

Alfredo NAPOLI

CIRAD/UR BioWooEB – Montpellier - France



Physico-chemical characteristics of Biochars for remediation and sustainable economy: main challenge on pyrolysis process development – Study case with the European Cronus Project

Summer Camp | July 7 – 11, 2025 | Marseille, France



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Agri-food Waste Management for Sustainable bio-economy through Higher Education curricula and upskilling

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Goals

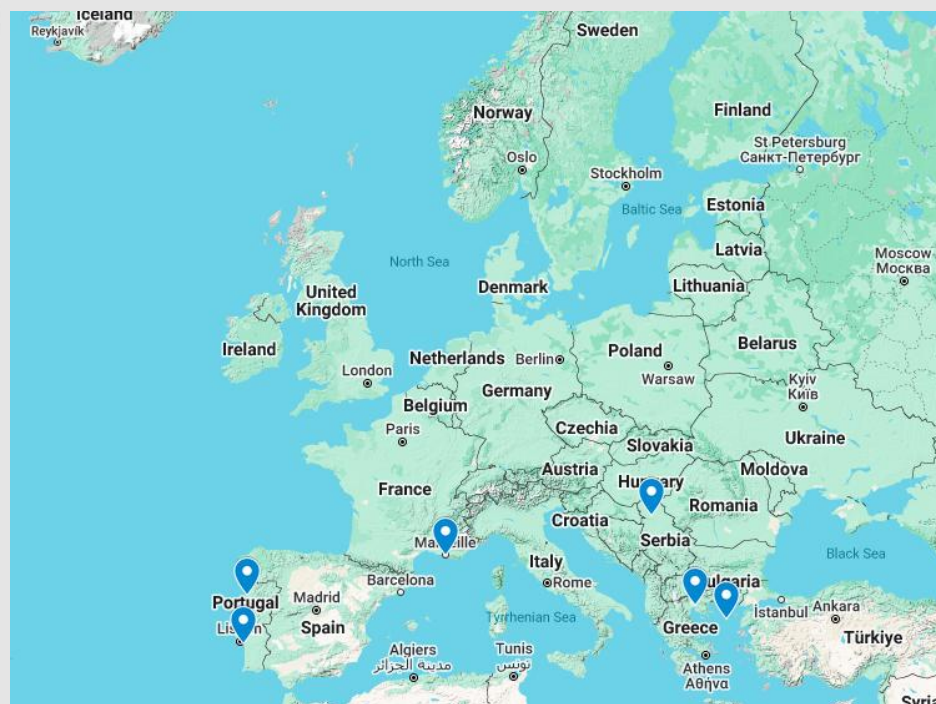
AGRIMA aims to foster universities' **capacity building** for the **green transition** through **innovative practices** and **higher education curricula updating** in **agri-food waste management** for the **circular bioeconomy**.

AGRIMA addresses:

- 1. Advancing pedagogical methods** for industrial agri-food waste valorisation **based on business-academia synergies**.
- 2. Integrating citizen science** in bio-economy-enhanced waste valorisation as a means of **civic engagement and environmental advocacy**.



Partners



CIRAD

Centre de Coopération Internationale en Recherche Agronomique pour le Développement



CIRAD is the French agricultural research and international cooperation organization working for the sustainable development of Tropical and Mediterranean regions

WORKING TOGETHER FOR
TOMORROW'S AGRICULTURE

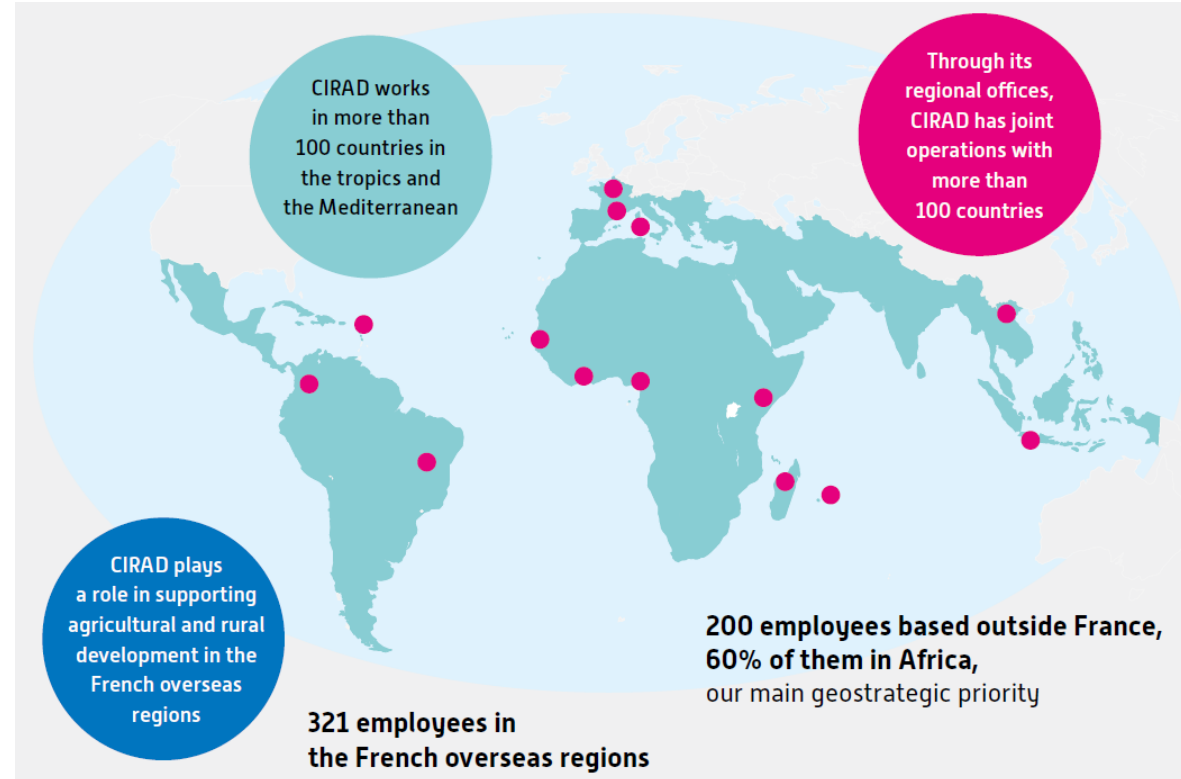
CIRAD Worldwide

- A staff of 1750 including 1 200 scientists
- € 240M in 2024
- Three scientific departments

Biological Systems Department (BIOS)
9 research units

Tropical Production
and Processing Systems Department (PERSYST)
10 research units (BioWooEB)

Environment
and Societies Department (ES)
10 research units



RESEARCH • TRAINING • INNOVATION • PUBLIC POLICY SUPPORT

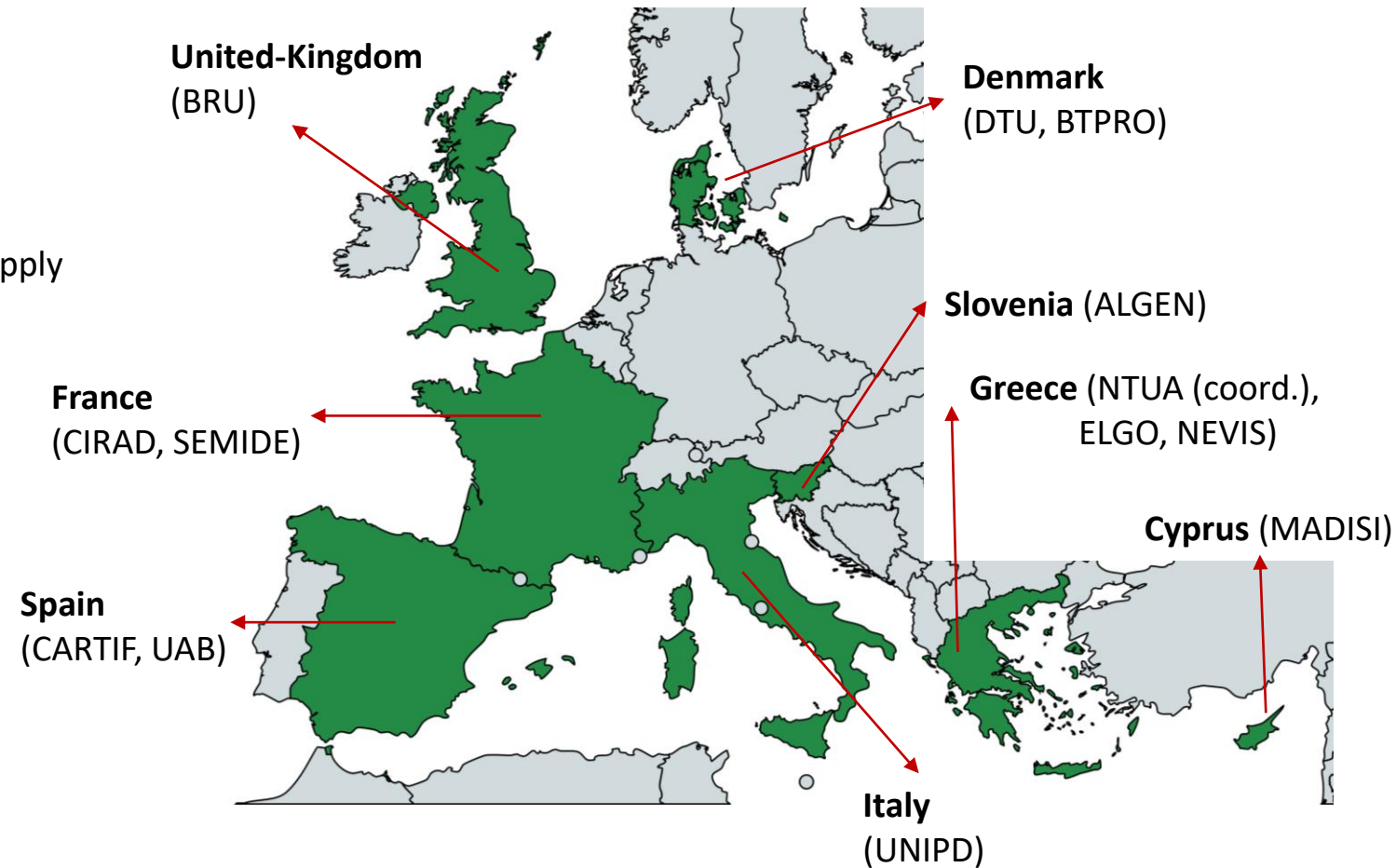
Biochar challenge

CRONUS Project

Capture and Reuse Of biogenic gases for Negative-emission - sustainable biofuels

INFORMATIONS :

- Funding : European Union
- Program : HORIZON-CL5-2021-D3-03
- Thematic : Sustainable, Secure And Competitive Energy Supply
- Budget : 5 MEuros
- Number of Partners : 13
- Duration : 45 months

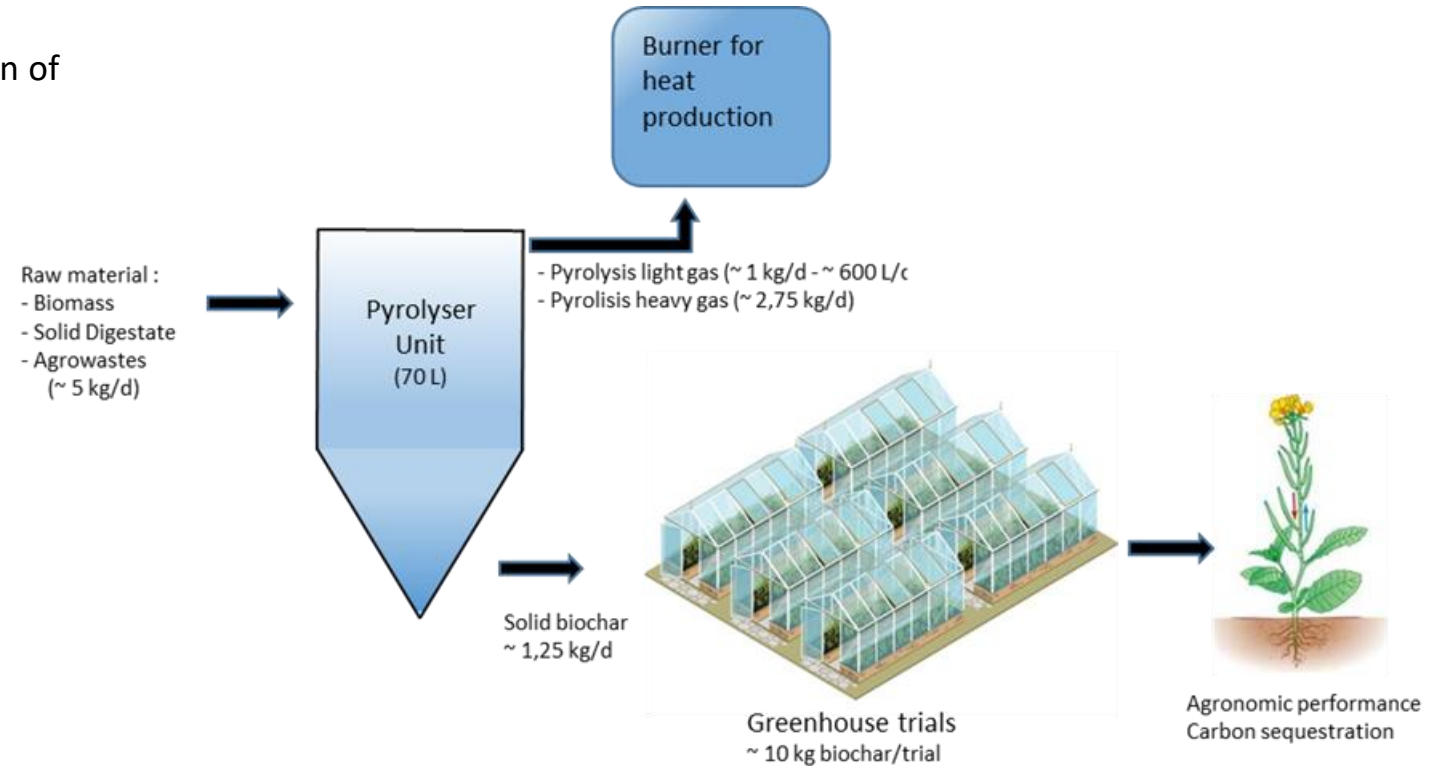


CRONUS Project

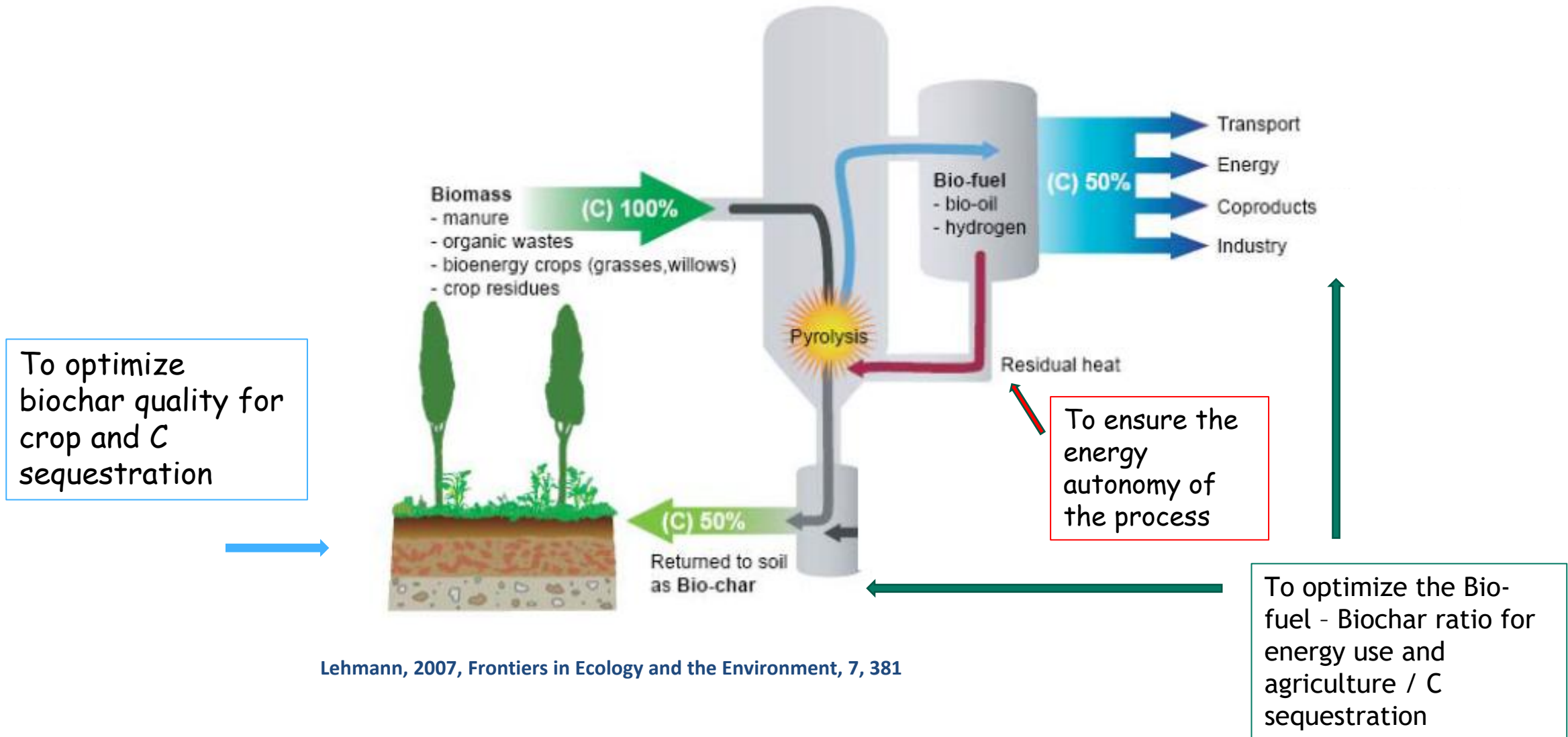
Capture and Reuse Of biogenic gases for Negative-emission - sustainable biofuels

OBJECTIVE :

- To develop technologies for Biofuels production and the utilisation of biogenic effluent gases
- TRL 2-3 (laboratory scale) to TRL 5 (small pilot scale)
- Technical, economic and environmental assessment
- 5 technologies :
 - Enzymatic capture of CO₂ (autotrophic algae cultivation)
 - Biological CO₂ hydrogenation
 - Syngas biomethanation
 - **Biogenic carbon storage through biochar production**
 - Microbial electrolysis cells
- Link : <https://cronushorizon.eu/>

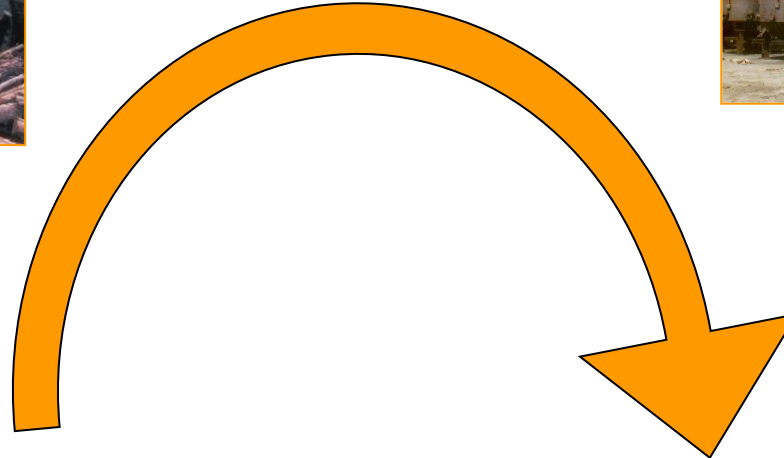
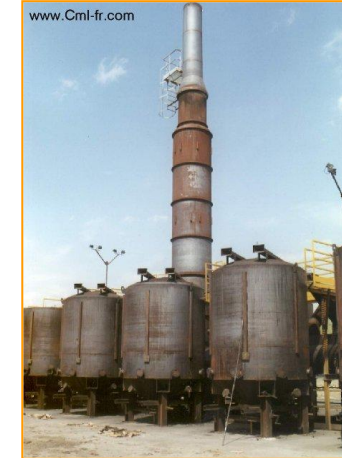
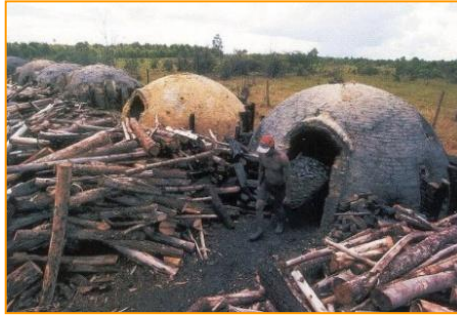


Main Challenge for Pyrolysis Technology



Lehmann, 2007, *Frontiers in Ecology and the Environment*, 7, 381

Overview of charcoal technology -> biochar



Pyrolysis study at laboratory scale

1. Methodology

Raw Materials

I - Choice and collect of raw materials :

- Biomass : wood chips
- Agricultural residues : Rice husk and rice straw (as model)
- Solid digestate (provided by DTU partner)



II - Characterization of the raw materials :

- Proximate analysis (FC, VM & Ash) and High heating Value
- CHN(O) Elemental Analysis & ash composition
- Composition : cellulose, hemicellulose and lignin



1. Methodology

Pyrolysis study

I - TG Analysis (1 g max) :

- Activation Atm : N_2 , CO_2 , H_2O
- Under pressure : 0,1 and 0,5 MPa

➔ Biochar yield vs pyrolysis parameters (T, HR, Atm, P)

II - Pyrolysis at laboratory scale (10 g) :

- Rice straw, Rice Husk, Oak wood, Digestate
- ➔ Heat & Mass balance, syngas composition

III - Biochars characterization :

- pH, Point of Zero Charge (PZC)
- Surface chemistry, Surface area



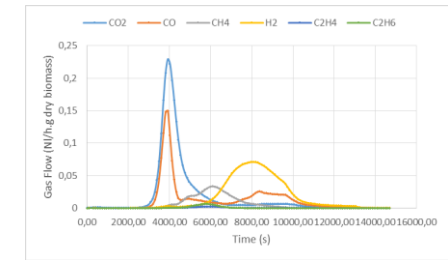
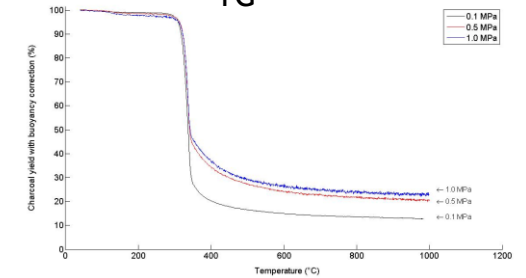
Key Performance Indicators (KPI) determination

IV - Pyrolysis at pilot scale - prototype (5 kg) :

➔ Biochar production for greenhouse trials



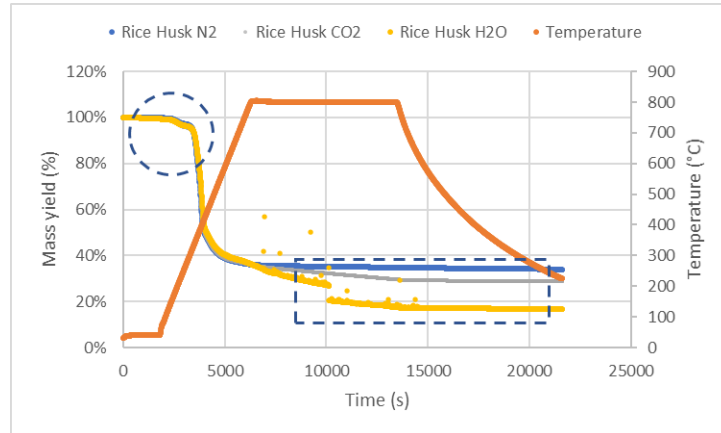
Example of Biochar yield by TG



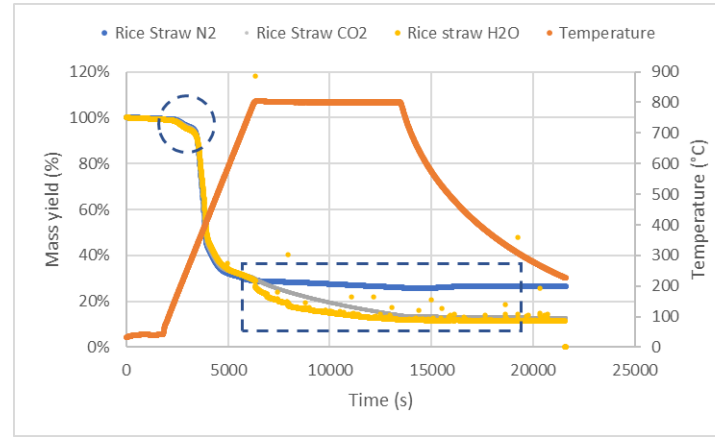


I - TG Pyrolysis/Activation under N₂, CO₂ or H₂O : Main results

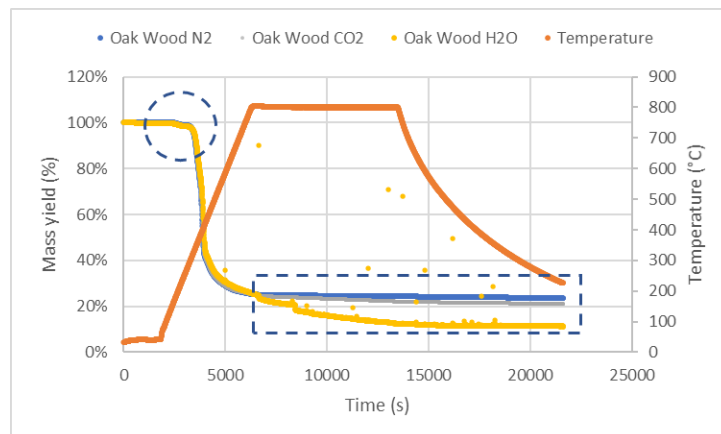
Rice Husk



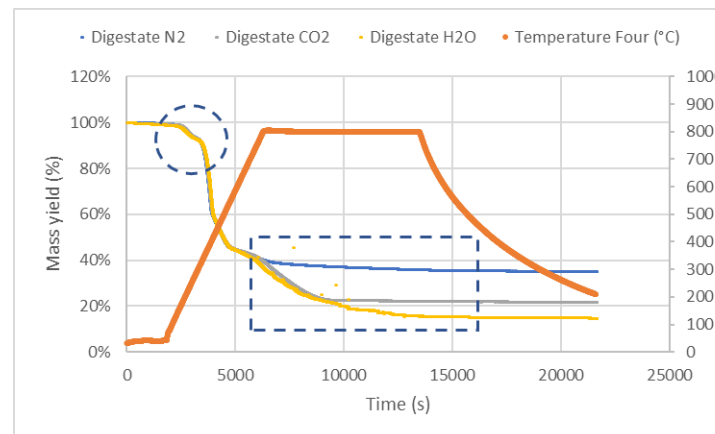
Rice Straw



Oak Wood



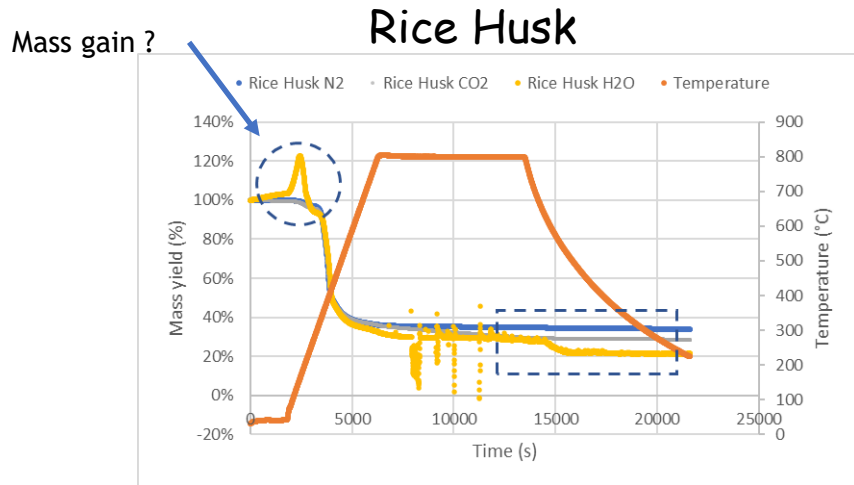
Digestate



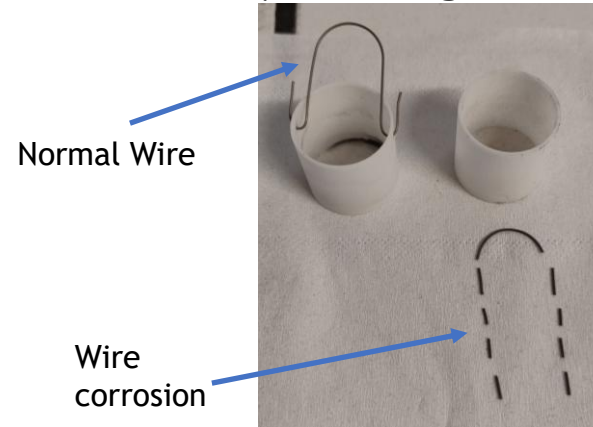
Main conclusion :

- Activation at T °C > 750 °C
- Steam activation is higher than CO₂
- Oak wood steam activation appears
- Kinetics laws of pyrolysis step (100-750 °C) is unchanged with N₂, CO₂ or H₂O

Pyrolysis - activation under H₂O : Trouble to be solved

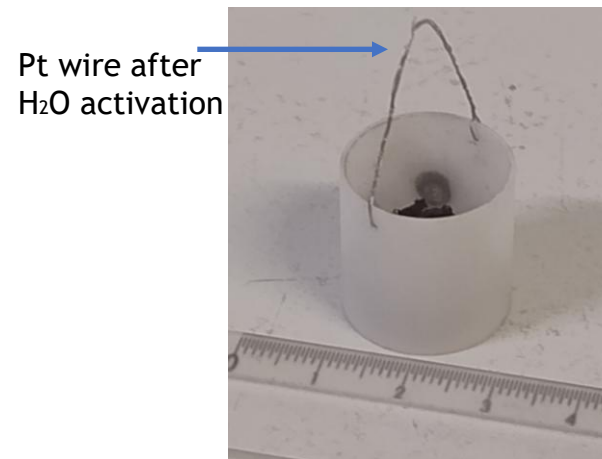
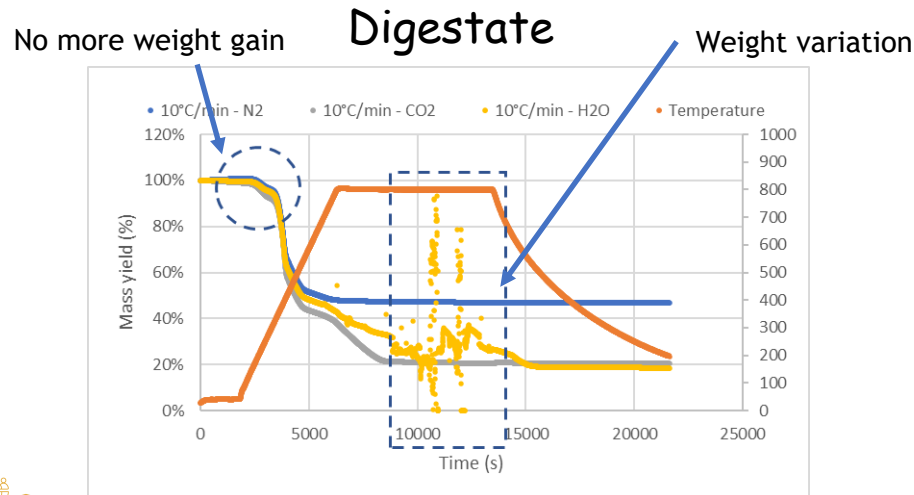


Only with digestate ?



Main actions :

- Mass gain : ATG protocol has been modified to clean the top of the reactor before each experiment (elevated temperature)
- Wire corrosion by H₂O activation is solved by using Pt wire

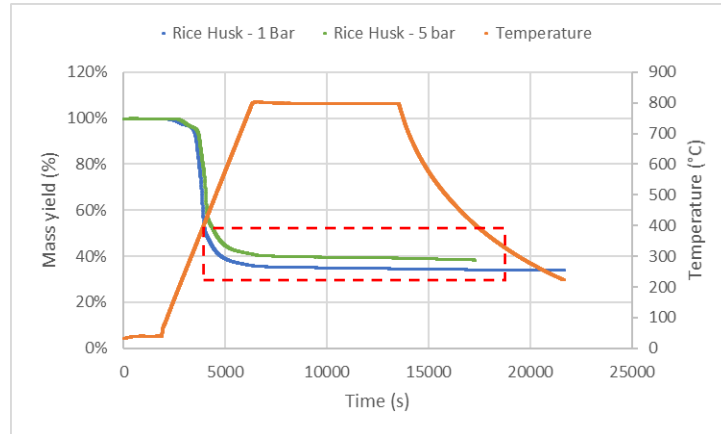


Steam generator system

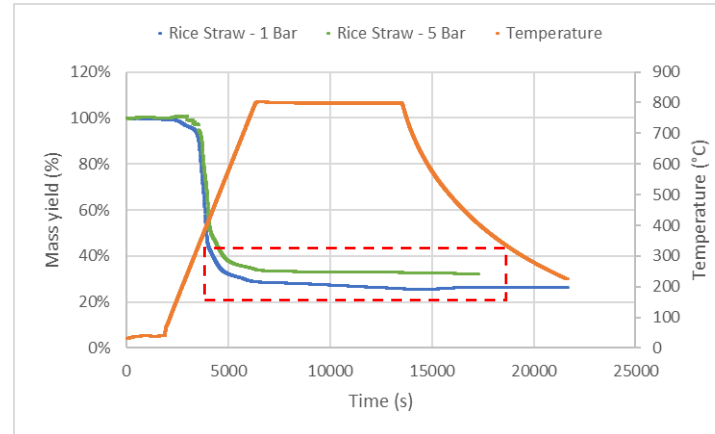


I - TG Pyrolysis under pressure (5 bar) : Main results

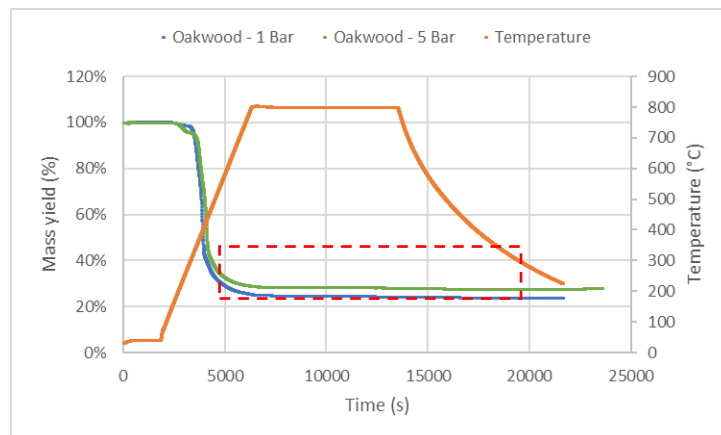
Rice Husk



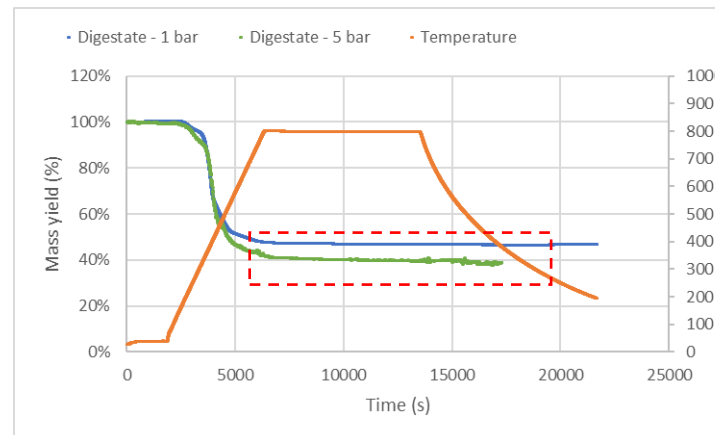
Rice Straw



Oak Wood



Digestate



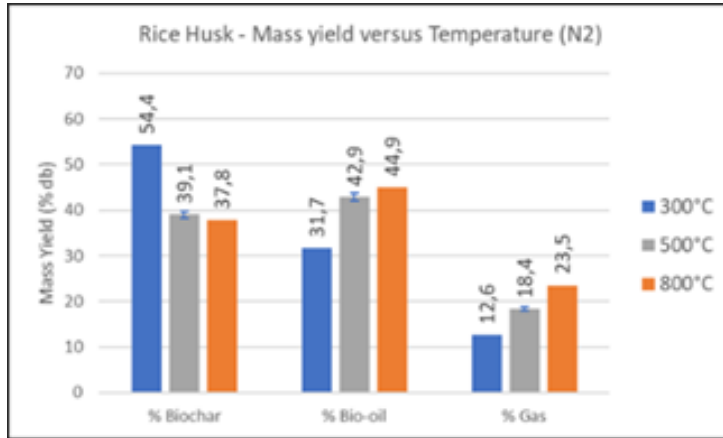
Main conclusion :

- Small effect of the pyrolysis pressure (5 bar) on the biochar yield for Rice and Wood raw material
- Very small effect of the pressure on digestate raw material
- The kinetic law of pyrolysis conversion (100-500°C) is unchanged, so secondary reactions may explain the small yield change

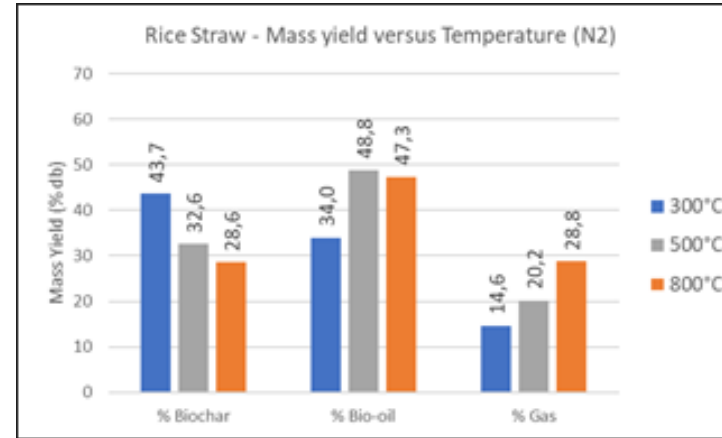
Laboratory scale (10g)

Mass balance

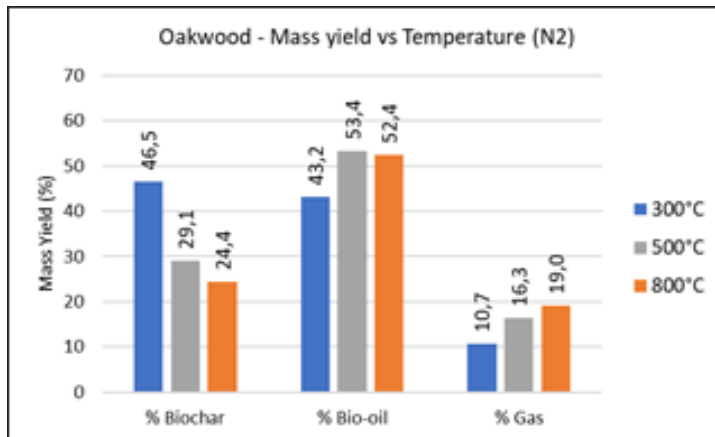
Rice Husk



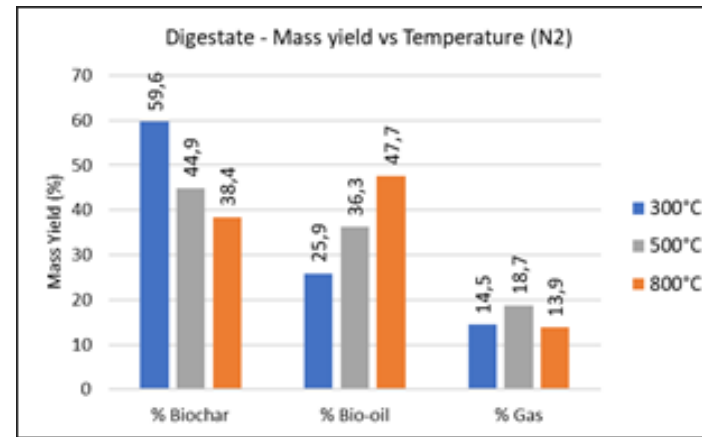
Rice Straw



Oak Wood



Digestate



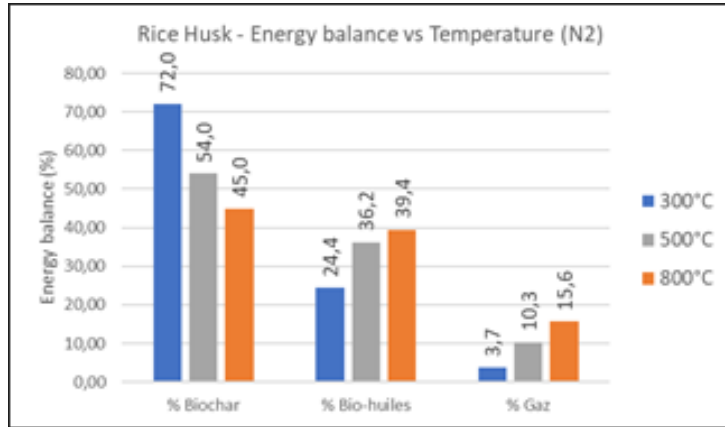
Main conclusion :

- Biochar yield decrease with the temperature up to 500°C (24-38%)
- Bio-oil yield increase with temperature (25-55%)
- Gas yield increase with the temperature (10-28%)

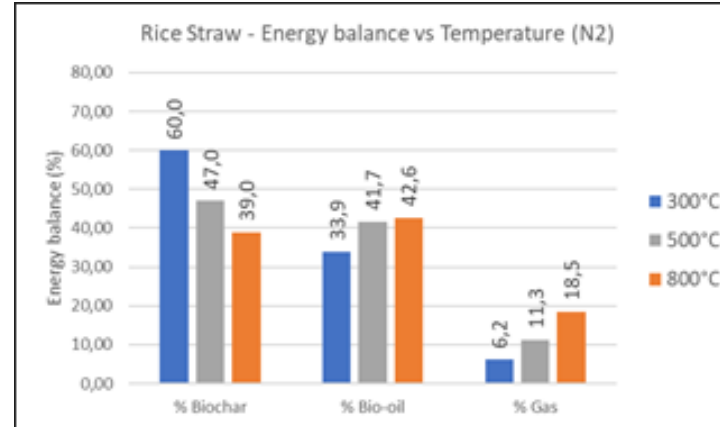
Laboratory scale (10g)

Energy balance

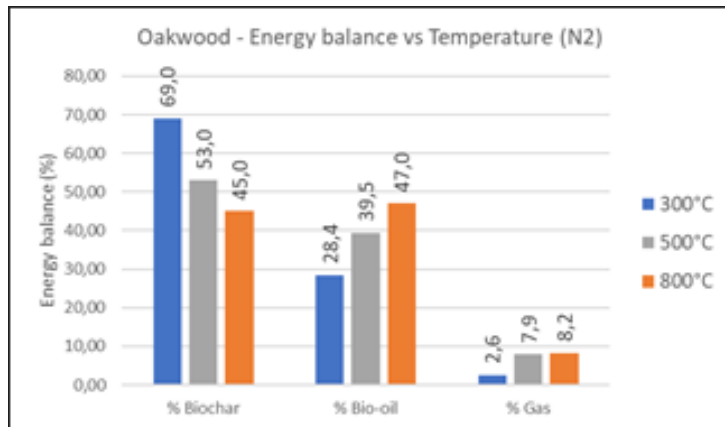
Rice Husk



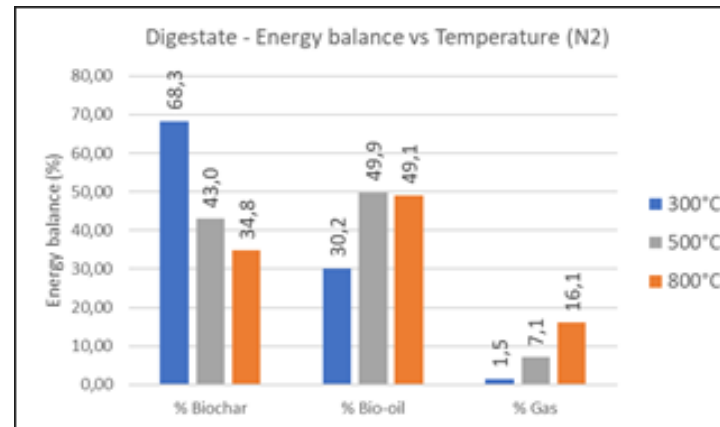
Rice Straw



Oak Wood



Digestate

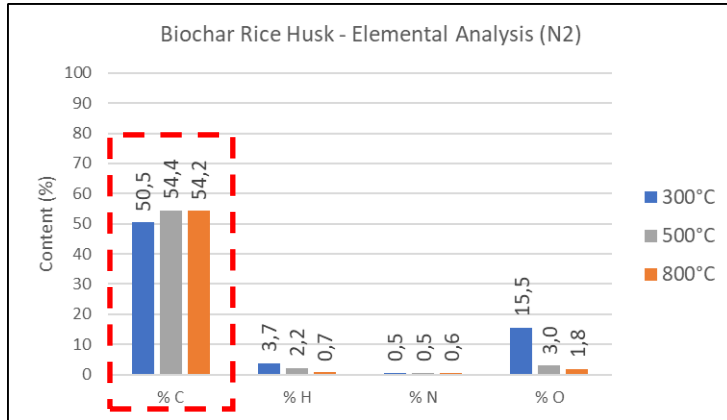


Main conclusion :

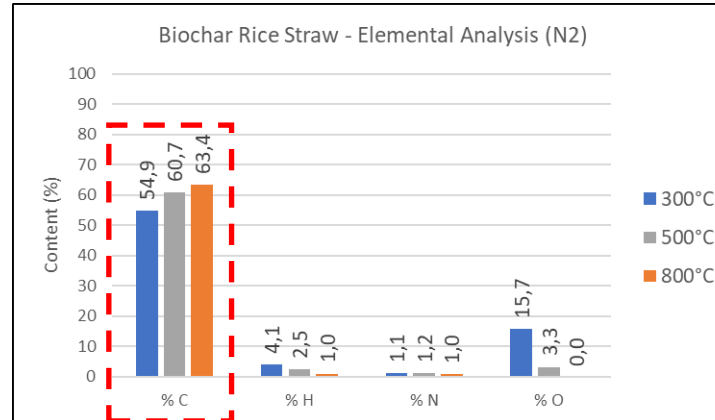
- Biochar contains a large part of the energy (34 - 72%) and decrease with the temperature
- Bio-oils is the co-product with large part of the energy (24-50%) and is stable at 500 °C
- Gas contains low energy (2-18%) and increase with the temperature

Biochar characterization - Elemental analysis

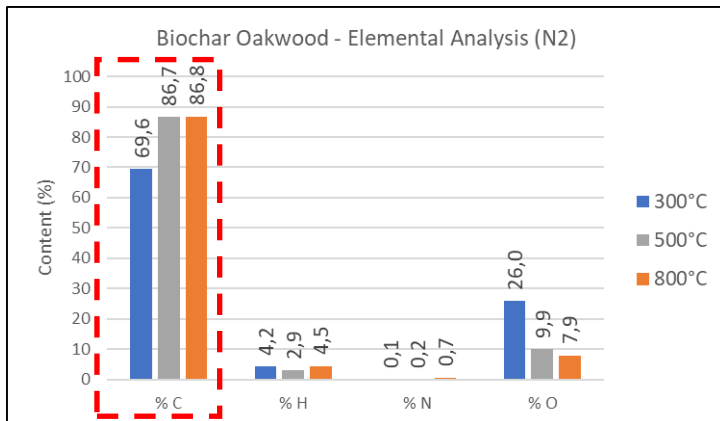
Rice Husk



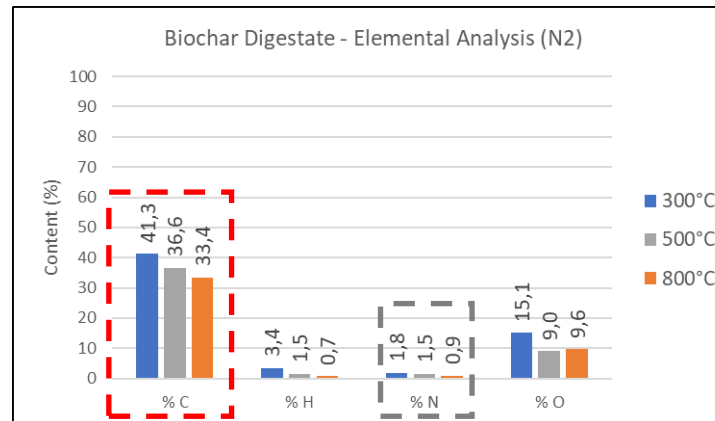
Rice Straw



Oak Wood



Digestate



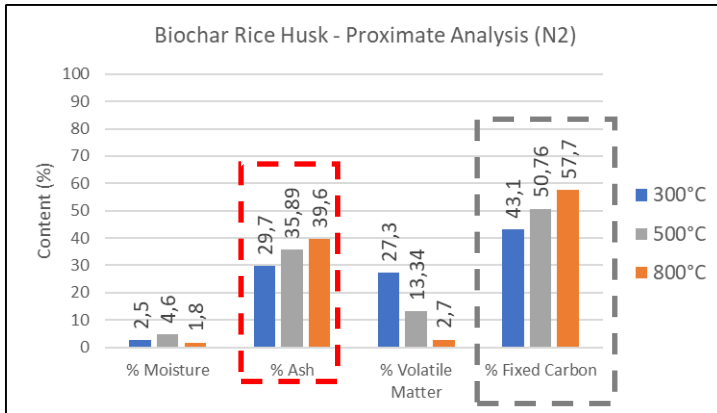
Main conclusion :

- %C increase in biochar with the temperature (except for digestate)
- Digestate contains low %C and high %N

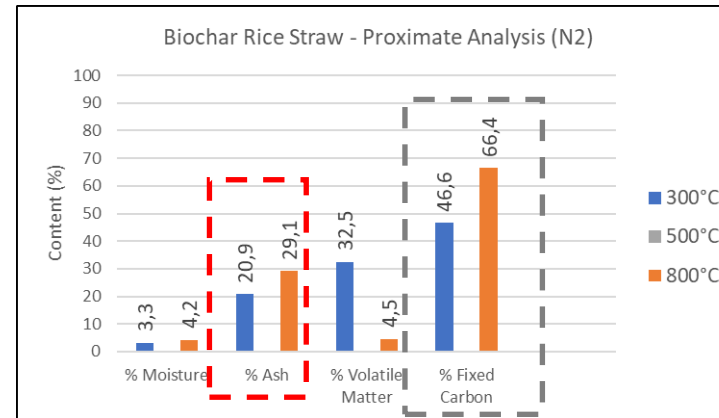
Biochar characterization - Proximate analysis



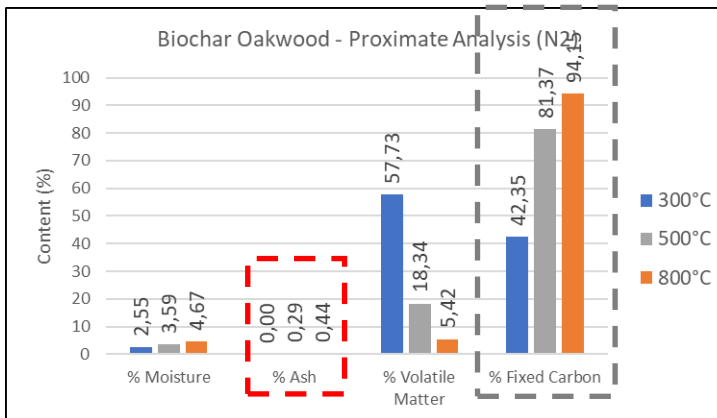
Rice Husk



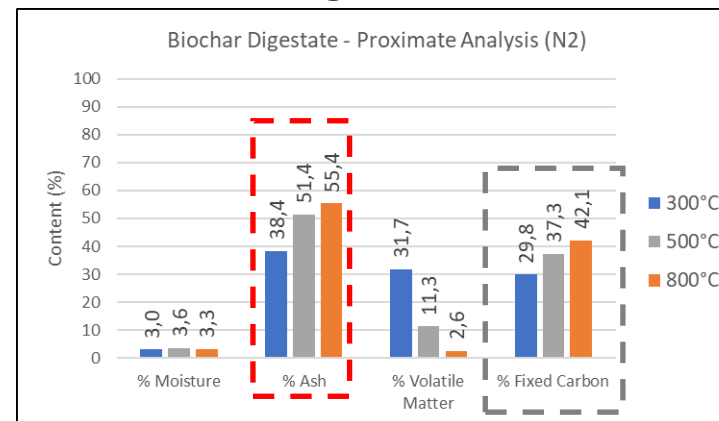
Rice Straw



Oak Wood



Digestate



Main conclusion :

- %Fixed Carbon is the parameter for C sequestration (Oakwood>Rice>Digestate)
- % Ashes very high for digestate biochar

Biochar characterization - Surface area for activated biochars

Biomass	Activation	m2/g			cm3/g		
		SSA BET	SSA micro	SSA extern	Vtotal	Vmicro	Vextern
Oakwood	CO2	645	630	15	0,32	0,29	0,03
	H2O	1000	971	29	0,50	0,45	0,05
RH	CO2	480	461	19	0,23	0,19	0,04
	H2O	450	384	66	0,27	0,16	0,11
RS	CO2	368	320	48	0,19	0,13	0,06
	H2O	432	333	99	0,32	0,14	0,18
Digestat	CO2	21	13	8	0,02	0,008	0,012
	H2O	24	11	13	0,02	0,007	0,013

Biomass	Activation	NLDFT (SAIEUS) CO2/N2		CO2 273 K DA parameter
		SSA micro (m2/g)	Vmicro (cm3/g)	
Oakwood	CO2	906	0,25	2,11
	H2O	1084	0,37	1,58
RH	CO2	633	0,19	1,35
	H2O	483	0,16	1,22
RS	CO2	445	0,14	1
	H2O	410	0,15	1
Digestat	CO2	n/a	n/a	n/a
	H2O	n/a	n/a	n/a

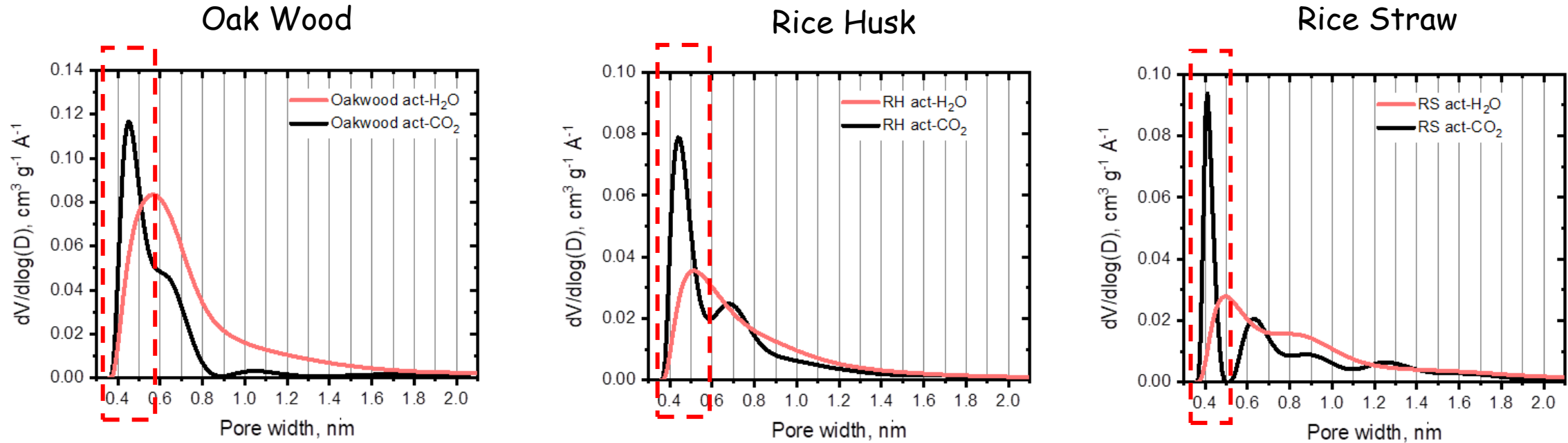
N₂ adsorption for micropores and mesopores determination

CO₂ adsorption for ultramicropores and micropores determination

Main conclusion :

- Activation treatment is function of the biomass (Oakwood > Rice > Digestate)
- The activated biochars surface area values are in the range 20-1 000 m2/g
- Activation with H2O significantly increases the surface area of oakwood biochar (1000 m2/g)
- While CO₂ activation slightly increases the surface area of rice husk biochar (480 m2/g)
- No surface area for Digestate biochar

Biochar characterization - Surface area for activated biochars

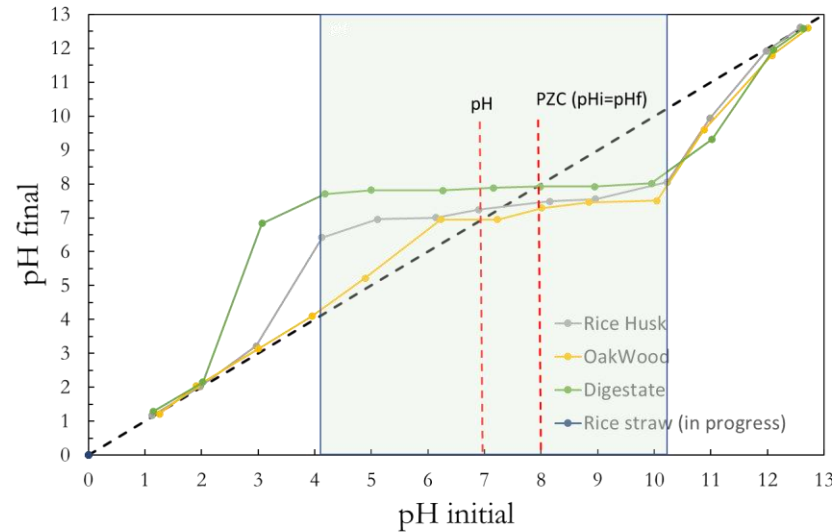


Main conclusion :

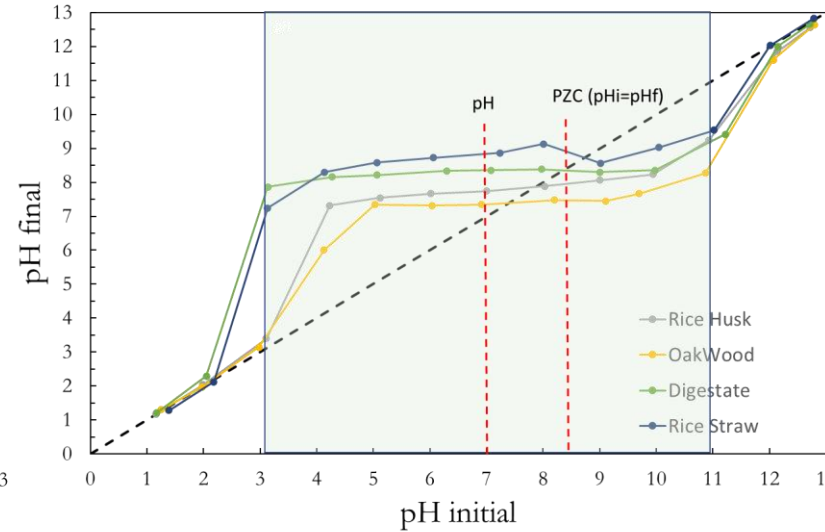
- Activation under CO₂ generates a very narrow microporous distribution (0 < size < 0,5 nm) as a function of the biomass
- Activation under H₂O makes this microporous distribution wider, indicating different activation reactions between Carbon and CO₂/H₂O
- Microorganism and biochar porosity ?

Biochar characterization - Ph and Point of Zero Charge (PZC)

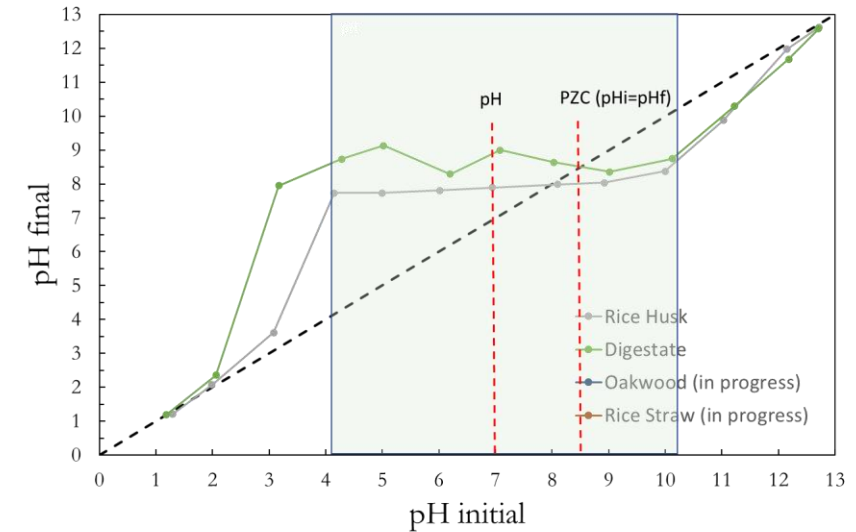
PZC 300 °C



PZC 500 °C



PZC 800 °C



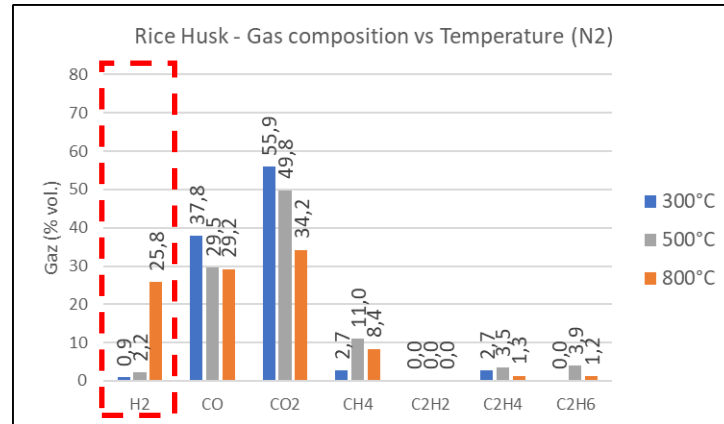
Main conclusion :

- Ph change with the nature of the biomass resource and the pyrolysis temperature ($pH > 7$)
- Range of constant final pH changes with temperature (and biomass resource)
- Digestate biochar has the highest pH value (with rice straw biochar)

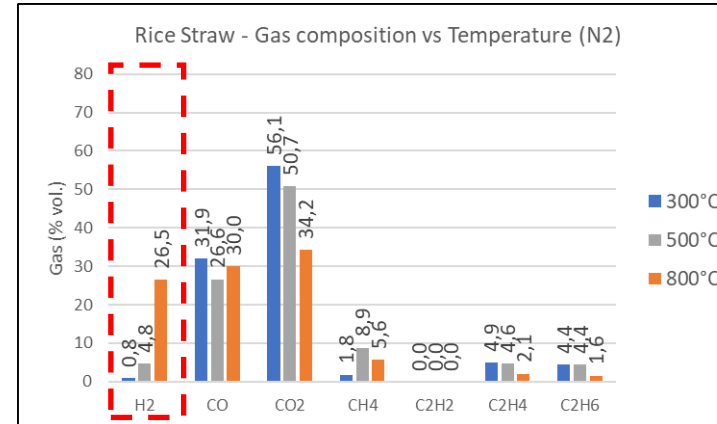
Light & heavy pyrolysis gases



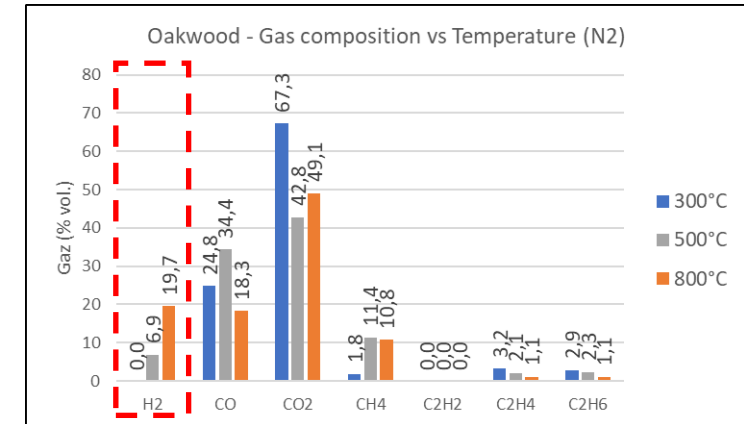
Rice Husk



Rice Straw



Oak Wood



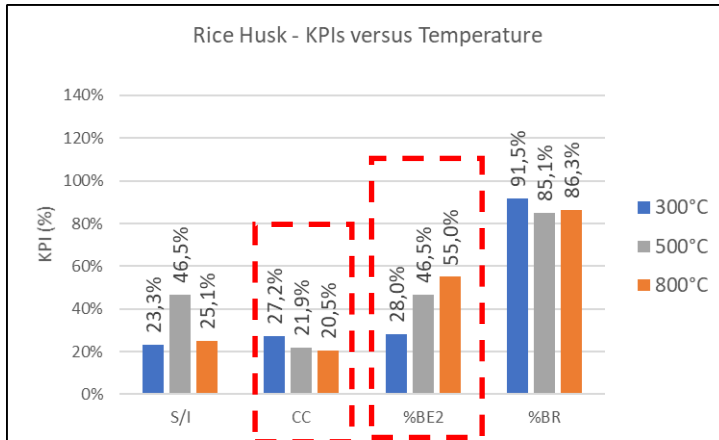
Main conclusion :

- Biochar yields decrease at higher pyrolysis temperature and gas yields increase
- Bio-oils yields is constant between 500°C and 800°C
- H2 yields increase at 800°C

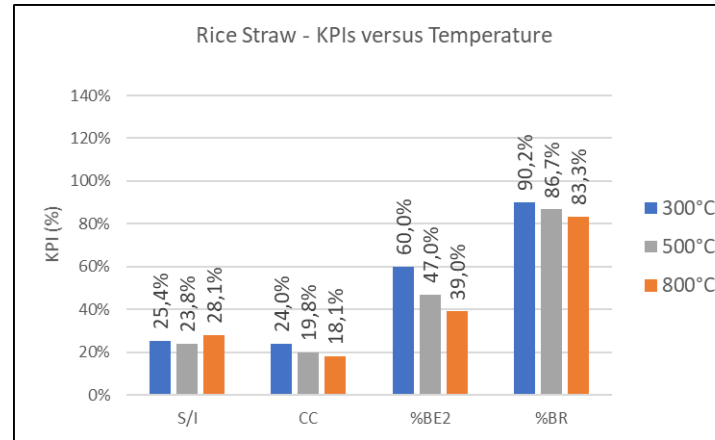
2. Main results

Key Performance Indicators

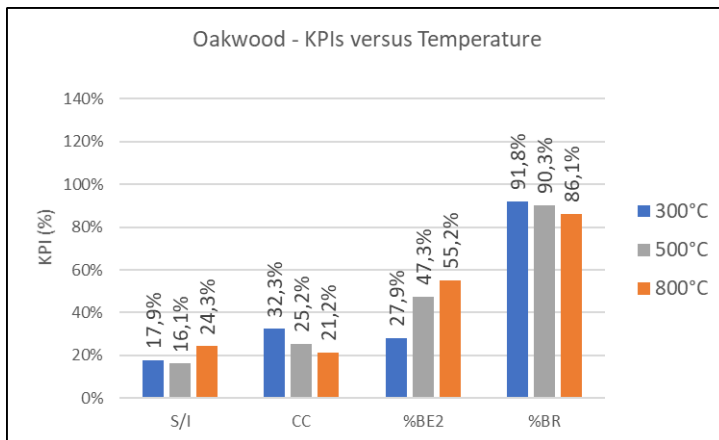
Rice Husk



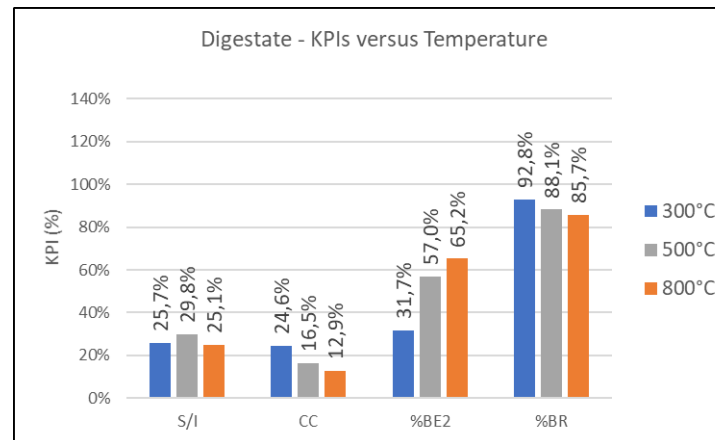
Rice Straw



Oak Wood



Digestate



	Indicator	Equation
(a)	CO ₂ emissions (S/I)	$\frac{\text{kg CO}_2 \text{ emissions}}{\text{kg biofuel produced}}$
(b)	C captured/ utilised (CC)	$\frac{\text{kg C captured}}{\text{kg initial feedstock}}$
(c1)	Bioenergy efficiency 1 (%BE ₁)	$\frac{\text{Energy content of produced biofuels}}{\text{Energy input in the whole system}}$
(c2)	Bioenergy efficiency 2 (%BE ₂)	$\frac{\text{Energy content of produced biofuels}}{\text{Energy content of initial feedstock}}$
(d)	Biomass resource utilization (%BR)	$\frac{\text{kg products}}{\text{kg initial feedstock}}$

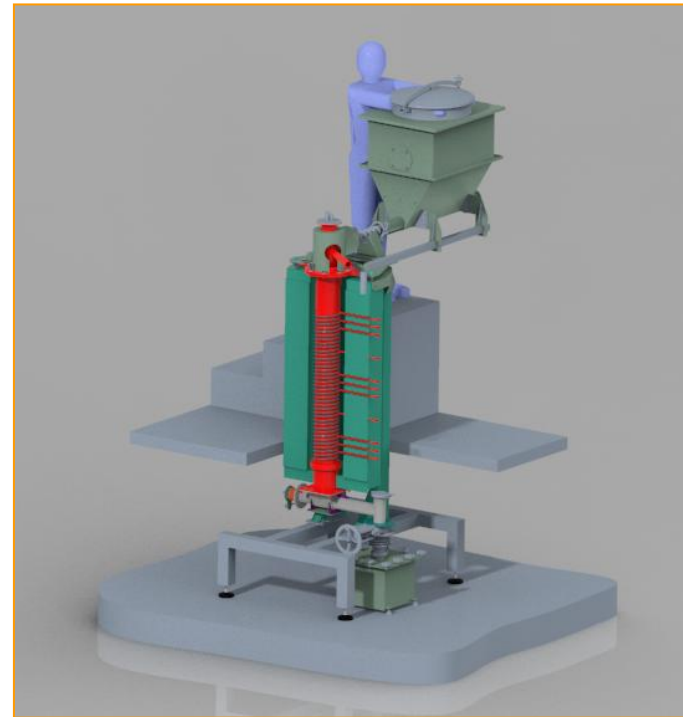
Our current conclusion:

- Rice husk and/or Oak Wood
- Digestate ?
- 500 °C or 800 °C ?

Pyrolysis device at pilot-scale

3. Pyrolysis prototype

- The pilot pyrolysis device has been developed to work in **batch or continuous conditions**
- 9 kWe furnace, 3 heating zones – T° max 1000°C – Heating Rate Max 10°C/min
- Pyrolysis (N₂) and activation (CO₂) – up to 10 NI/min

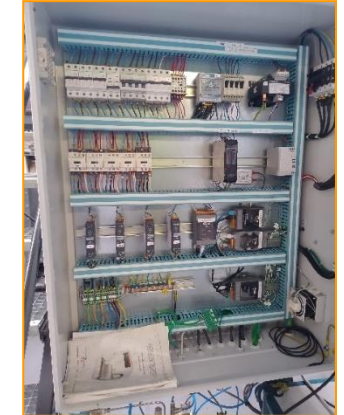


3. Pyrolysis prototype - Input

- Biomass capacity: 1- 4 kg batch mode
1-4 kg/h continuous mode



Biomass & biochar



Main electrical board and datalogger unit



The 3 PID for the heating control unit

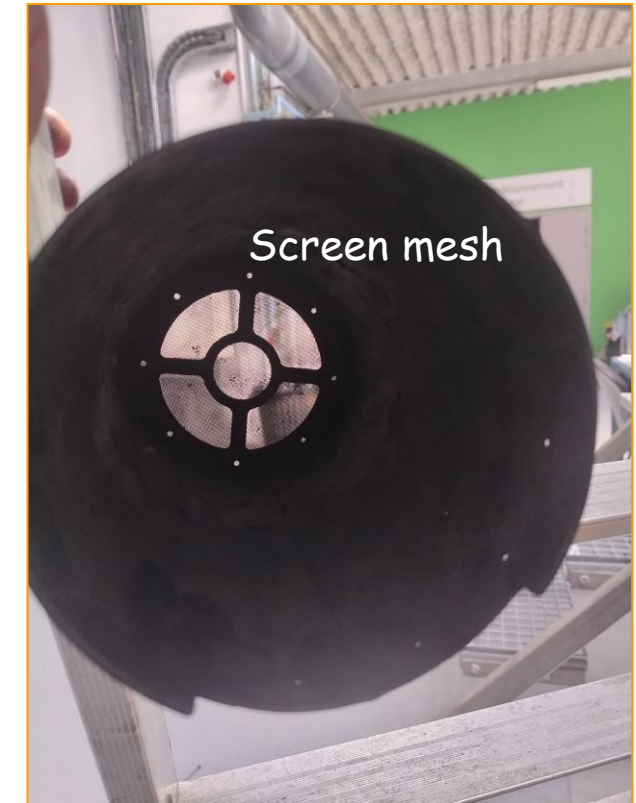
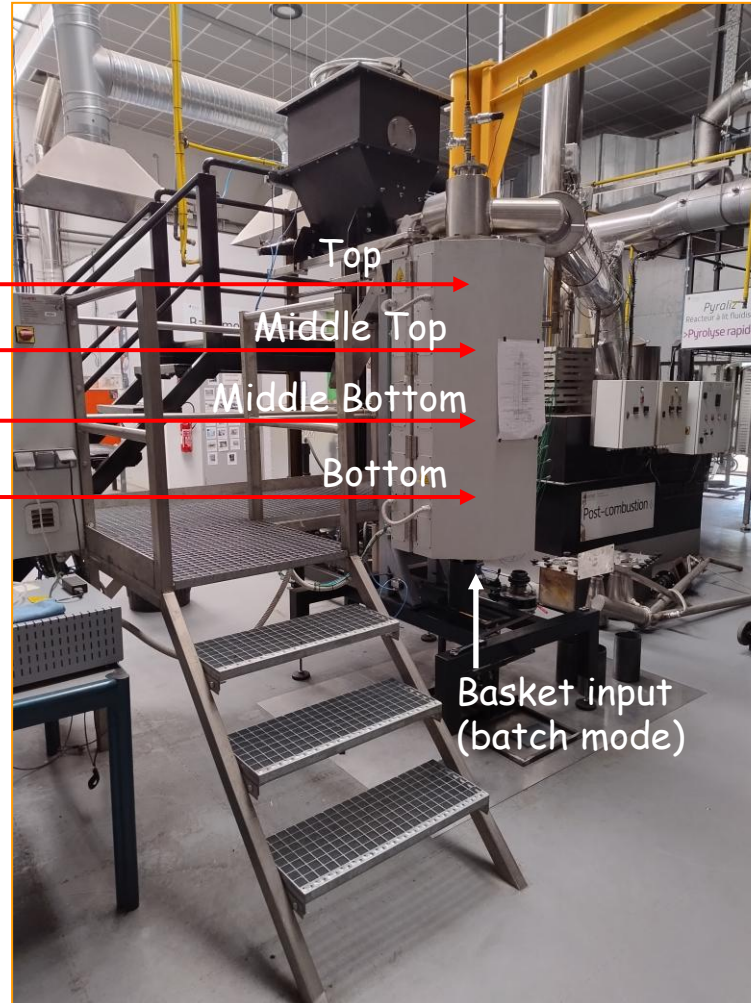


Gas flowmeters

3. Pyrolysis prototype - batch mode

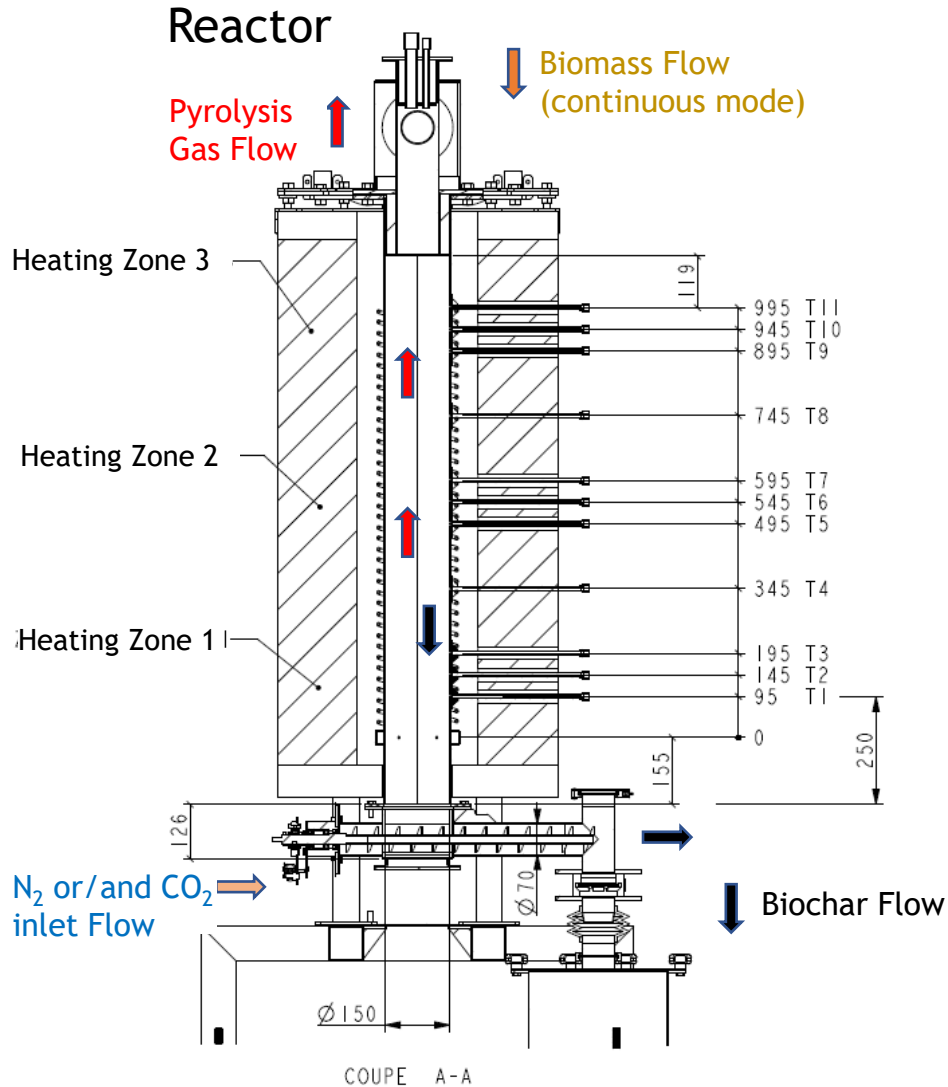


Biomass baskets

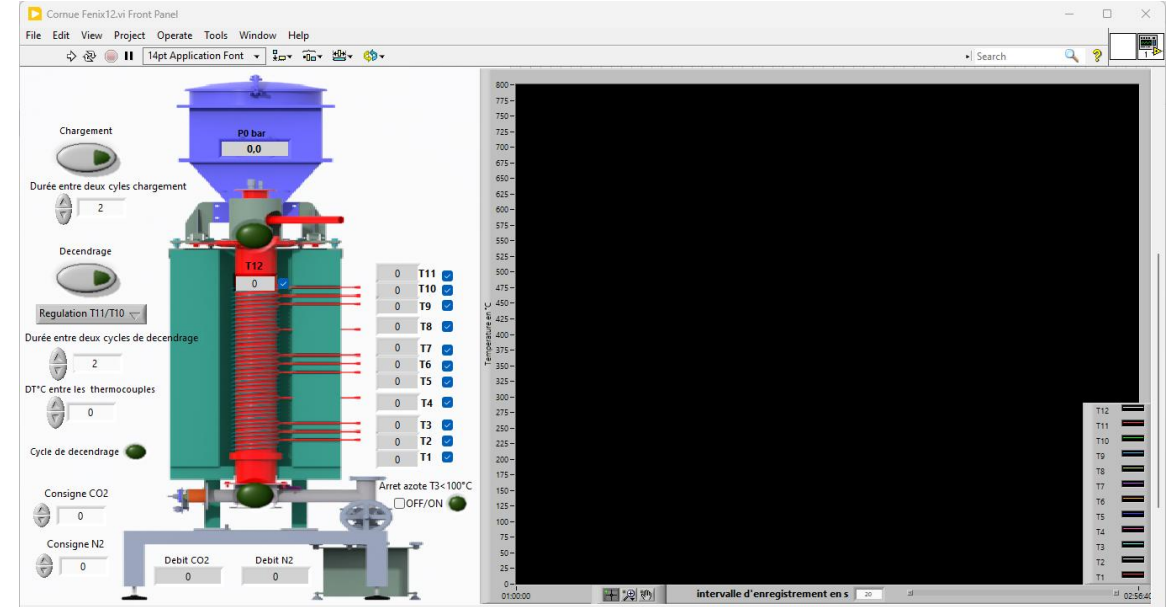


Inside basket

3. Pyrolysis prototype - continuous mode



Software and data acquisition



- Temperature set up and measurements
- N₂ and CO₂ flows set up
- Heating rate (batch mode)
- Biomass flow (in continuous mode)

Gas release and treatment before evacuation

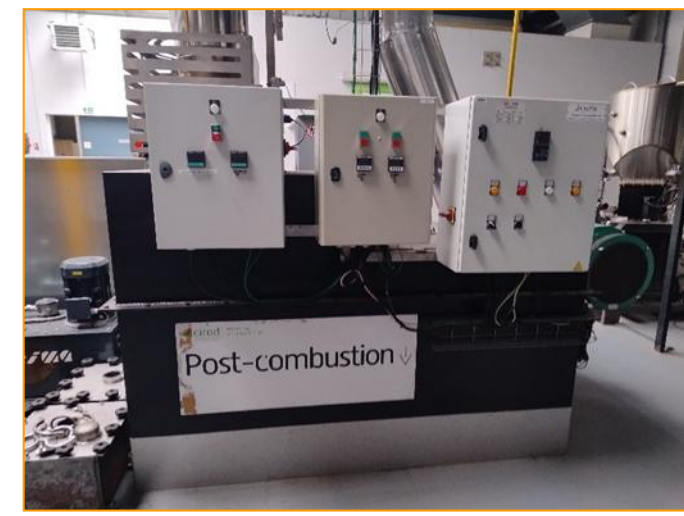
Combustion of pyrolysis hot gases on post-combustion chamber



Pyrolysis gas outlet



Heated pyrolysis gas
exhaust pipe



Pyrolysis gas
combustion chamber

Pyrolysis trials

3. Pyrolysis prototype

→ Pilot plant pyrolysis activity (Batch mode)

- Preliminary tests performed with rice husk (batch conditions)
 - Pilot plant Mode: batch
 - Biomass: Rice Husk
 - Temperature: 300 °C, 500 °C, 800 °C
 - Heating rate: 10 °C/min
 - Residence time: 2 hours
 - Atm: N₂



- Pyrolysis pilot plant tests:
 - Rice straw:
 - 500 °C, 800 °C under N₂
 - 800 °C under CO₂
 - Oak wood:
 - 800 °C under N₂, CO₂
 - Rice husk:
 - 800 °C under N₂, CO₂



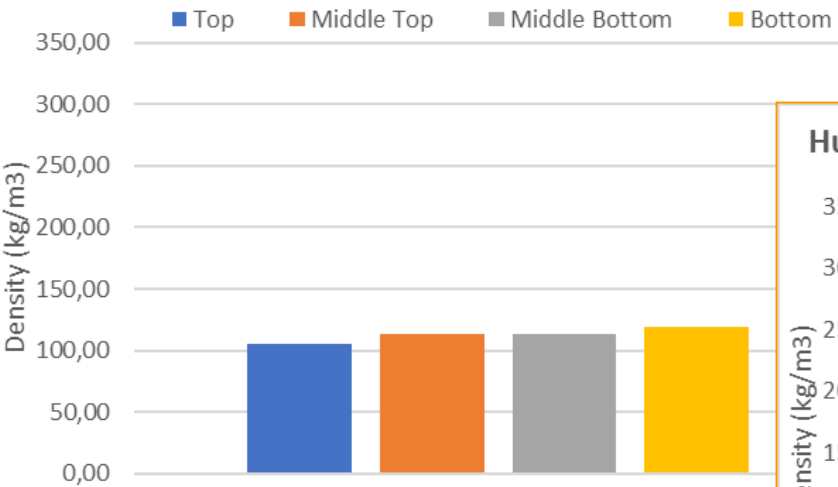
3. Pyrolysis prototype - results

➔ Pilot plant pyrolysis activity

- Biomass density (kg/m³)

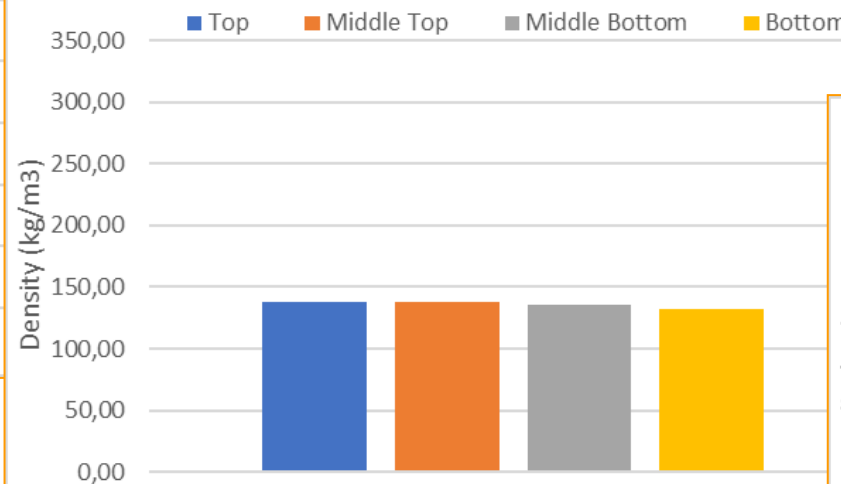
Rice Straw

Straw density - Mean value : 112 kg/m³



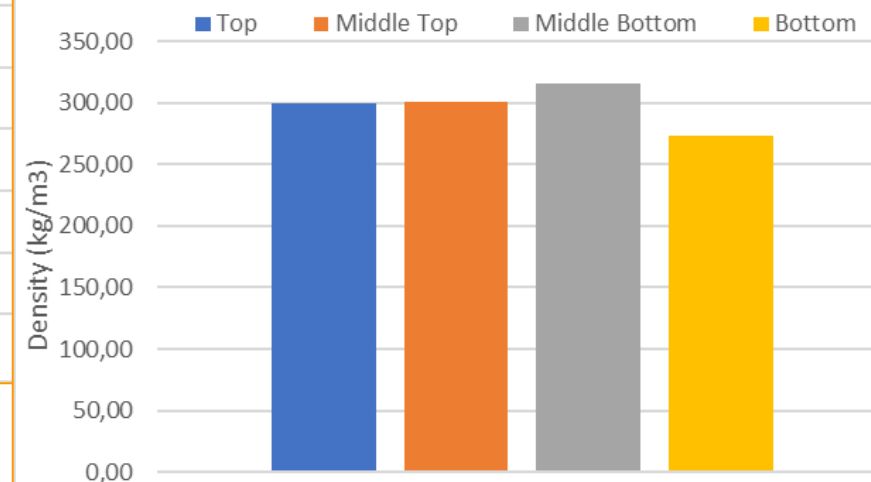
Rice Husk

Husk density - Mean value : 136 kg/m³



Oak wood

Oak wood density - Mean value : 297 kg/m³

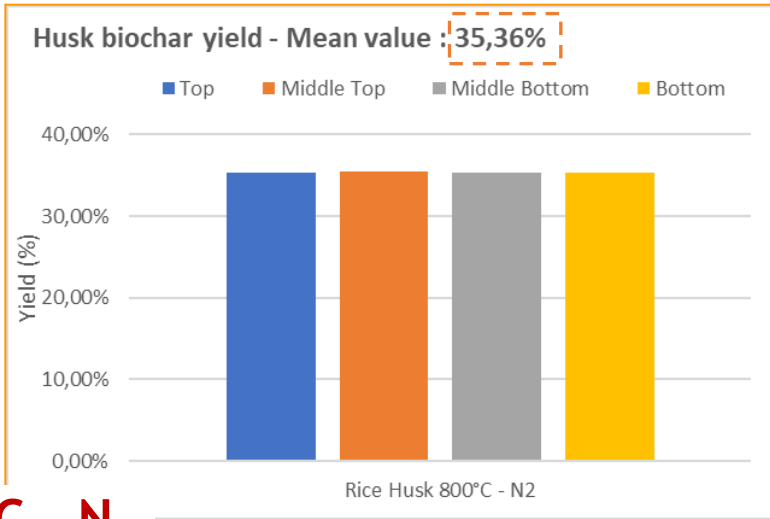
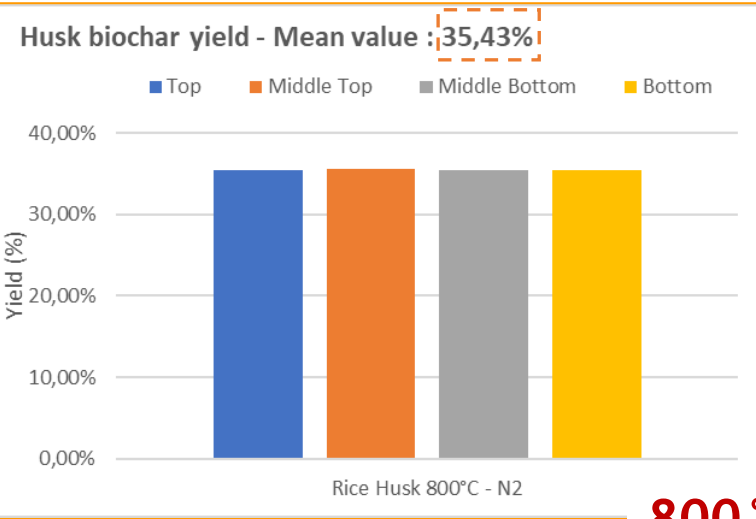


3. Pyrolysis prototype - results

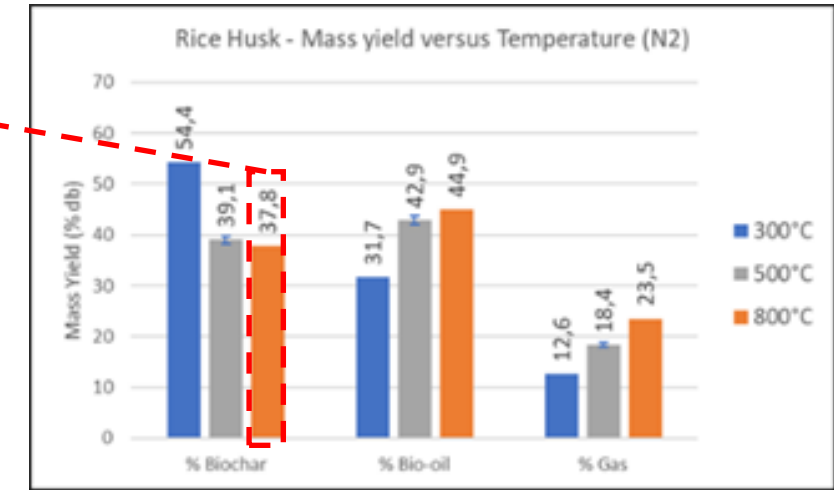
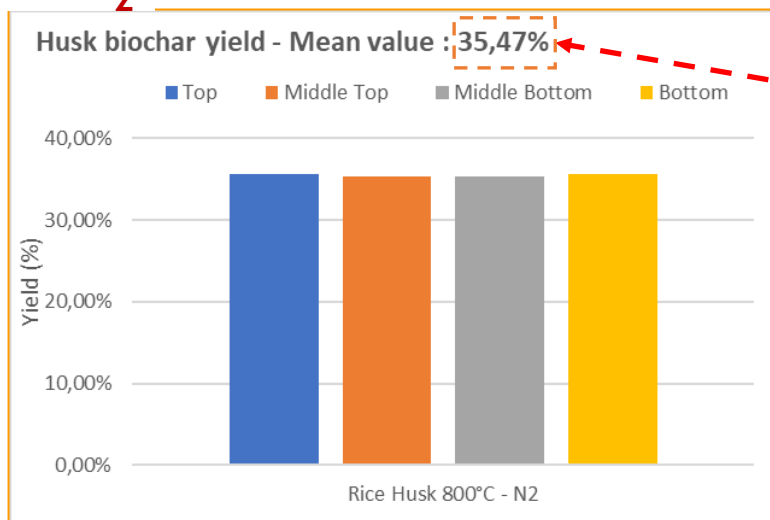
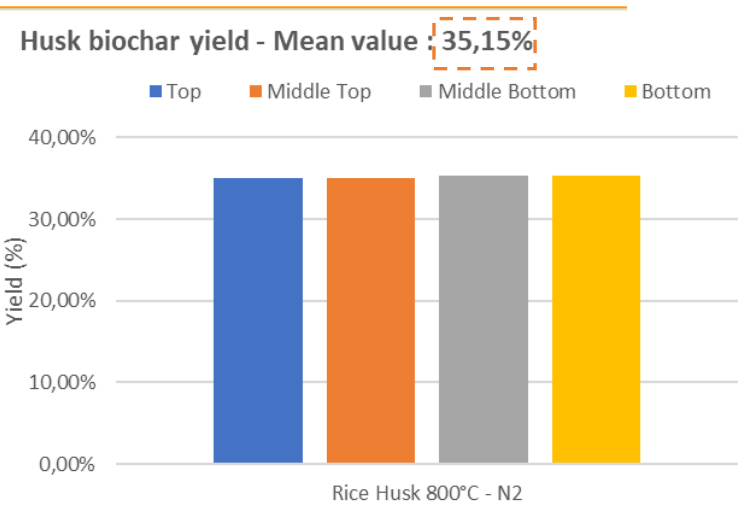
Repeatability tests - Rice husk biochar yield (%)



- Similar results in different baskets
- Good repeatability
- Results close to lab-scale results



800 °C - N₂



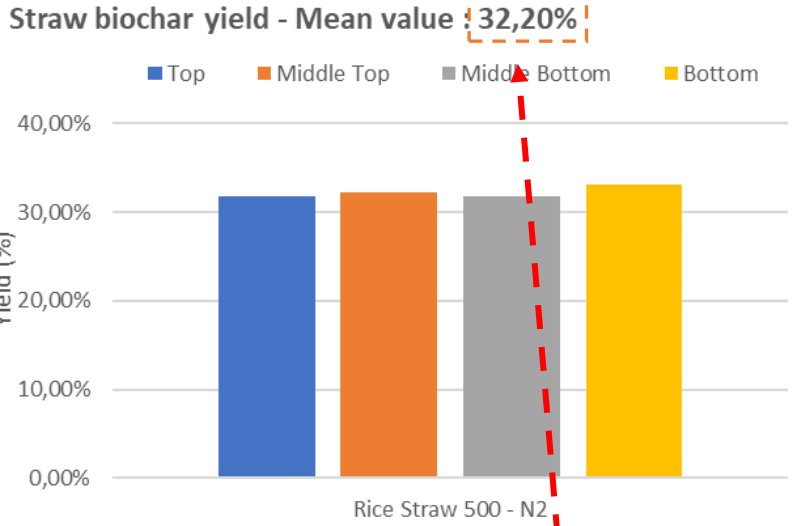
Mass balance at lab-scale (10 g)

3. Pyrolysis prototype - results

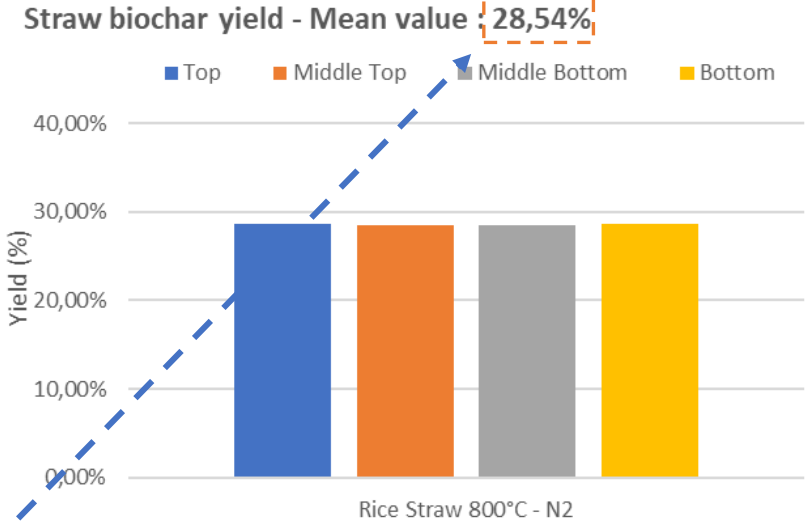
→ Rice straw biochar yield (%)

- Results close to lab-scale results
- Biochar yield decreases when temperature increases
- Biochar yield is lower under CO₂ than under N₂

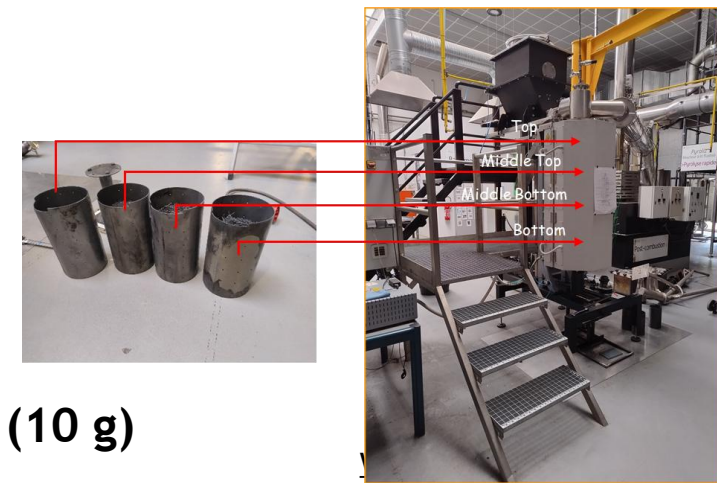
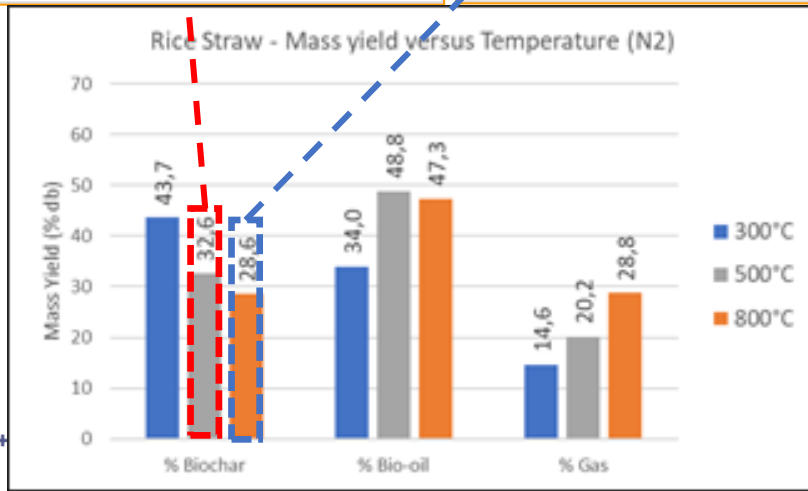
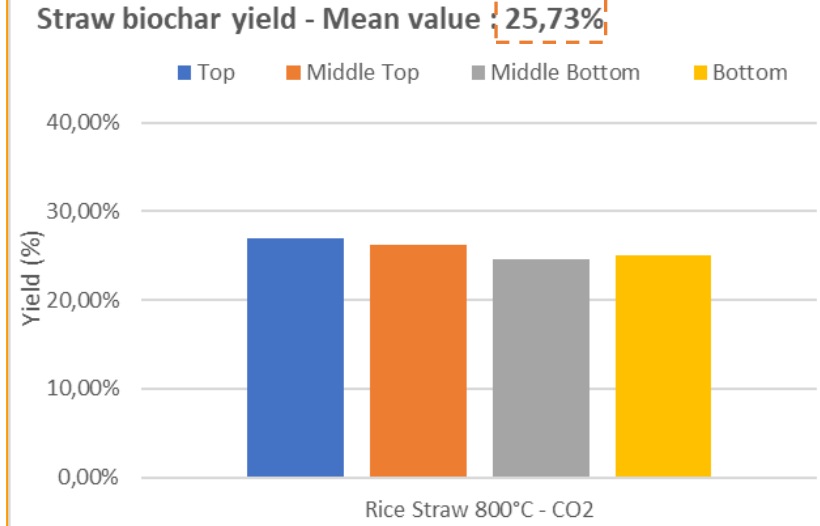
500°C - N₂



800°C - N₂



800°C - CO₂

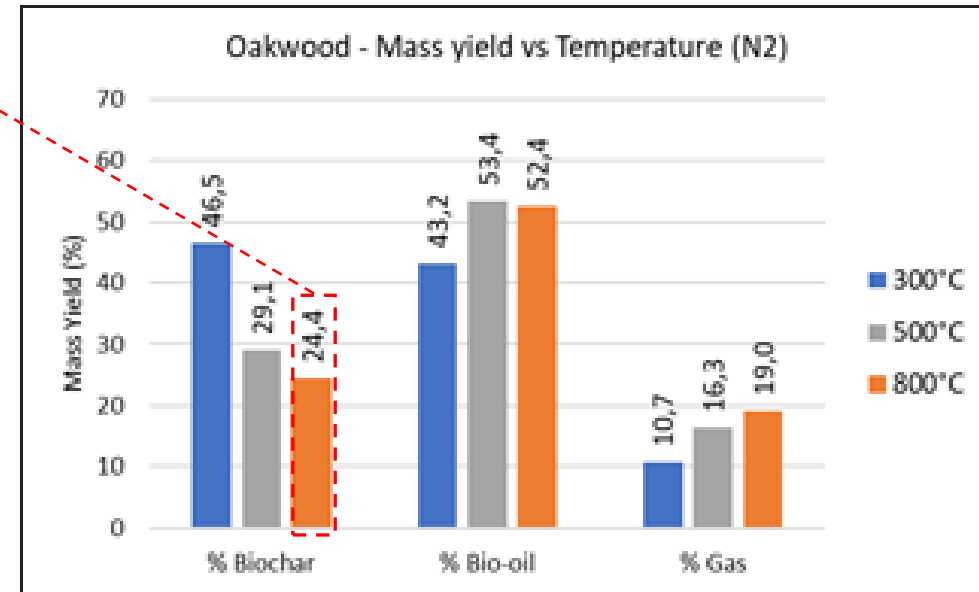
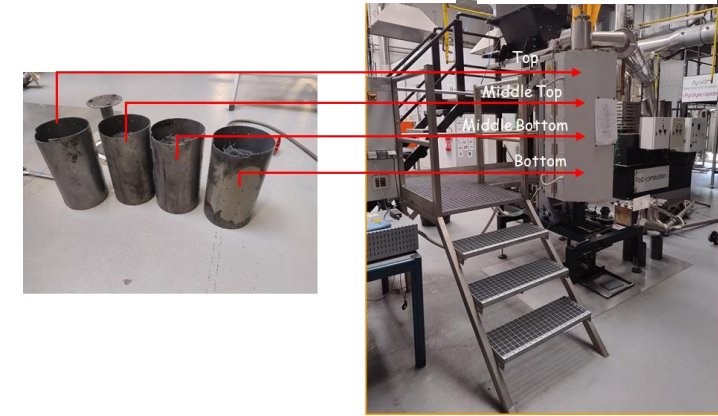
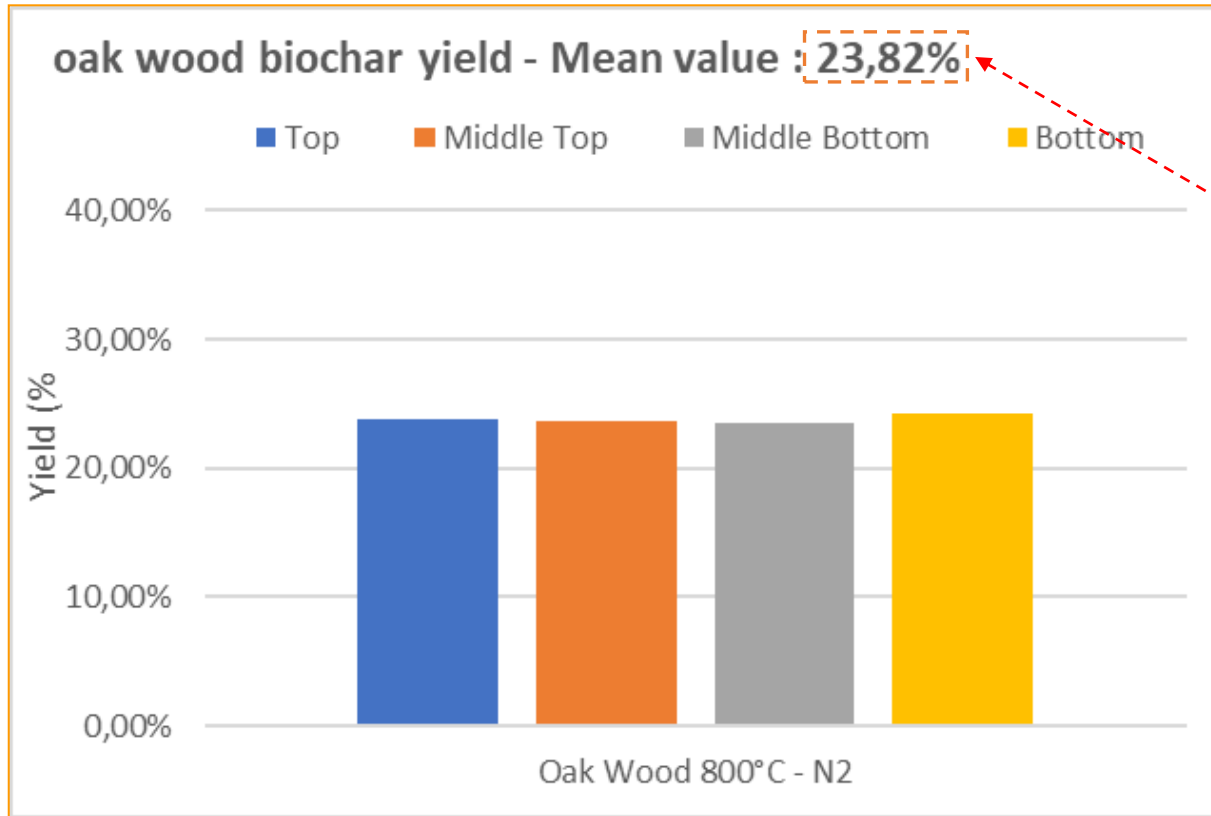


Mass balance at lab-scale (10 g)

3. Pyrolysis prototype - results

→ Oak wood biochar yield (%)

800 °C - N₂



Mass balance at lab-scale (10 g)

- Results close to lab-scale results
- Oak wood biochar yield is lower than rice straw biochar yield

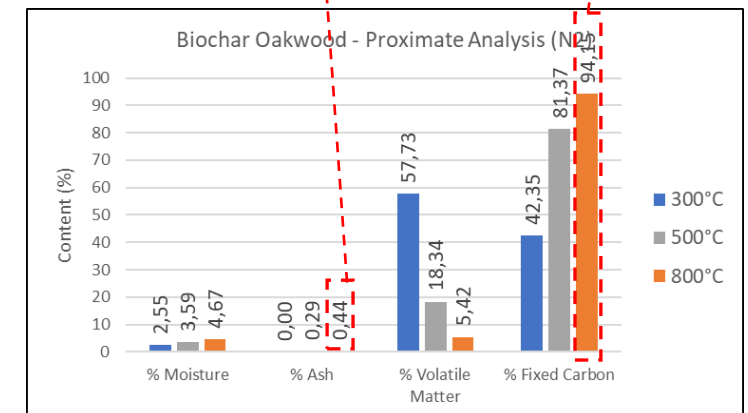
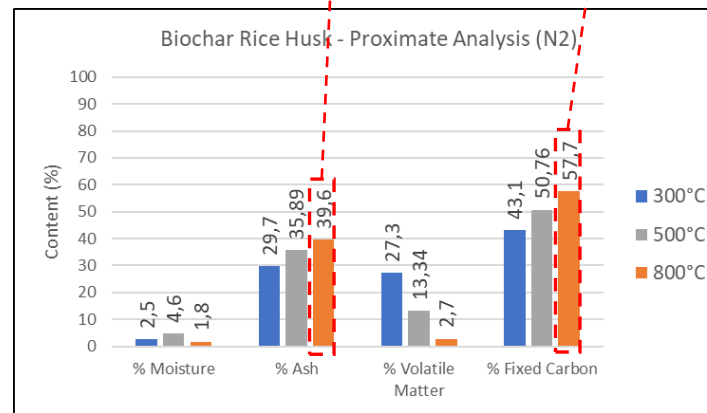
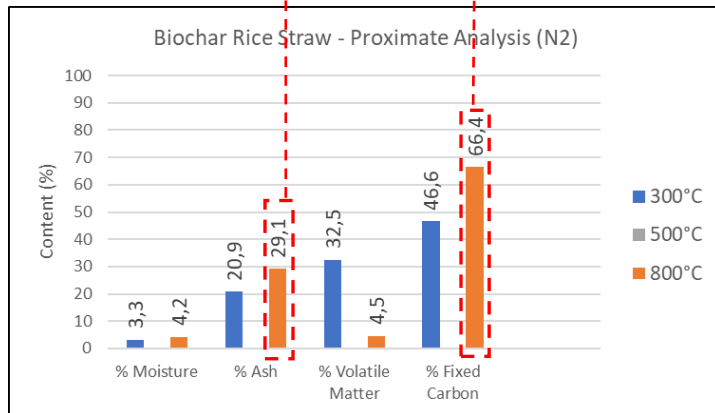
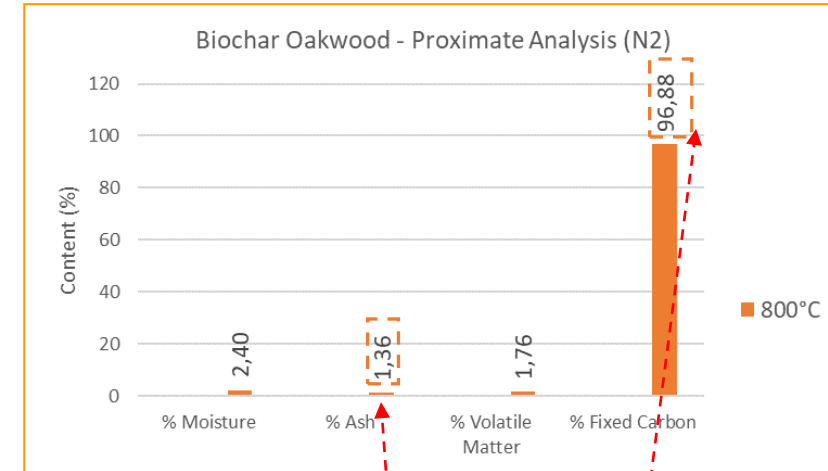
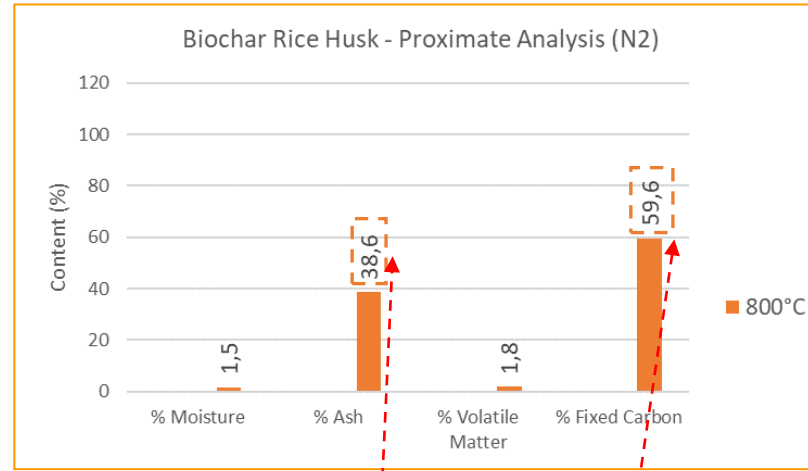
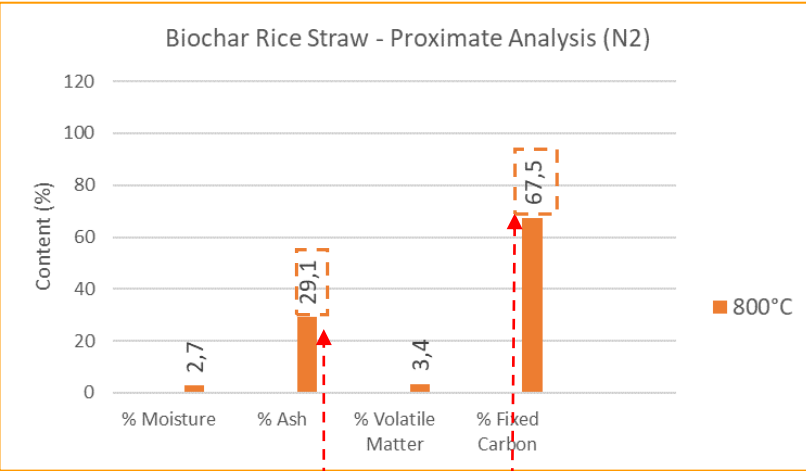
3. Pyrolysis prototype - results

Biochar - proximate analysis

Rice Straw

Rice Husk

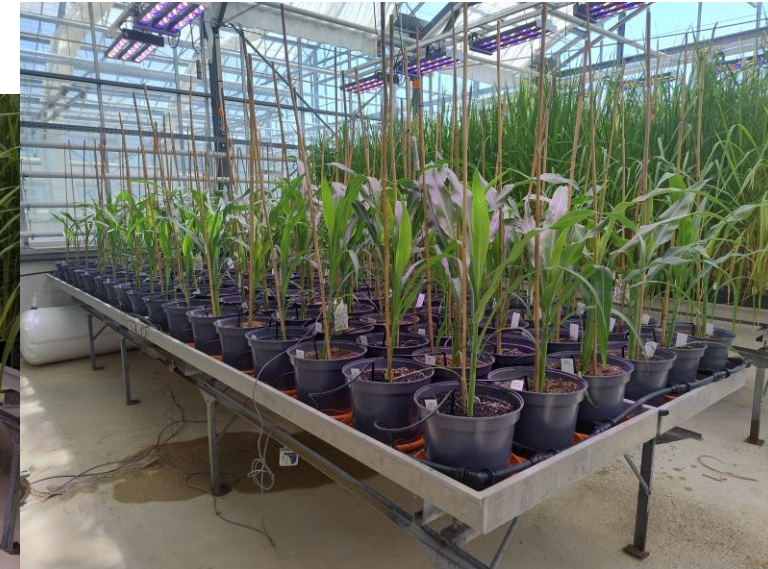
Oak wood



- Ash content higher for rice than for oak wood
- Ash content and fixed carbon content close to lab-scale results
- Fixed carbon content higher with wood than with rice co-products

Agronomic trials

4. Agronomic trials - on progress



0

4

10

Time (days)

4. Agronomic trials - in progress

➔ Agronomic trials (*in progress*)

- Crop: Sorghum (model plant for food and non food use and water adaptation)
- Two biochars selected :
 - Rice husk 800° C
 - Oak wood 800° C
- Biochars production
 - Rice husk -> 2,2 kg produced
 - Oak wood -> 0,9 kg produced
- Trials have started in May 2025 for a 4 months cycle
 - 2 biochars
 - 1 control trial with soil
 - 2 soils : acid and alcalin
 - 3 biochars doses : 2 t/ha, 5 t/ha and 10 t/ha
 - 5 repetitions trials
 - TOTAL : 80 pots



Thank you!

Do you have any questions ?

Alfredo NAPOLI - alfredo.napoli@cirad.fr

<https://www.cirad.fr/>

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