Pyrolysis technologies for solar integration

PYSOLO - Stakeholder Event 6 November 2025

Giacomo Lombardi (RE-CORD), Andrea Maria rizzo (RE-CORD)
José Manuel López (CSIC)

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   - Slow pyrolysis auger reactor
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Pyrolysis process

- Endothermic thermochemical process
- Inert atmosphere (or slightly oxidizing)
- Temperature: 400-650°C
- Conversion of wide range of feedstocks in high value products.
- Pyrolysis classification: Slow, Intermediate and Fast

Pyrolysis key-parameters

Process parameters

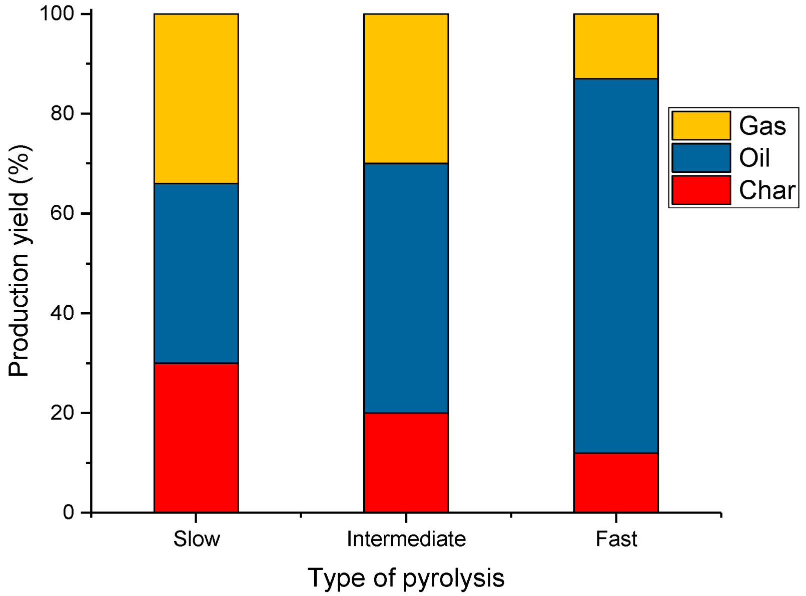
- Temperature
- Solid and vapours residence time
- Heating rate

Feedstock properties

- Size and shape
- Chemical-physical characteristics
- Moisture content

PYROLYSIS	SLOW	FAST
Biomass size	Chips (~cm), logs	Powder (~ 0.1 -3 mm)
SRT*	Very long (hours to days)	Short
HVRT**	Long (> 5 s)	< 1 s
Heating rate	Low (< 50 °C/min)	High (10-200 °C/s)
Target product	Biochar	Bio-oil

*SRT = Solid residence time
**HVRT = Hot vapours residence time



[1] Slezak, R.; Unyay, H.; Szufa, S.; Ledakowicz, S. An Extensive Review and Comparison of Modern Biomass Reactors Torrefaction vs. Biomass Pyrolizers—Part 2. *Energies* **2023**, *16*, 2212. https://doi.org/10.3390/en16052212

Heat demand and heat supply strategies

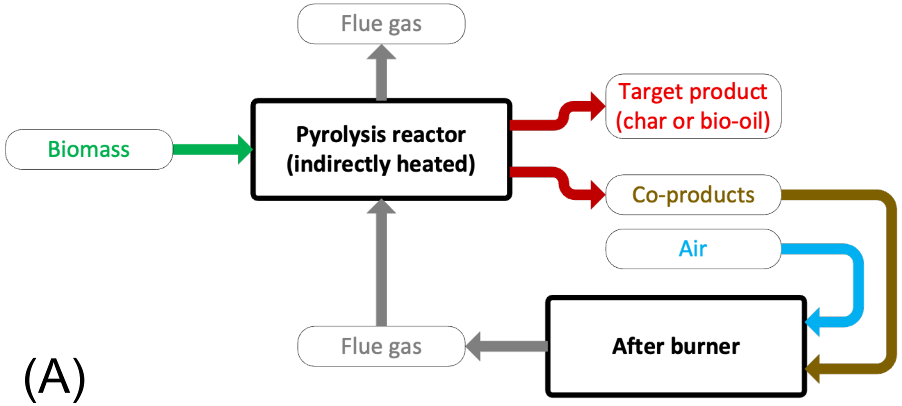
- Reactor heat demand (Q_{tot})= Heat for biomass pyrolysis (ΔH_{py}) + Reactor heat losses (Q_{loss})

  - T = 500-550°C
  - Lign. biomass
  - LHV = 18.8 MJ/kg

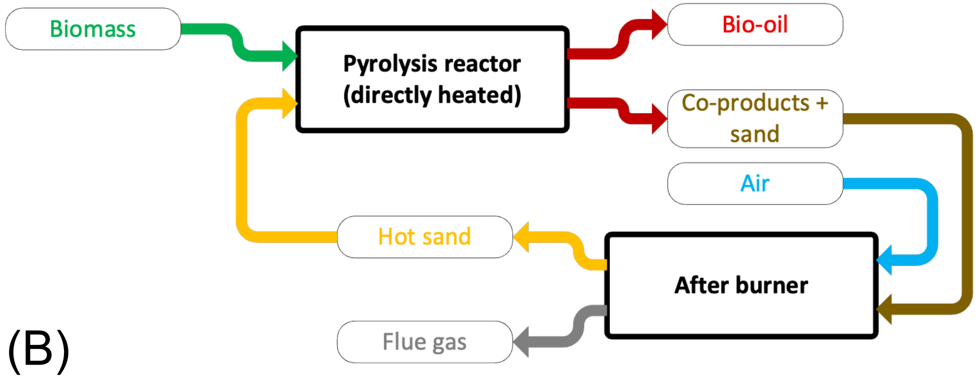
  ΔH_{py} = 0.8 – 1.6 MJ/kg [2-5]

[2] D. E. Daugaard and R. C. Brown, “Enthalpy for pyrolysis for several types of biomass,” *Energy and Fuels*, vol. 17, no. 4, pp. 934–939, 2003, doi: 10.1021/ef020260x.
[3] H. Yang *et al.*, “Estimation of enthalpy of bio-oil vapor and heat required for pyrolysis of biomass,” *Energy and Fuels*, vol. 27, no. 5, pp. 2675–2686, 2013, doi: 10.1021/ef400199z.
[4] A. Mati *et al.*, “Fractional Condensation of Fast Pyrolysis Bio-Oil to Improve Biocrude Quality towards Alternative Fuels Production,” *Appl. Sci.*, vol. 12, no. 10, 2022, doi: 10.3390/app12104822.
[5] W. Jerzak, M. Reinmöller, and A. Magdziarz, “Estimation of the heat required for intermediate pyrolysis of biomass,” *Clean Technol. Environ. Policy*, vol. 24, no. 10, pp. 3061–3075, 2022, doi: 10.1007/s10098-022-02391-1.

- Co-products are typically burned to meet reactor heat demand.
- Conventional heat supply strategies: (A) indirectly heated (flue gas) or (B) directly heated (heat carrier)



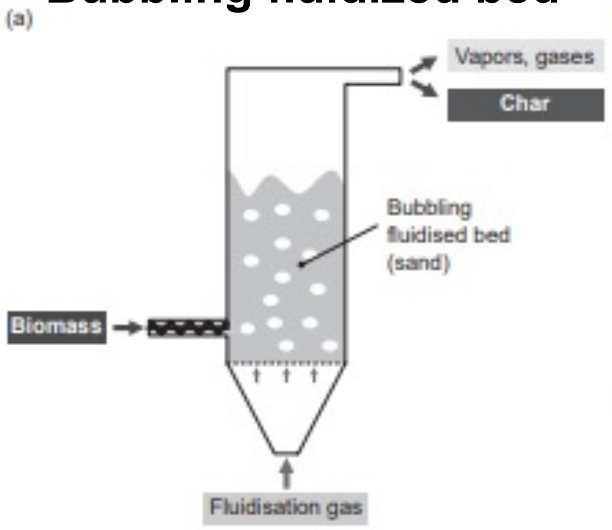
(A)



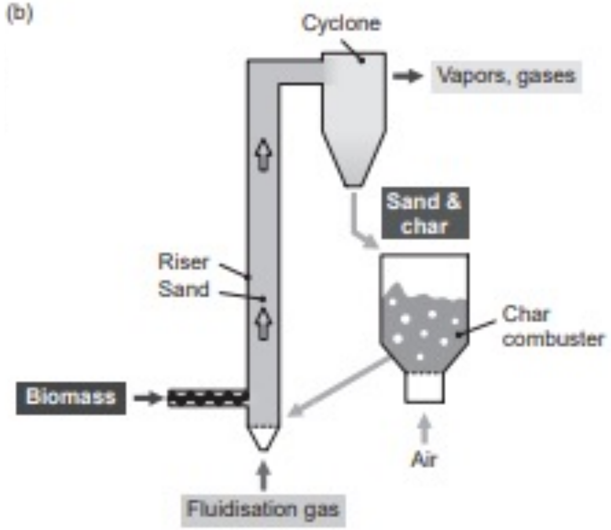
(B)

Reactor concepts for fast pyrolysis

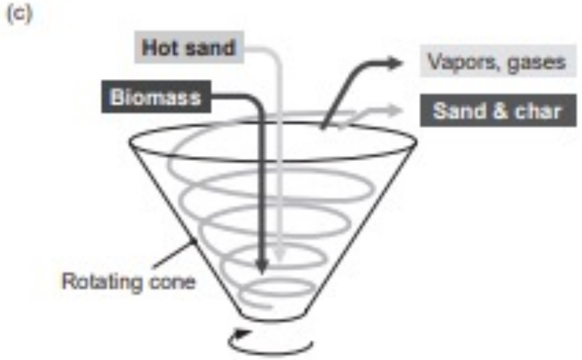
Bubbling fluidized bed



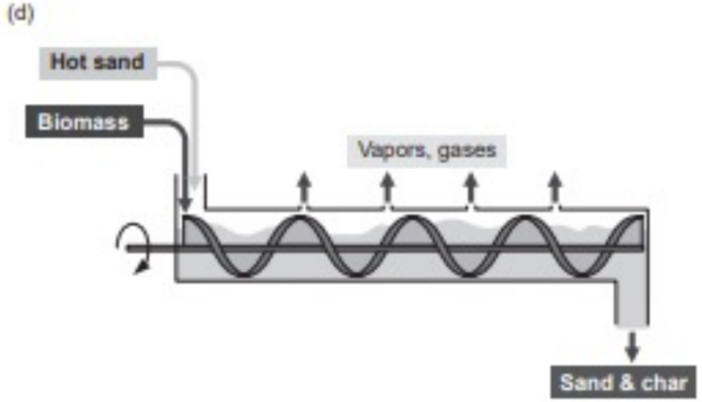
Circulating fluidized bed



Rotating cone



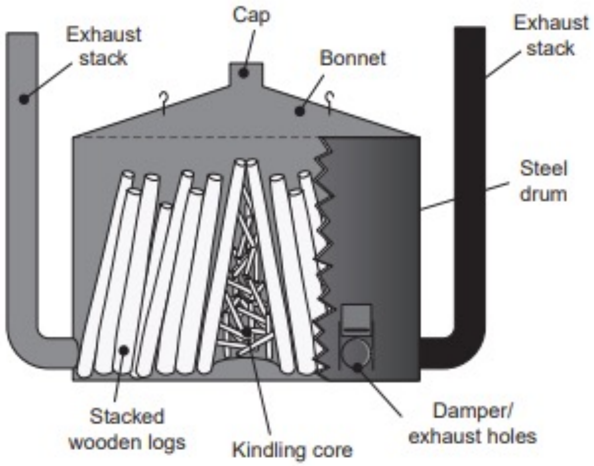
Auger



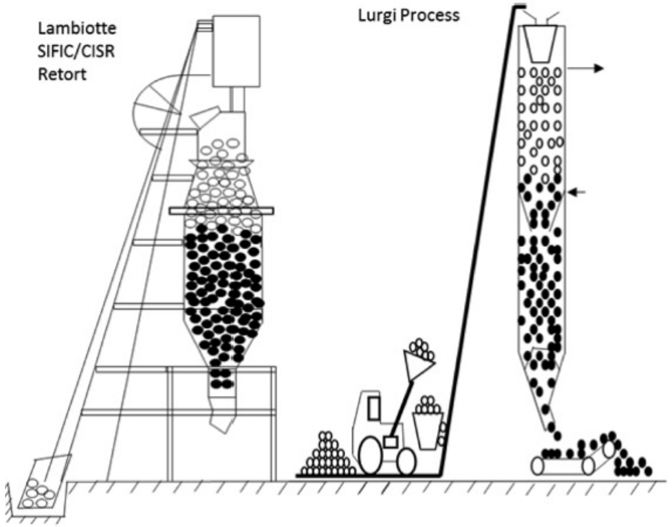
[6] Ronsse F. Biochar Production. In: Bruckman VJ, Apaydın Varol E, Uzun BB, Liu J, eds. *Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation*. Cambridge University Press; 2016:199-226.
[7] Historical Developments of Pyrolysis Reactors: A Review J. A. Garcia-Nunez, M. R. Pelaez-Samaniego, M. E. Garcia-Perez, I. Fonts, J. Abrego, R. J. M. Westerhof, and M. Garcia-Perez *Energy & Fuels* 2017 *31* (6), 5751-5775 DOI:10.1021/acs.energyfuels.7b00641

Reactor concepts for slow/intermediate pyrolysis

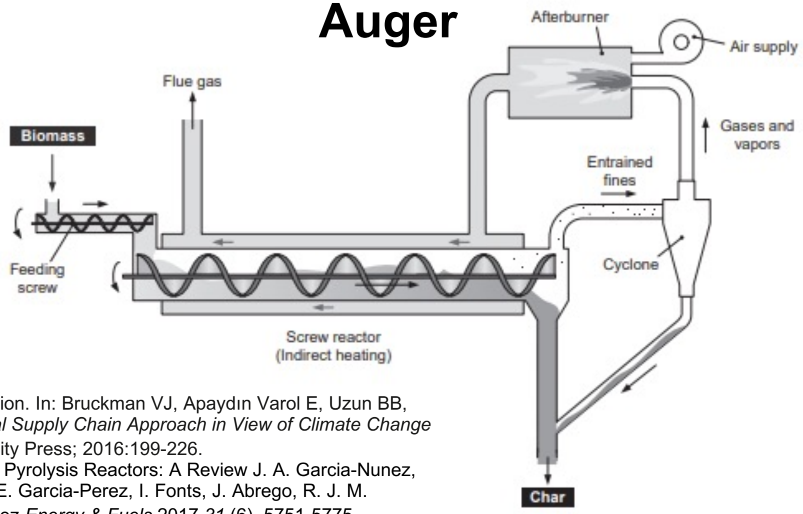
Traditional mound/steel kiln



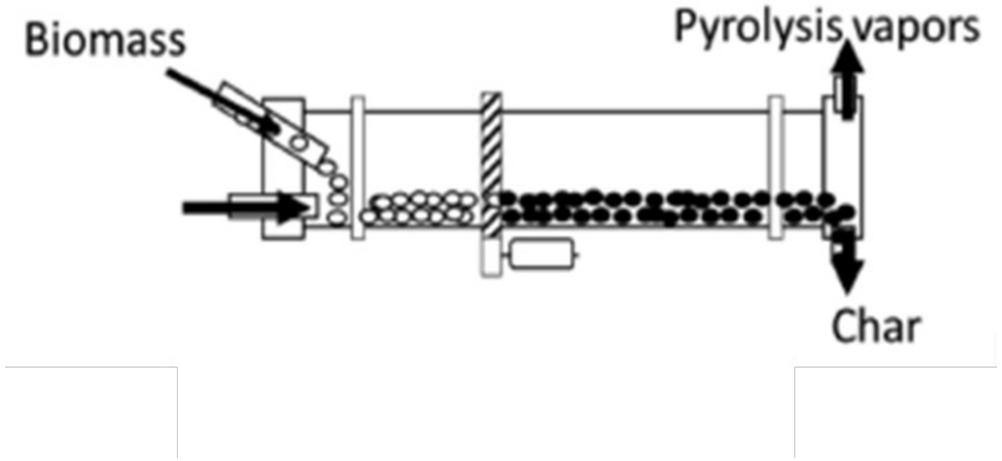
Retort



Auger



Rotary kiln



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Auger reactor for slow/intermediate pyrolysis

- Increased attention from many small and mid-size industries*

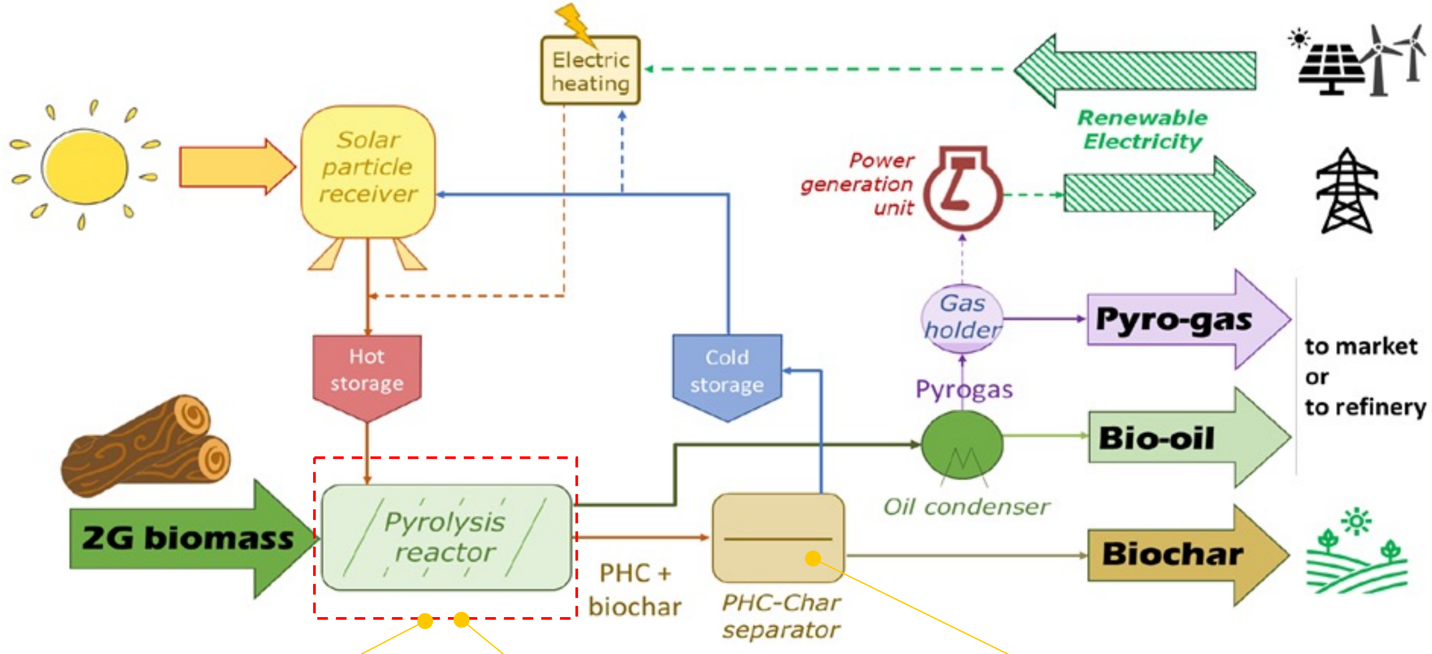
Company	Country	Capacity	Website
Biogreen-energy	France	12000 ton/year	https://www.vowasa.com/
BlackCarbon A/S	Denmark	800 ton/year	http://www.blackcarbon.dk/
NGe	Austria	2800 ton/year	https://nge.at/
PyroCore Ltd**	UK	8000 ton/year	https://pyrocore.com
PYREG GmbH	Germany	13000 ton/year	https://pyreg.com/

Ref. Nge pyrolysis reactor TCR 5000D https://nge.at/

- Overview on technology specific advantages
  - Simplicity of construction and operation
  - Less sensitive to feedstock type and particle size Suitable for the conversion of non-homogeneous material (pruning, agricultural and forest residues)
  - Broad range of residence time achievable by varying the rotation speed of the screw
- Drawbacks of conventional indirectly heated auger reactor
  - Heat transfer can be problematic in large-scale auger reactors.
  - Co-products consumption to meet reactor heat demand

*Konstantin Moser, Elisabeth Wopienka, Christoph Pfeifer, Markus Schwarz, Irene Sedlmayer, Walter Haslinger, Screw reactors and rotary kilns in biochar production – A comparative review, Journal of Analytical and Applied Pyrolysis, Volume 174, 2023, 106112, ISSN 0165-2370, https://doi.org/10.1016/j.jaap.2023.106112.
**Dissolved on 13 September 2025

PYSOLO PROJECT – Development of pyrolysis reactors



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Slow pyrolysis auger reactor

Fast pyrolysis fluidized bed reactor

CSIC

PHC-char separator

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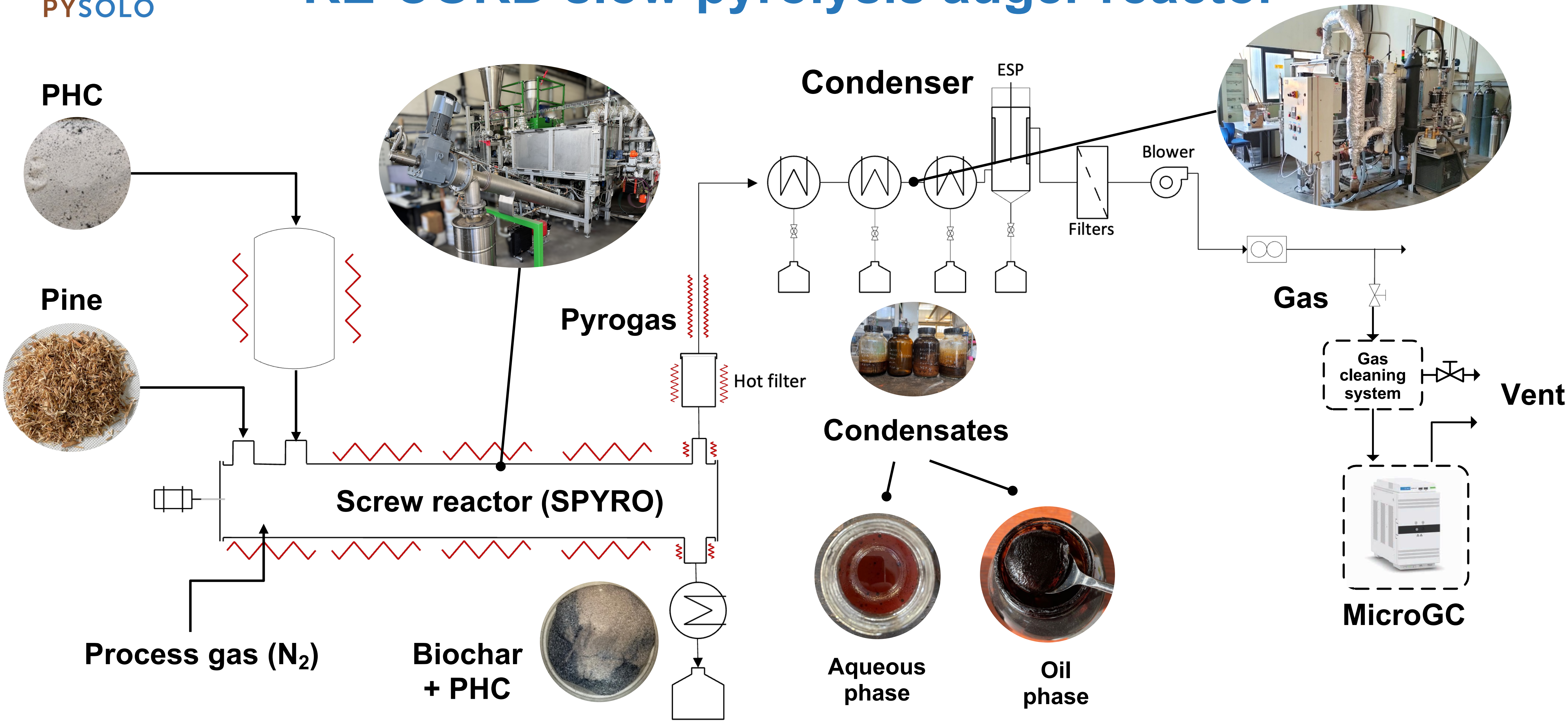
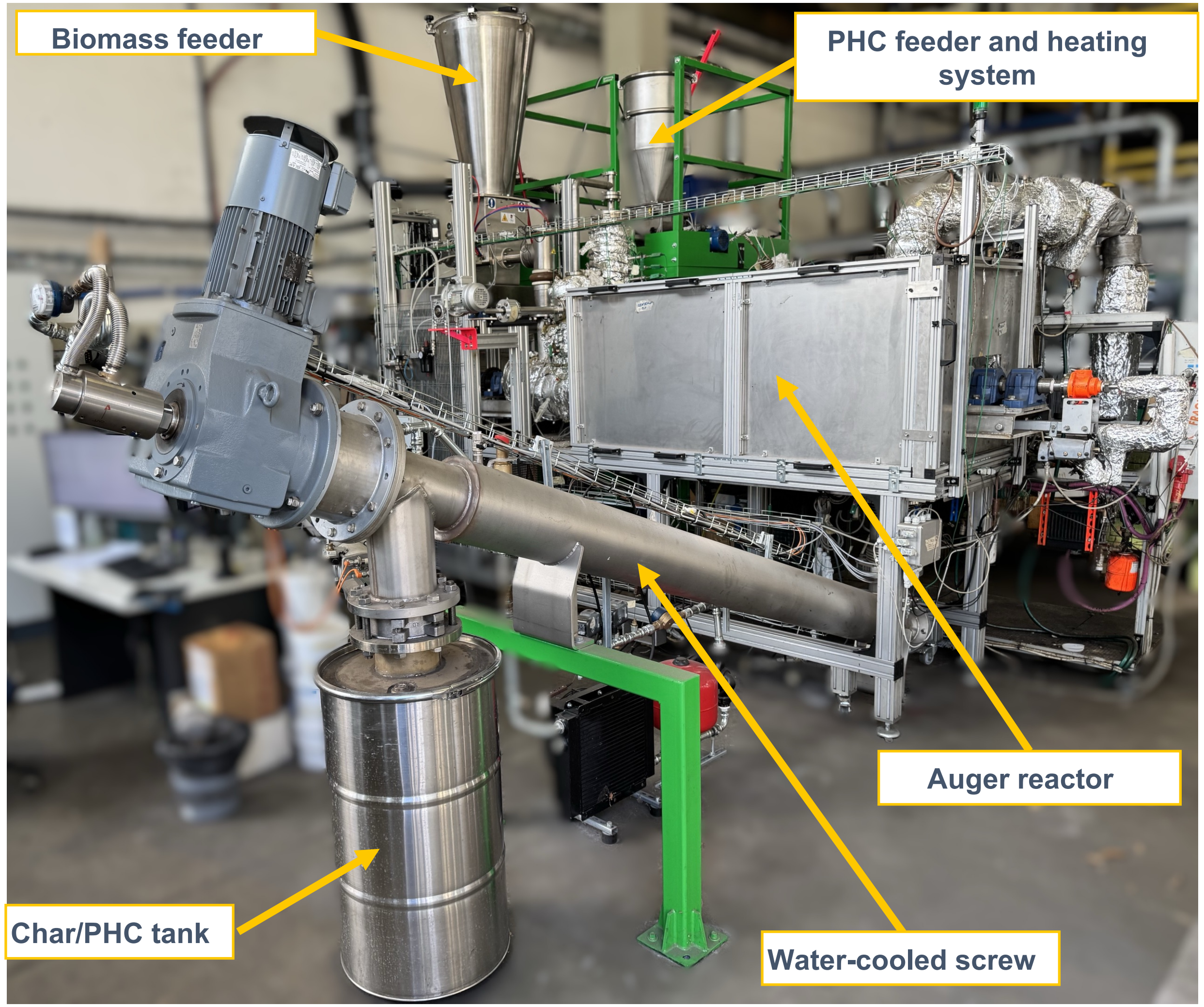
RE-CORD slow pyrolysis auger reactor



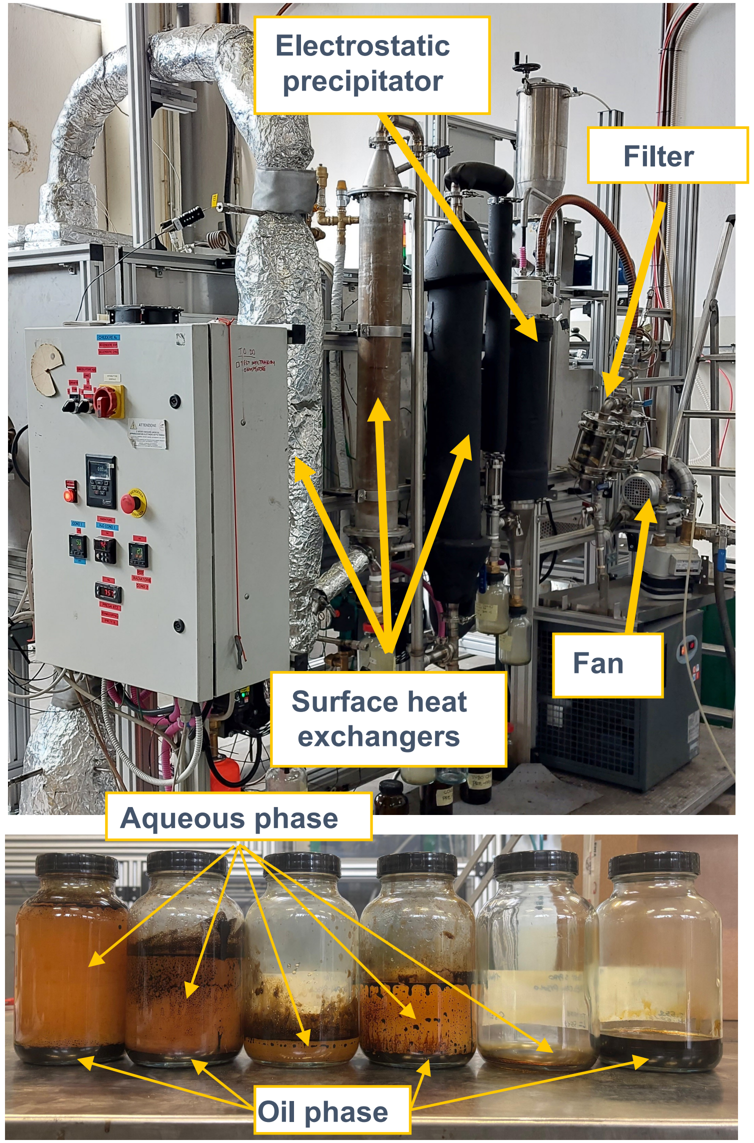
RE-CORD slow pyrolysis auger reactor



- Continuous reactor based on auger-type technology
  - Technology less sensitive to feedstock type*
  - Biomass feed rate of 1-5 kg/h
  - PHC to biomass mass ratio: 3-12
- Max operating temperature: 650°C
- Solid residence time: 5-60 min
- Process heat supplied via hot PHC
- Heat losses compensated by electric heaters
- Char yield achievable: up to 30 wt.% (lign. biomass)

*Suitable for the conversion of non-homogeneous material (pruning, agricultural and forest residues)

RE-CORD slow pyrolysis auger reactor



- Condensation unit
  - Tube-in-tube heat exchanger (from 550 to 120 °C)
  - Shell-and-tube heat exchanger (from 120 to 20°C)
  - Shell-and-tube heat exchanger (from 20°C to 0°C)
  - ESP (20 kV) □ to capture and collect bio-oil aerosols
  - Cotton and metallic wool filters
  - Side channel blower □ - 2 mbar in the reactor
  - Volumetric counter
- MicroGC
  - Permanent gas sampling (H_2, O_2, N_2, CH_4, CO, CO_2, C_2H_6, C_3H_8)

Slow pyrolysis products

T = 500°C, SRT = 30 min

Lign. Biomass

Char

Aqueous phase

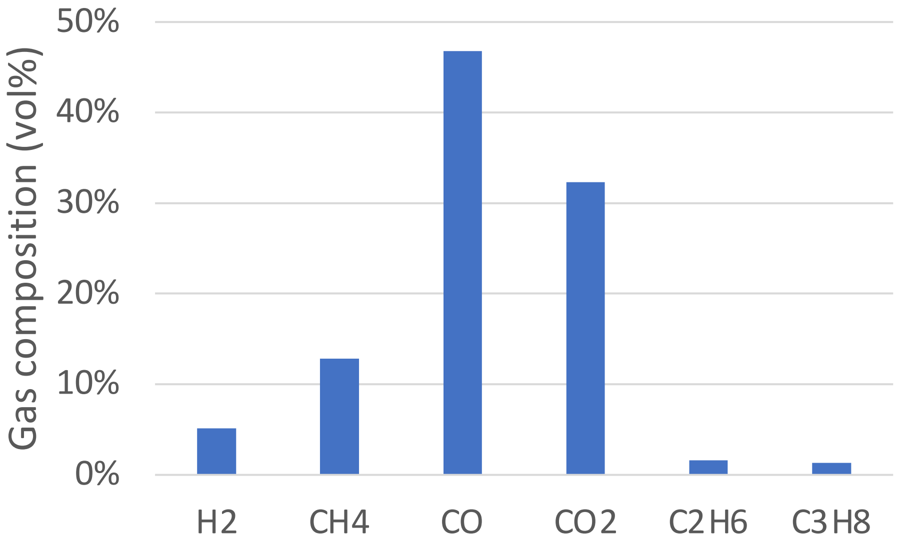
Oil phase

Gas

Phase	Yield [wt. %]
Char	25,3
Liquid	39,5
Gas	25,4
Total	**90,0**

Parameter	Biomass	Char
Ash (wt.% d.b.)	0.9	3.6
Volatile (wt.% d.b.)	79.9	14.3
Fixed carbon (wt.% d.b.)	19.2	82.1
C (wt.% d.b.)	50.0	86.2
H (wt.% d.b.)	5.9	3.1
N (wt.% d.b.)	0.2	0.9
HHV (wt.% d.b.)	20.0	33.1

Parameter	Aqueous phase	Oil phase
Water content	73.5	12.1
Ash (wt.% d.b.)	-	0.2
C (wt.% a.r)	15.2	56.8
H (wt.% a.r.)	9.8	7.4
N (wt.% a.r.)	0.3	0.8
HHV (wt.% a.r.)	6.1	24.4
TOC (g/l)	55.1	-
M_w (g/mol)	-	1020



PYSOLO Project goal –> effect of PHC feeding on pyrolysis product yields and composition

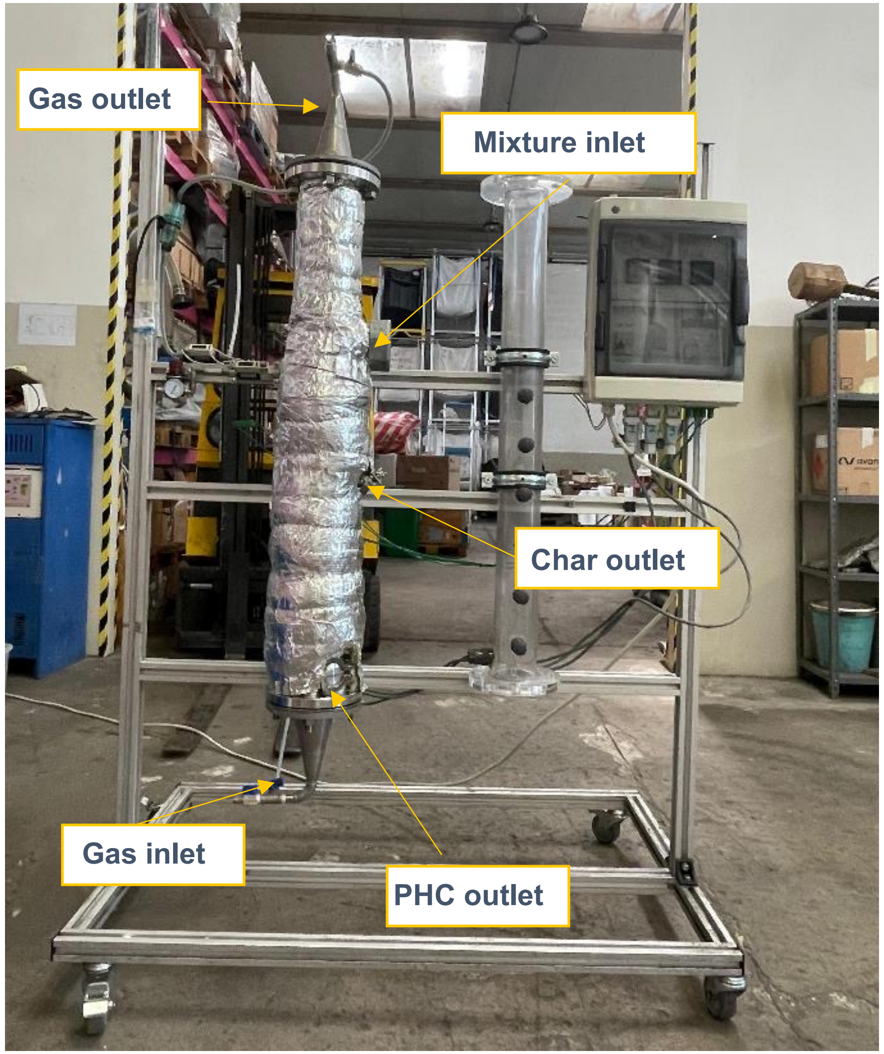
Experimental activity on REC auger reactor

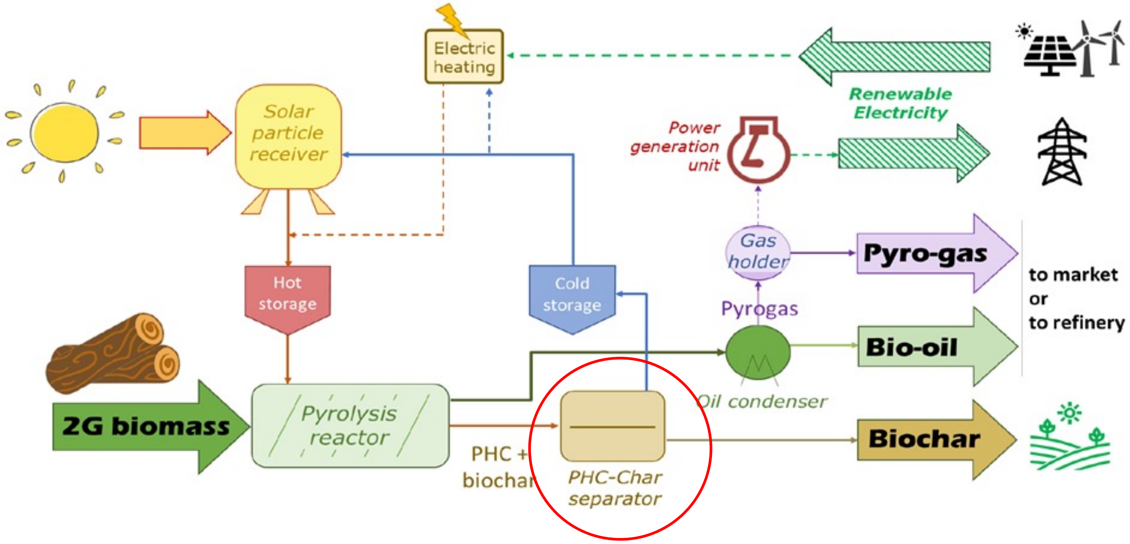
1. **Screening phase**: Four PHCs tested under the same operating conditions (fixed T_{PHC} = 600°C, solid residence time 30 min).
    - Silica, Bauxite, Char, Olivine

2. **Parametric study**: Investigation of the effect of operating conditions on the yields and quality of pyrolysis products
    - Key process variables:
        - Solid residence time (30, 15, 5 min).
        - Reactor temperature (400, 450, 500°C)
        - PHC-to-biomass mass ratio (3-12)

3. **System validation:** validating at TRL4 the operation of the developed fully auger reactor
    - Set of best performing parameters and the best PHC/char identified within the project
    - Test Run Duration: 6 Hours

PYSOLO challenge: development of a char-PHC separation unit





- Main goal: separation of char from PHC
- Development of a char-PHC sep. unit based on **fluidized bed technology**
  - Main dimensions: 1 m and 88.9 mm (3'') stainless steel column
  - Capacity: 4 kg of mixture
  - PHC-biochar volume ratio:1.5-6.0 (~ PHC to bm ratio mass 3-12)
  - Electrically heated
  - Max operating temperature: 600°C

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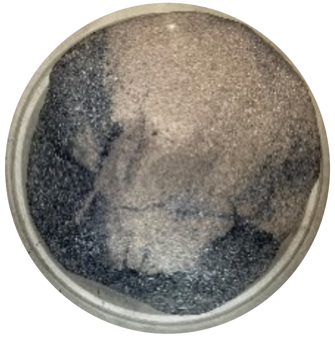
PYSOLO challenge: development of a char-PHC separation unit

Main challenges addressed:

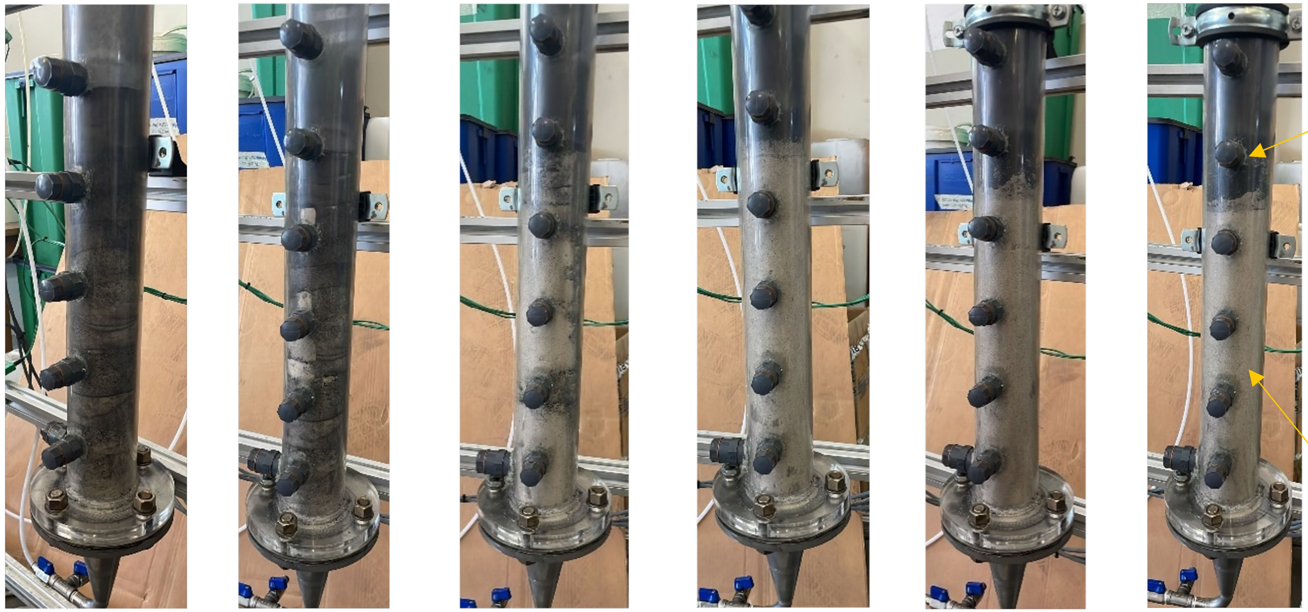
- Separated PHC mixture □ reduction of char content to prevent char ignition in solar receiver
- Separated char mixture □ reduction of PHC content —> agricultural use of char



Initial PHC/char mixture

Gas velocity (Ug/Umf)

0.88 **1.05** **1.23** **1.4** **1.58** **1.75**



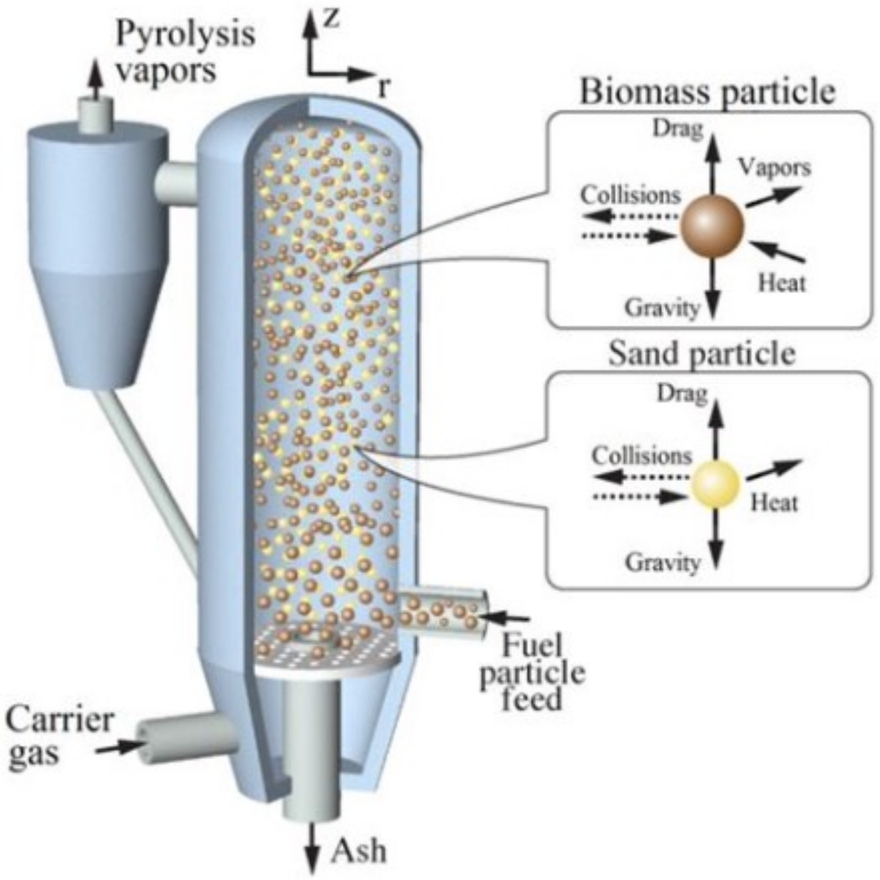
Char segregation on the top

PHC segregation on the bottom

Separated char mixture

Separated PHC mixture

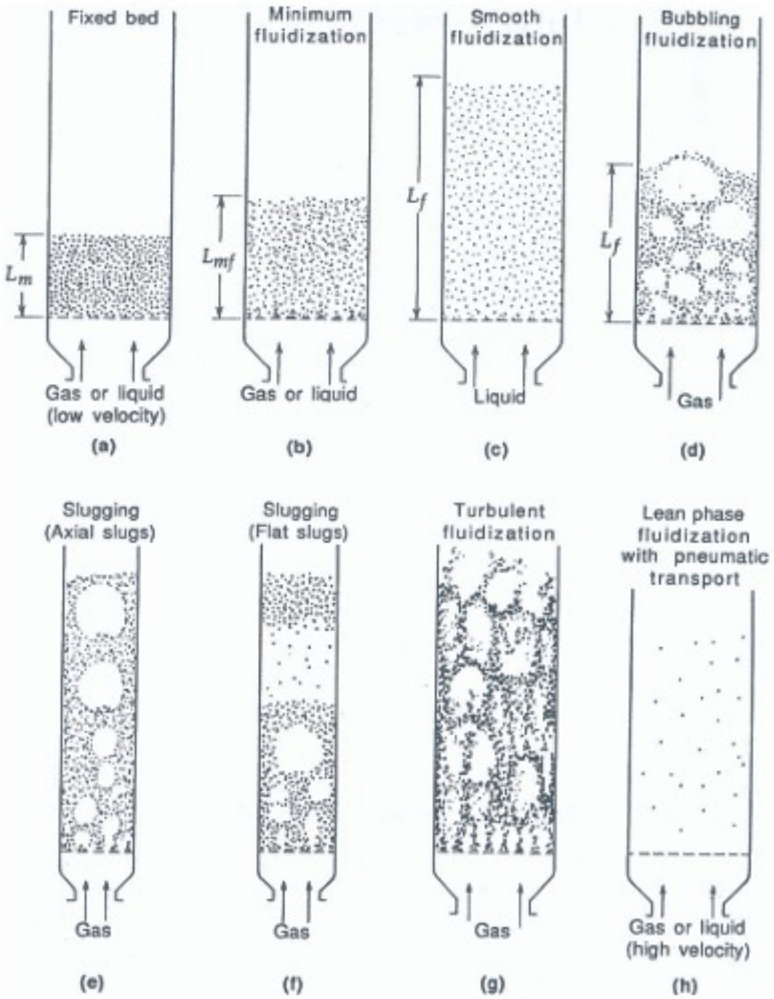
Fluidized Bed Reactor
Key features and benefits of FBRs:



- A fluidized bed reactor (FBR) is a type of reactor where **solid particles are suspended and agitated by a gas** or liquid, making the mixture behave like a fluid.
- The fluid-like behavior and large surface area of the fluidized bed facilitate **efficient heat and mass transfer** between the fluid and solid phases. **Fast pyrolysis**.
- The mixing action within the fluidized bed promotes a **uniform temperature distribution** preventing hot spots.
- **Continuous Operation:** Suitable for continuous processes, reducing downtime.

Fluidized Bed Reactor
Key parameters:

Fluidization Regimes



Reproduced from Kunii & Levenspiel (1991)

1. **Minimum Fluidization Velocity** (V_{mf}):

- This is the superficial gas velocity at which the solid particles in the bed become suspended and begin to behave like a fluid. Ergun equation:

$$(\rho_p - \rho_f)\, g = \frac{150\, \mu_f\, V_{mf}\, (1 - \epsilon_{mf})}{\phi_s^2\, D_p^2\, \epsilon_{mf}^3} + \frac{1.75\, \rho_f\, V_{mf}^2}{\phi_s\, D_p\, \epsilon_{mf}^3}$$

2. Bed Pressure Drop (ΔP):

- **The pressure drop** across the fluidized bed is an important factor in determining the energy requirements for fluidization.
- It's related to the weight of the particles and the void within the bed.

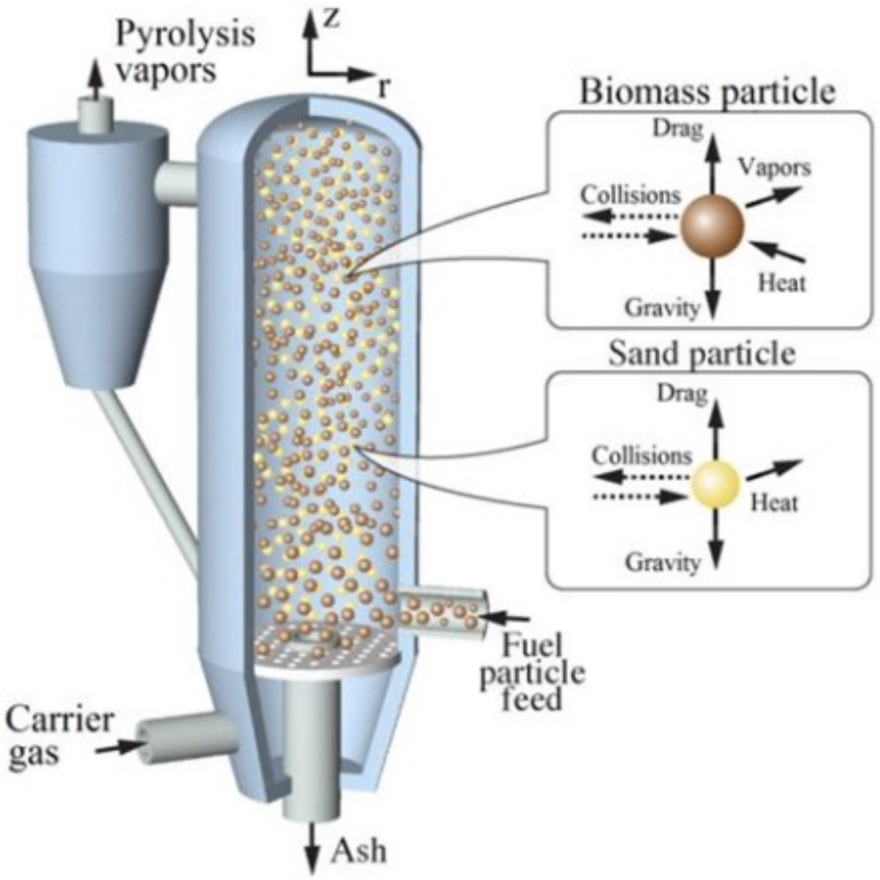
3. Distributor Design:

- **The distributor plate**, which distributes the inlet gas or liquid, plays a crucial role in the fluidization quality. It needs to provide uniform gas distribution to prevent channeling or slug flow.

4. Reactor Geometry:

- The dimensions of the reactor, including diameter and height, are determined based on the desired reaction volume and fluidization characteristics.
- **The freeboard** (the section above the bed) also needs to be considered to prevent particle elutriation.

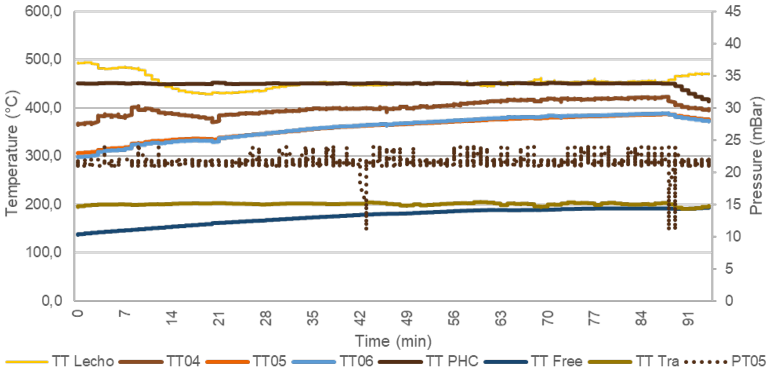
Fluidized Bed Reactor
Applications and disadvantages:

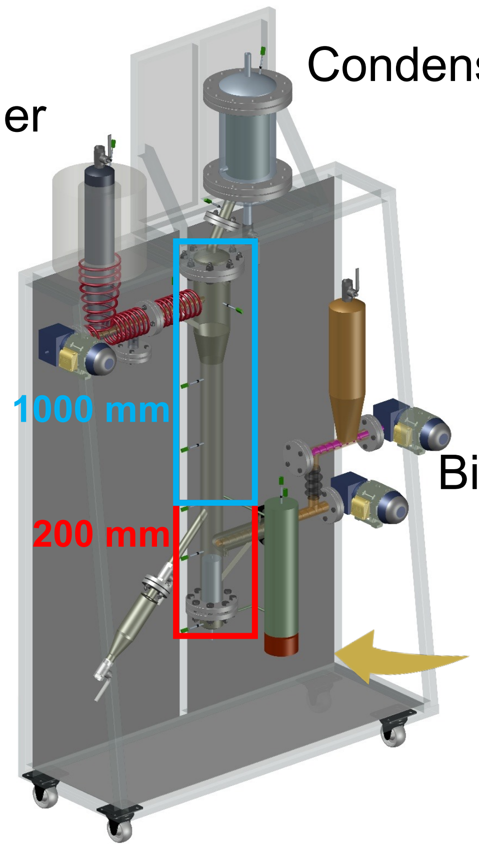


- **Petrochemical Industry:** Fluid catalytic cracking, hydro cracking, and reforming.
- **Waste Treatment:** Incineration and gasification of waste materials.
- **Power Generation:** Coal combustion and gasification.
- **Higher Capital Costs:** Generally, fluidized bed reactors can have higher initial costs compared to other reactor types.
- **Erosion and Attrition:** The movement of particles can cause erosion and attrition, potentially requiring particle recovery systems.
- **Complex Design and Operation:** Requires careful design and operation to maintain fluidization and prevent issues like channeling or slugging.

CSIC fast pyrolysis FBR reactor: Overview and Capabilities

- 7 heating elements (350-3750 W).
- 4 mass flow controllers (300-1200 Nl/h).
- 12 temperature sensors.
- 4 pressure sensors.





PYSOLO TRL-4 FBR

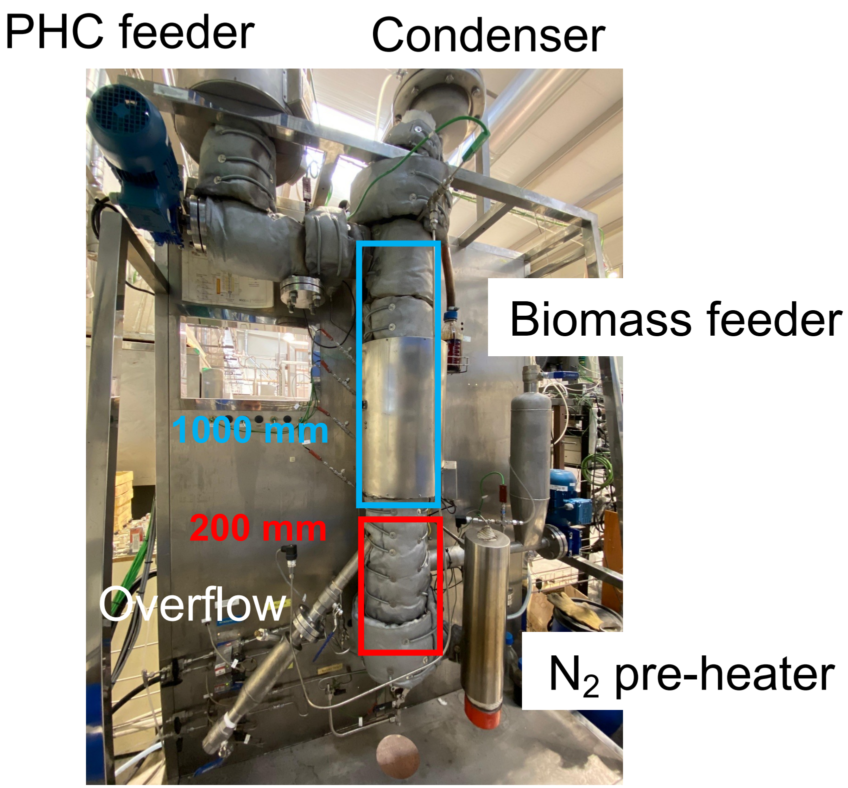
Pyro-gas

Bio-oil

Bio-char+PHC

- Biomass feeding rate: 0.7-1.5 kg/h
- PHC feeding rate up to 8 kg/h

CSIC fast pyrolysis FBR reactor: Operation parameters



PYSOLO TRL-4 FBR

Particle Heat Carrier (PHC)
Type of carrier material

- *Bauxite*
- *Sand*
- *Olivine*
- *Char*

Bed Temperature
Temperature operating range

- *400°C - 550°C*

PHC temperature
Carrier material temperature

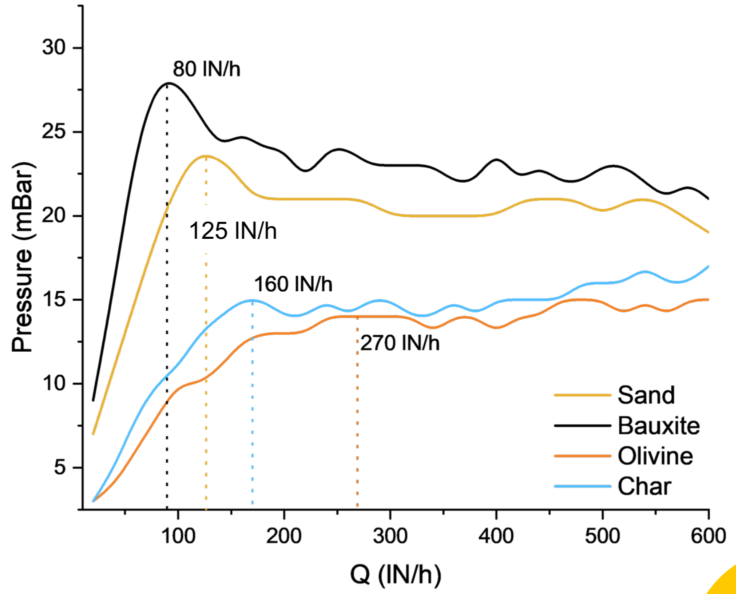
- *450°C - 650°C*

Fluidization
Bed fluidisation velocity

- 3 vmf
- 5 vmf
- 7 vmf
- 9 vmf

+ 45 experiments
+ 150 hours

Fluidization parameters, such as the fluidization curve and minimum fluidization velocity, were determined **for all PHCs**



CSIC fast pyrolysis FBR reactor: Experimental data

Experimental Conditions

- Bed: 450 °C + Bauxite 300–100 µm
- PHC: 550 °C + 6 Hz
- Vf: 7 × Vmf (510 L/h)

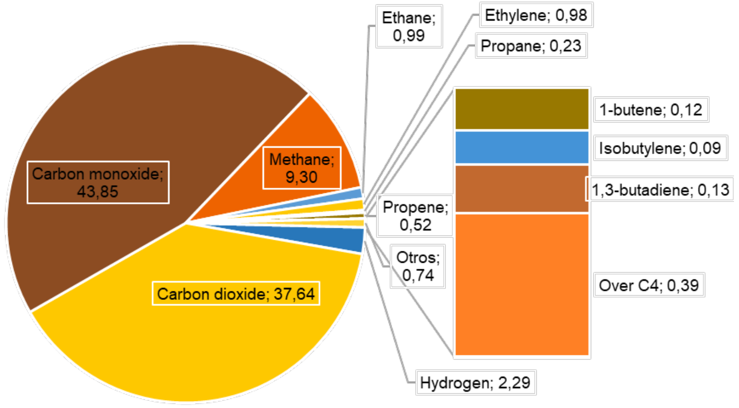
Feedstock

- Pine Wood Chips 3.5–1.3 mm
- Load: 1145.2 g
- Flow rate: 23 Hz ± 1200 g/h

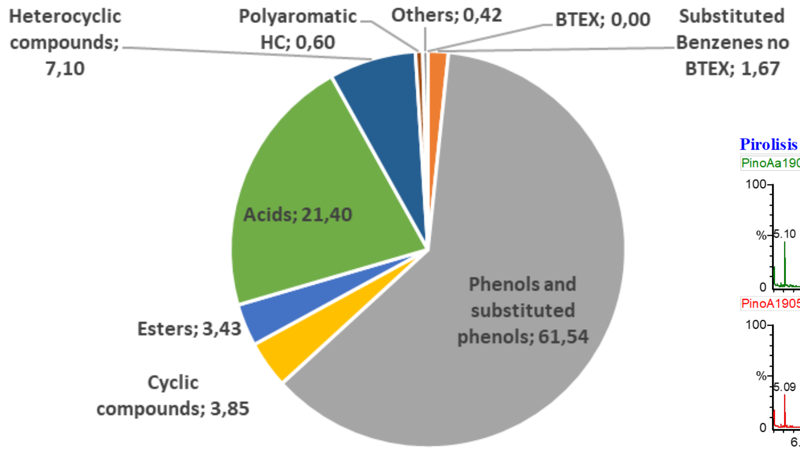
Product yields

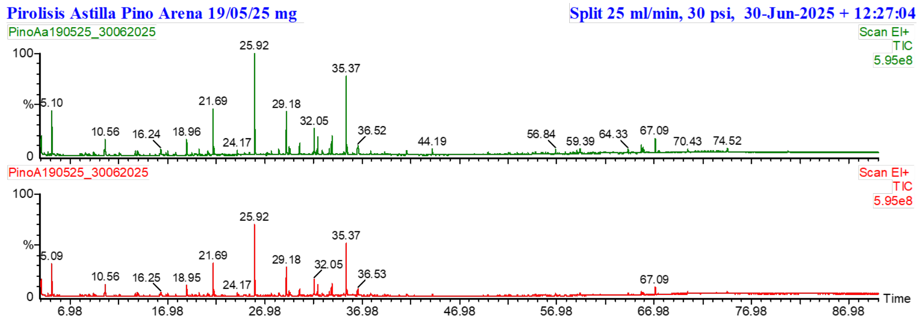
Phase	Mass [g]	Yield [wt. %]
Solid	271,8	**23,73**
Liquid	590,5	**51,56**
Gas (balance)	282,9	24,70
Gas (calculated)	239,94	**20,95**
Total		**96,3**

Gas composition

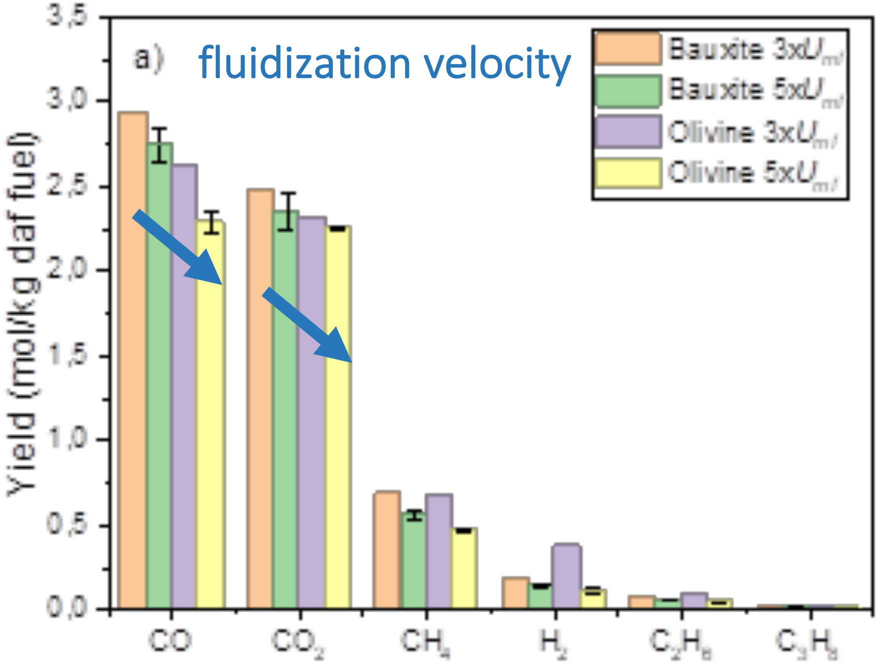


Liquid composition





CSIC fast pyrolysis FBR reactor: Pyro-gas



Higher fluidization velocity lower residence time less non-condensable gases

Bauxite increasses CO and CO_2 formation due to higher thermal conductivity and heat capacity promotes more uniform and intense heating of the biomass particles accelerate primary decomposition and increase the extent of decarboxylation reactions

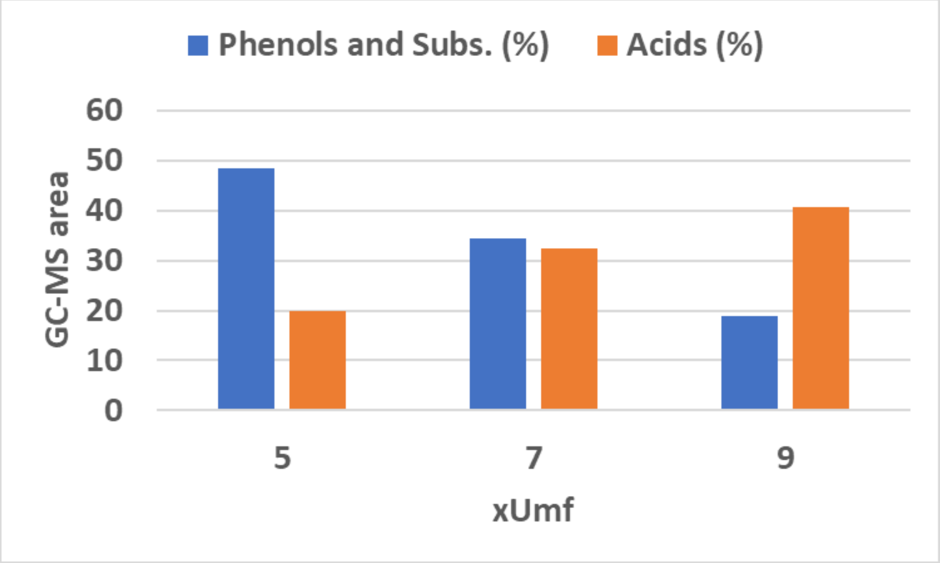
On average, pyro-gas is primarily composed of CO_2 and CO, which together account for around 80% of its content, followed by methane (about 10%), hydrogen (2.5%), and traces of other light hydrocarbons.

The pyro-gas produced has a relatively low energy content, which makes it **unsuitable for direct injection into the natural gas grid**. However, it offers promising opportunities as a **CO_2-neutral fuel for biomass drying or for electricity production in an internal combustion engine**, or as a **feedstock for the synthesis of valuable chemical compounds**—such as methane or methanol—when combined with renewable hydrogen.

CSIC fast pyrolysis FBR reactor: Bio-oil

Ultimate analysis

(wt %)	Sand 1	Sand 2	Bauxite 1	Bauxite 2	Bauxite 3	Bauxite 4	Bauxite 5	Bauxite 6
C	61,2	58,9	59,6	61,8	56,8	61,0	56,4	54,0
H	7,4	7,5	7,2	7,5	7,4	7,5	7,2	7,1
N	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
O	31,1	33,4	33,0	30,4	35,6	31,2	36,1	38,6



Ultimate analysis

- One phase liquid with **high O content** leading to different handicaps like **corrosive problems, low heating value and poor chemical stability**

Phenols and Guaiacols

- A high yield of **these compounds indicates successful lignin degradation** and provides **valuable fractions for** the **chemical industry** (e.g., resins, adhesives, aromatic fuels).

Light Acids, Aldehydes and Ketones

- **Primary products** from the **pyrolysis** of hemicellulose and cellulose, and **crucial for bio-oil quality control**.

Bio-oil is a very complex liquid with a **high oxygen content**, which makes it **unsuitable for direct use in standard energy systems**. It can, however, be used in **specially adapted engines and boilers**. To make it compatible with today's fuel infrastructure as a "drop-in" alternative, it needs **further upgrading**. Industrially, this is achieved through processes such as hydrodeoxygenation and subsequent distillation, which allow the **production of biofuels that can replace conventional ones**.

CSIC fast pyrolysis FBR reactor: Endnotes

- The PYSOLO project successfully demonstrated the potential of fast pyrolysis using a fluidized bed reactor (FBR) for solar-integrated biomass conversion (4 different PHC and temperatures under test).

- The FBR showed efficient heat transfer and stable continuous operation under various conditions (Umf, Bed temperature)

- Experimental results highlighted that while the produced pyro-gas can serve as a CO_2-neutral energy carrier, the bio-oil still requires upgrading due to its high oxygen content and instability. However, its rich composition in phenolic compounds offers added value for the chemical industry.

- Overall, solar-assisted fast pyrolysis represents a promising route toward sustainable and carbon-neutral fuel production.

Thank you!