperature [19,21–23].

By adapting the operating temperature, heating rate and/or residence time of the biomass in the reactor, biochar yields of up to 81 wt% have been measured. The remaining products are pyrolytic oil and pyrolytic gas, the former representing about two times the weight of the gas.

To maximize the yield of biochar, specific attention should be paid towards some essential principles, as demonstrated by mostly lab-scale research.

Biochar contains both primary and secondary biochar. The secondary biochar is derived from the decomposition of the organic vapours onto the solid carbonaceous solid, probably catalysed by the biochar itself.

To enhance the production of secondary biochar, several conditions need to be respected. These conditions are met by slow biomass pyrolysis [22–25]:

- The gas and vapour flow rates should be limited, to provide increased opportunities for relative volatile matter to interact with the carbonaceous primary biochar
- Production should be carried out at atmospheric pressure, since vacuum favours the formation of liquid pyrolysis oil
- Slow heating and prolonged holding times improve the fixed carbon yields
- The size of the feedstock has a considerable effect on the biomass decomposition chemistry. The larger the biomass feedstock size, the higher the biochar production yield, and the more the process moves from endothermic to slight exothermic process, due to the formation of secondary biochar that resulted from the decomposition of volatile matter that was unable to rapidly escape from the coarser biomass.
- The bulk biomass density has an effect on the biochar density, with a proportionality factor of 0.67 to 0.82 cited in the literature, in function of the biomass species.
- As expected, the biochar yield is influenced by the biomass composition in lignin, holocellulose and extractives. Biomass species with high lignin content offer higher biochar yields, although the biochar yield is strongly dependent upon the vapour phase conditions present in the pyrolytic reactor.
- An increased water content of the biomass increases the biochar yield: the creation of temperature gradients within the biomass during water evaporation is deemed responsible.
- Heat evolved during the pyrolysis is proportional with the amount of biochar produced by the primary and secondary carbonisation reactions. If the feedstock is dry, and biochar yield high, the exothermic evolution of heat can elevate the temperature of the feedstock sufficiently to initiate the biochar formation mechanisms.

These state-of-findings are entirely applied in the proposed project concept, as will be further discussed. To our knowledge, there are only a few slow biomass pyrolysis plants in operation.

3.2. Main Innovations

In comparison with the state-of-the-art, the main innovations can be emphasized as follows:

- Design and testing of an innovative biomass slow pyrolysis concept, based upon a well-mixed updraft moving bed reactor with electrical heating.
- The production of mainly 2 (possibly 3) energy carriers for short (pyrolysis gas) and medium (biochar) term applications in power generation. The production of pyrolytic oil will be investigated and applied if the non-thermal plasma catalysis tested at lab-scale provides technical and economically viable results. Non-thermal plasma is an ionized gas generated at low T using high voltage (10–30 kV). Electrons are accelerated to high energies while the background gas and vapor (ions and neutrals) are attacked by the highly reactive radicals formed [26–28].
- Quantification of the performance of the selected global concept at pilot scale for converting 20 kg/h of dry biomass. The expected product flow rates are 60 wt% to 70 wt% biochar, and 30% to 40% pyrolytic gas. The 30% to 40% of gas phase can only be obtained by incorporating an innovative thermal catalytic conversion in the process scheme.
- Catalysts, mostly zeolites [29] and Ni-Al_2O_3 [30] can selectively dissociate higher hydrocarbons into lower molecular weight ones and gaseous components, thus reducing the bio-oil production in favor of bio-gas.
- Development of a pyrolytic gas storage, compressed to approximately 1 MPa.
- The use of compressed biogas where production will preferably be ruled both by the “grid demand” principle and by the production during peak-hours (when electricity fetches a bonus price).
- The development and testing of a CHP application whereby residual process heat will be gathered within a hot water circuit, partially used for biomass drying, but also partially made available for residential use (in winter) or continuous use (in neighbouring industruies).
- Biomass particle handling at low and moderate temperatures, avoiding clogging or silo apex bridging.

- Complete heat analysis with respect to traditional non-biomass alternatives (coal, lignite, heavy fuel oil i.e., business as usual) and in comparison with currently commercialized fast pyrolysis plants.
- A complete Safety, Health and Environmental (SHE) impact assessment, to be integrated in a SHE impact report and providing sufficient data and arguments in view of possible societal unfavorable feelings towards a plant construction and operation within industrial or rural environments.
- A complete economic and business analysis on the basis of a case study (i.e., for a feed rate of 1–5 ton/h biomass).
- The project will make sufficient quantities of biochar, of appropriate quality, available for industrial testing by potential users.
- Finally, the project aims to better understand the slow pyrolysis of biomass in general, with special emphasis on a high energy efficiency, reduced CAPEX/OPEX costs, and applicable from a small decentralized scale close to sufficient biomass resources, to a larger scale (close to power generation plants of larger scale, where biochar might alleviate the CO_2 burden of fossil fuel burning).

4. Relevant Impact

4.1. Mass and Energy Balances

The mass and energy balances are presented in Figure 5. The overall energy balance is presented in Table 1.

Table 1. The overall energy balance.

Produced		**Consumed**	
650 kg/h biochar	4514 kW	-	
Electricity	416 kWel	Pyrolysis reactor	−120 kWel
		Heating before catalytic reformer	−41 kWel
		Shredder, conveying	−15 kWel
		Water belt dryer	−10 kWel
		Gas compressor	−20 kWel
		Pumps, exhaust fan, …	−7 kWel
		Miscellaneous (lightening, offices, lab, …)	−10 kWel
		Biochar cooler	−5 kWel
Total	416 kWel	Total	−218 kWel
Net production	198 kWel (1)		
Process heat	599 kWth	Biomass dryer	−311 kWth
Net production	288 kWth (2)		

(1) It is understood that electrical energy management will probably implement a scenario where cheap electricity is purchased from the grid at nighttime (11 pm–6 am) whereas the stored energy pyrolysis gas will be used at peak periods (6–8 am; 6–10 pm) and sold at bonus price. (2) If non-industrial heating applications are envisaged, the net heat production will only be used during 6 months, i.e., between October and March. It will however be investigated if available heat can be continuously applied in the neighbouring industries.

This efficiency can be compared with commercial fast pyrolysis plants (e.g., BTG, Fortum) where 65 wt% of pyrolytic oil is produced (at 17 MJ/kg), biochar and/or pyrolysis gas are consumed for reactor heating, and about 20 wt% of pyrolysis gas remains available (at 10 MJ/kg) for heating purposes.

The total net energy available, per ton of biomass, is 3069 kWth (oil) and 555 kWth (gas), or 3625 kWth. The energy efficiency, related to 5555 kW of biomass feedstock is 65.3% (this value should be reduced by the unknown electricity consumption of the plant itself.

The slow pyrolysis of biomass hence offers a considerable energy potential, with an increased efficiency of $(87 - (\max)65.3)/87 \times 100 > 25\%$.

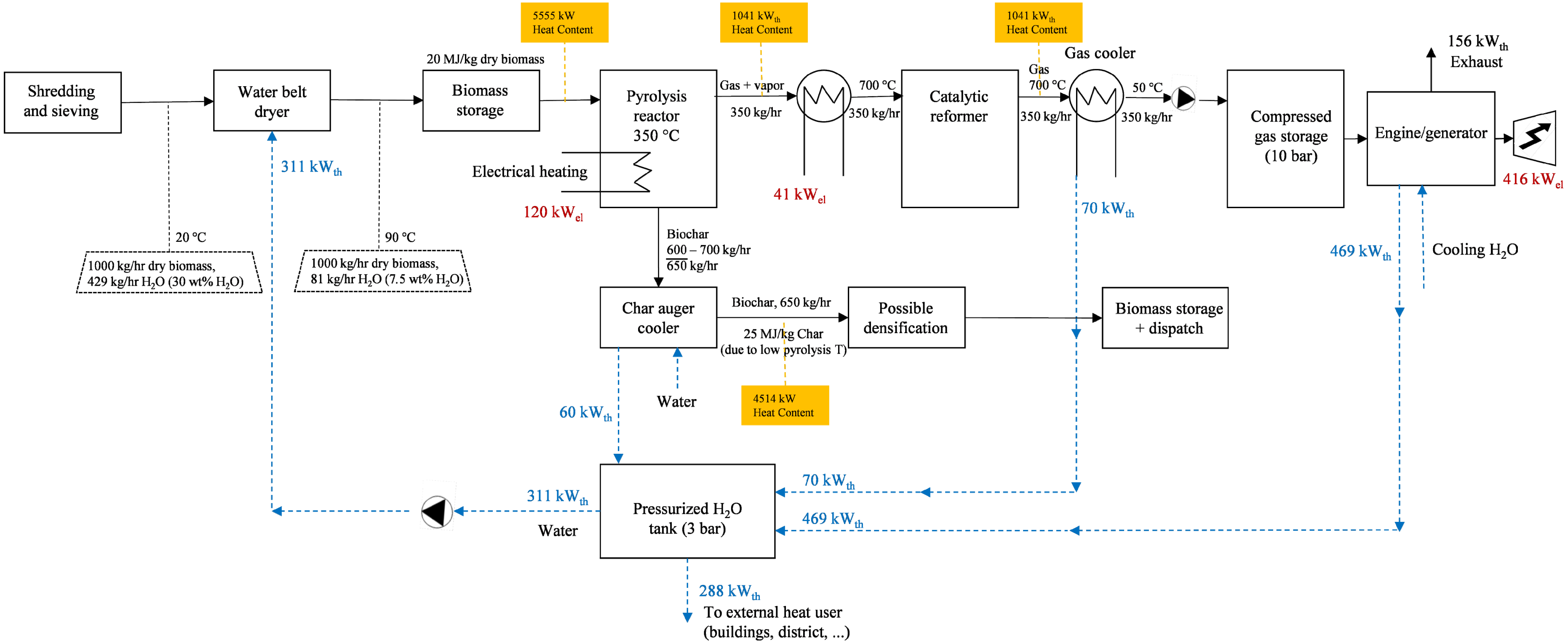

Figure 5. Mass and heat/power balances of the process for 1 T/h dry biomass (or 1.43 T/h wet biomass) application.

4.2. CAPEX

The investment cost for a 1 T/h biomass pyrolysis plant was estimated based upon quotations from suppliers and engineering practice. A summary is provided in Table 2, costs expressed in €.

Table 2. CAPEX of a pyrolsis plant for 1 T/h dry biomass.

Item	**1 T/h Dry Biomass**
Pretreatment	
Biomass shredder/sieving/conveying	140,000
Biomass water belt dryer	143,000
Silo with extraction	90,000
Conversion	
Electrically-heated updraft moving bed pyrolysis reactor	1,120,000
Dedusting (sintered metal fibre filters; 1 in stand-by)	120,000
Thermal catalytic reformer	850,000
Heat exchangers	130,000
Gas compressor	180,000
Gas storage	210,000
N_2 network	50,000
Product/energy recovery	
Biochar cooler/conveyors	95,000
Densification	110,000
Silo and dispatch	90,000
Genset (MAN 200–500 kWel) and grid connection	395,000
Total equipment (A)	3,723,000
Various	
Foundation, support, building	
Installation + start-up	
Electrical/instrumentation	
Piping	
Insulation and painting	
Engineering/supervision [10% of (A)]	
Contingencies [5% of (A)]	
Total of Various section [47% of (A)]:	1,748,800
TOTAL	5,471,800

4.3. OPEX of a 1 t/h Pyrolysis Plant (7500 h/yr, 7500 T/yr of Products), without Feedstock Cost

This operation cost of Table 3 should be compared with the earnings through products and electricity, as shown in Table 4. 1kWth, as hot water, is valued by the amount of natural gas required for its production (0.05 €/kWth).

Table 3. OPEX of the target pyrolysis plant.

Variable	**Basis of Calculation**	**Cost/Year (€)**
Catalyst	Replacement rate of 10% of catalyst inventory (50T) at 6500€/T	32,500
Water	0.2 kg per kg of product at 0.05 €/kg	75,000
Start-up energy	Natural gas 5000 kg/y @ 0.5 €/kg	2500
Operating labor	8 operators @ 40000 T/y	320,000
Supervision	15% of operating labor	48,000
Maintenance and repair	3% of total investment cost (5.5 M€)	165,000
Laboratory changes	8% of operating labor	25,600
Taxes and insurance	1% of total investment cost	55,000
Financing	2% of total investment cost	110,000
Depreciation time	Linear depreciation over 20 years	275,000
Overhead and administration	15% of operating labor	48,000
Total production cost		1,156,600
Distribution and marketing	2% of production cost	23,100
Research and Development	2% of production cost	23,100
Contingencies (waste product, water treatment)	5% of production cost	57,800
TOTAL OPEX		1,260,600

Table 4. Overall mass and energy balance.

Product	Production/Year (7500 h/y)
Biochar	4875 Ton
Electricity	1,485,000 kWh
Heat	1,080,000 kWth

Since electricity will be sold mostly during peak-hours, an average value of 0.15 €/kWh is assumed.

From this analysis, it is clear that biochar should be sold at approx. 200 €/T. Coal prices are about €120–188 per ton in 2026. Substituting coal only makes economic sense in markets where there are economic or regulatory benefits to replacing fossil carbon.

Biochar is, however, prepared under more severe conditions. Currently, a significant amount of biochar that is produced is used as feeds to produce syngas. A potentially more valuable market for biochar as a soil amendment agent is emerging. Currently, the market is primarily for high value crops like nuts and fruits. It is considered highly desirable by organic farmers. Recent reports indicate that global biochar production exceeded 350 kilotons annually by 2023–2024, with rapid further growth expected due to increasing interest in carbon sequestration and sustainable agriculture. Current bulk biochar prices are typically in the range of approximately €400–1000 per ton depending on feedstock quality and application, while premium horticultural products for home gardening may still reach €5–15 per kg. Organic farmers and specialty crop producers are often willing to pay premium prices for biochar products because of their potential benefits in soil fertility, water retention, nutrient utilization, and long-term carbon sequestration.

Part of the reason for this interest is that biochar is marketed as a natural product. The carbon in the biochar is locked in the soil so the char can qualify for environmental credits since carbon is derived from atmospheric carbon dioxide. It is possible to produce similar products from other “chemical” carbon sources at lower production costs. However, these would not qualify for environmental credits.

It is thus evident that the project will need to divide its sales between the energy and the agricultural markets. This market flexibility is an additional advantage of the project in comparison with pyrolytic oil, where a pure comparison with equivalent fuel prices, and corrections for the ratio of calorific values is severely negative unless regulatory benefits are granted.

5. Impact on the Energy System: Flexibility by an Energy Mix

Common sense dictates to avoid a high generation of electricity by biomass-based heat carriers during daytime since photovoltaic (PV) can do it at a fraction (less than half) of the cost. This always applies, no matter how the power is sold to the grid:

(1) should the price of electricity reflect a market price, then the daytime price would be dictated by the (very low) marginal cost of PV that is available and precedes other renewable electricity generation processes in the merit order;
(2) should a 24/7 production be requested with a flat tariff, the correct solution would be a hybrid PV/biomass-based plant that produces with PV during the day and with biomass heat carriers otherwise;
(3) the solution should also accommodate seasonality (winter-summer), where there is also an increased heat demand in winter time, hence favouring CHP processes.

In the mid-term future, the net load (demand minus non-flexible production) of electric systems and markets will peak steeply during the afternoon. As often, California offers a good predictive picture of what will happen next in other areas of the world. The famous “Duck Curve” that represents the net demand in California (Figure 6 below) shows very clearly how the net load bottoms lower each year at about 14:00, then increases very steeply and peaks at about 21:00.

The drop in the net load (or the demand when subtracting the renewable electricity generation) occurs in the middle of the day, when solar generation is at its maximum. The outline of the load curve looks like the outline of a duck. With a growing input of solar energy in California, the dip between 10 a.m. and 4 p.m. is getting lower, leading to problems for grid operators.

This is confirmed by estimates for Spain, with the price of electricity (averaged over the days of the month) as a function of the hour of the day in Spain, according to a 2030 scenario with a 60% share of renewable in the energy mix. Each colour corresponds to a specific year as presented in Figure 7 (as can be seen, the spread depending on the year is not considerable).

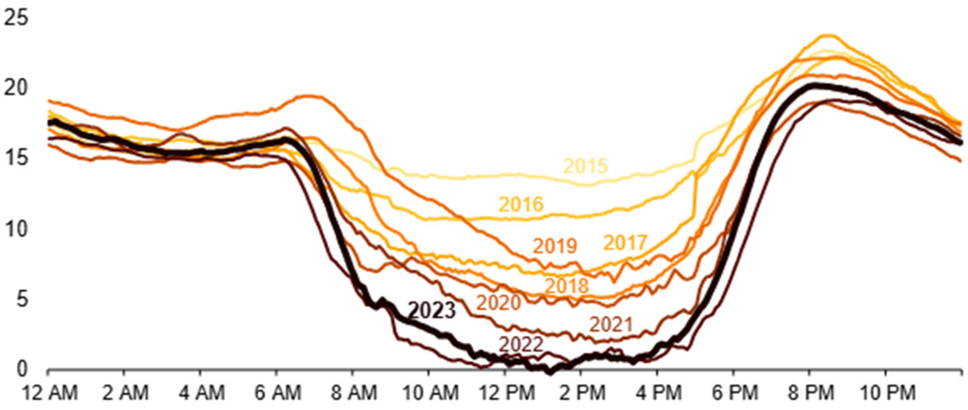

Figure 6. California Independent System Operator (Y-axis is Daily Net Load (GW) March–May 2015–2023—Source: CAISO [31].

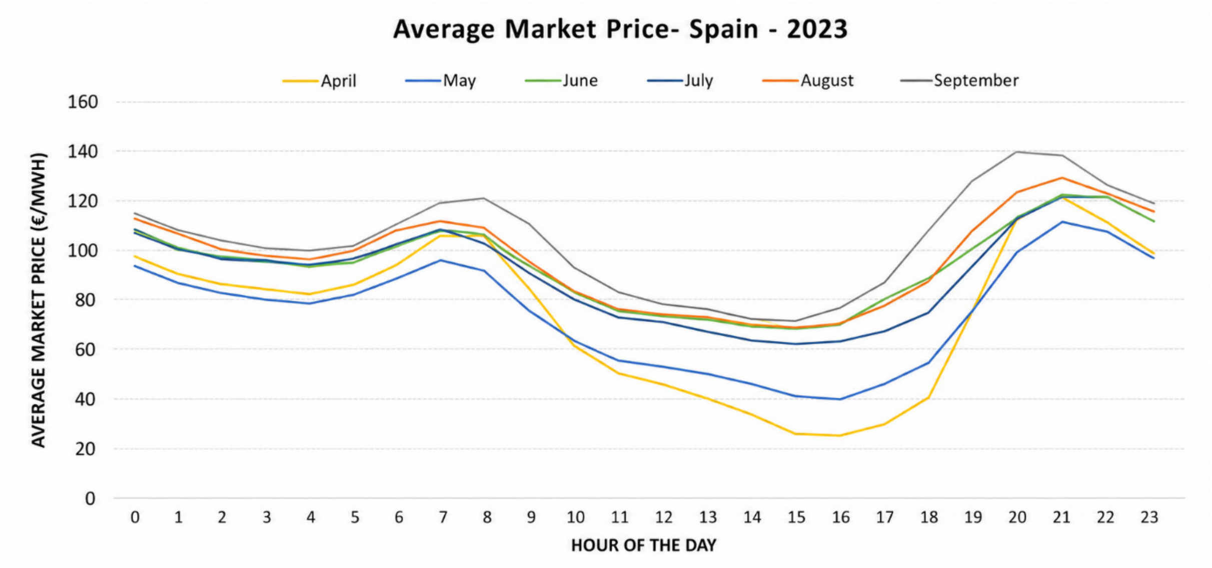

Figure 7. Average market price of electricity in Spain [32].

The most needed—and therefore valuable—electricity is produced during a period that lasts approximately 5 h (late afternoon/early evening). Another relevant indication is the steep ramp-up (and, to a lesser extent, the fast load reduction) that is required from the flexible power plants.

The future scaled-up, plant will be able to respond to such required flexibility. The major energy carrier (60–70 wt% of the biomass feed), i.e., densified biochar, can be stored and supplied to the power plants to accommodate for their peak power generation. The pyrolytic gas (30–40 wt% after catalytic reforming) will be stored in a pressurized vessel, prior to feeding the subsequent IC engine/generator (200–500 kW). Part of the produced gas (about 50% of its hourly production) will be used for supplying the 24/7 electricity needs of the process itself. The remaining gas will be stored, and on purpose be used for peak electricity generation (upon demand of the grid).

The energy density of baled or bulk biomass is normally between 2.8 GJ/m^3 and 4.7 GJ/m^3. The project will develop 2 main products, including 60% to 70% of biochar. Biochar (densified) will have an energy density in excess of 25 GJ/T, or >19 GJ/m^3 once densified to 750 kg/m^3.

Pyrolytic gas has a lower energy density, in the order of 12 MJ/Nm^3 to 13 MJ/Nm^3 or a tenfold if compressed to 1 MPa. The pyrolytic gas will, however, be used within the plant for power generation, and should hence not be considered in an energy density assessment.

The economics of pyrolysis techniques are highly variable, and production costs heavily depend on the local feed availability, its nature and costs. This fosters the development and attractiveness of small-scale units, located in areas where reliable sources of biomass feedstock are available within a close radius of a potential plant. Biomass pyrolysis can provide an economic stimulus to rural areas too. Locations with existing forestry or agricultural activities are very attractive not only due to their local feed stock but also due to the societal history and local culture, naturally fostering such schemes. Also agricultural waste (olive mills, fruit and vegetable canning...) could be considered for pyrolysis, especially in locations with restrictive landfill policies (such as Europe and California). Countries willing to preserve autochthonous currency and promote the use of local resources in Asia, Africa and the Far East have also shown interest in biomass production and use. The pyrolysis plants also provide the opportunity for local power generation in areas where the grid infrastructure in insufficiently developed to support a central power generation, or where remote regions are not connected to the power grid at all. These factors make pyrolysis plants viable on the long term and highly attractive, even at the current low prices for competitive fossil fuels. Note that the additional and primary benefit remains the reduction of the use of fossil fuels. Regulations that promote the use of renewable carbon resources and the availability of carbon credits will definitely tip the economics in favor of pyrolysis.

Finally, the concept has a positive impact on improving GHG emissions, as shown in Figure 8.

The concept will limit the use of external heat sources or electricity due to its advanced concept of own electricity generation combined with maximum heat recovery. The carbon content of the biomass will hence be completely recovered in mostly biochar-carbon, and in pyrolytic oil and gas to a lesser extent. Only at the first cold start-up of the system, natural gas and grid electricity will be used. This cold start-up will only last for 2 h. Once in operation, a sufficient amount of pyrolytic gas will be stored for subsequent re-start-up operations (e.g., after shut-down for maintenance operations) further reducing the emissions of the system by circular use of own energy.

The project-included electricity generator will be fed with pyrolytic gas. This will of course create CO_2 emissions and will need to be taken into account in the LCA (specifically regarding global warming potential), however the created carbon is entirely biomass-based. Towards the GHG performance, only CO_2 emissions related to the supplied biomass should be considered. The figure below demonstrates significant CO_2 savings in comparison with coal or natural gas [33].

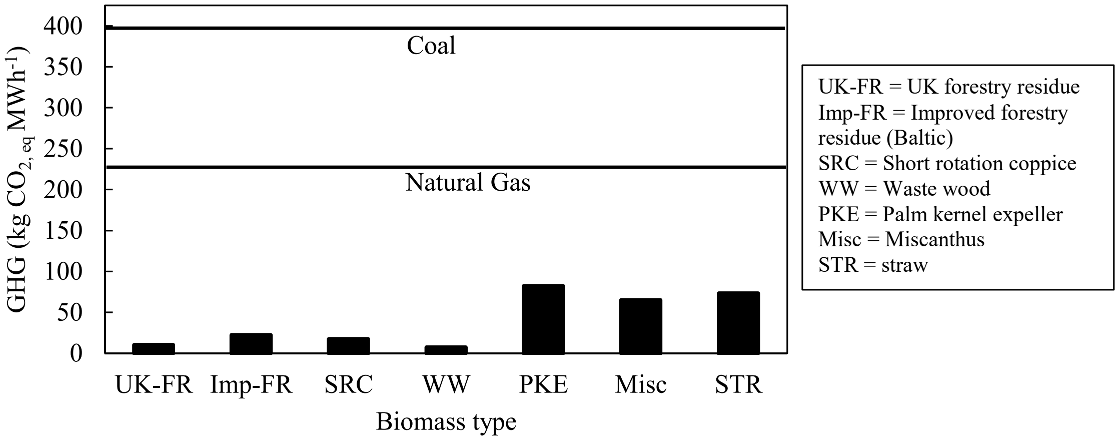

Figure 8. GHG profiles for different biomass species.

Towards the other GHG emissions, the expected emissions are negligible, since biomass contains only about 0.1 wt% of nitrogen. The combustion of the biomass-based energy carriers will however generate NO by mostly thermal NO production, since the low -content of the biomass will not create significant fuel-NOx formation [34]. At the common combustion temperatures applied in internal combustion engines or boilers, NO concentration will be very low (<<500ppmv), representing less than 10% of the expected NOx emissions from burning coal.

Since sulfur (S) contents of biomass are very low (<0.05 wt%, against ~3 wt% in heavy fuel oil and >5 wt% in coal), the emission of SO_x will be negligible.

Dust emissions will be abated using a high-efficiency sintered metal fiber filtration (emission < 1 mg/Nm^3). Heavy metals present in biomass species will be concentrated in the biochar/ash.

Fugitive emissions will be omitted through approved mitigation measures (N_2 blanketing, leak-free flanges, magnetic motor drives, emission-free storage silos, etc.

5. Results

Preliminary results do not involve the post-treatment of the pyrolysis vapors. Cornstover and sawmill dust we assessed between 300 °C and 400 °C, at atmospheric pressure and a slow heating rate.

Up to 40% of gaseous components were measured, with HHV between 6 MJ/Nm^3 and 10 MJ/Nm^3. The liquid fraction (<25%) had a HHV of ~20 MJ/kg, whereas up to 40% biochar was produced with a HHV of 30 MJ/kg.

The total heat requirements for corn stover were ~267 kJ/kg, against 434 kJ/kg for sawmill fines.

A model was based upon the following scheme of Figure 9.

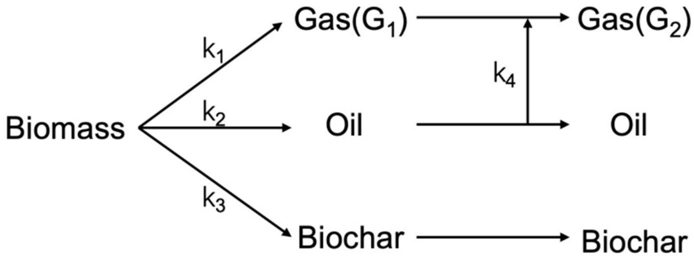

Figure 9. Structure of the slow pyrolysis model with secondary cracking of the produced bio-oil.

The concept proposed is currently being experimentally investigated in detail. Results of kinetics and updated economics will be presented in a follow-up paper.

6. Conclusions

A slow pyrolysis reactor to deal with biomass feedstock was developed to bring the technology to a TRL ≥ 5 level. The reactor is electrically heated. Pyrolysis gas will be compressed, stored and used for power generation at peak demand times. Biochar will be densified and sold as a reduction agent to foundries or for agricultural applications. Bio-oil will be catalytically upgraded to vehicle-fuel standards. Preliminary CAPEX and OPEX assessments indicate that the proposed system is economically feasible, particularly due to the valorization of biochar and stored pyrolysis gas, as well as the reduced dependence on fossil-derived energy carriers. Initial results demonstrate the highest production of biochar and biogas at T < 400 °C.

Author Contributions

Investigation & writing, Y.J.; Data Curation, D.Z.; Conceptualisation, X.F.; Visualization and Resources, T.T., R.D. and N.S. Review & Editing, H.Z. All authors have read and agreed on the published version of the manuscript.

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Data Availability Statement

Additional data will be made available upon a request with the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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