

# Gasification of different biomasses in a bubbling fluidized bed reactor: influence of process variables on gas yield and composition

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# Why gasify biomass and waste?

A thermochemical route to renewable gases, circular carbon and low-carbon fuels

## Biomass

Biogenic carbon, renewable feedstock, residues from forestry, agriculture and agroindustry.

## Waste

Non-recyclable fractions, RDF/SRF, plastics and mixed residues requiring robust pre-treatment.

## Syngas

Platform gas containing  $H_2$ ,  $CO$ ,  $CO_2$ ,  $CH_4$  and light hydrocarbons for energy or synthesis.

## Strategic value







- Reduces dependence on fossil feedstocks
- Can produce heat, power,  $H_2$ , SNG, methanol or FT liquids
- Enables carbon circularity when waste carbon is converted into products
- Requires integration with syngas cleaning and product specifications



# Historical perspective of gasification

From early gas lights to today's advanced technologies for clean fuels, hydrogen and negative emissions

**Gasification is a mature technology with more than 200 years of evolution, continuously adapted to society's energy needs.**

<b>1800s</b> <b>Town gas /</b> <b>Early gasification</b>	<b>1900–1940s</b> <b>Industrial gas</b> <b>and power</b>	<b>1940s–1950s</b> <b>Synthetic fuels</b> <b>(Fischer–Tropsch)</b>	<b>1970s–1990s</b> <b>Energy crisis and</b> <b>IGCC development</b>	<b>2000s–2010s</b> <b>Biomass and waste</b> <b>gasification</b>	<b>2020s and beyond</b> <b>Advanced concepts</b> <b>and climate goals</b>
					
<p><b>Gas for lighting</b></p> <ul style="list-style-type: none"> <li>• Coal gasification in fixed beds.</li> <li>• “Town gas” for street lighting and cooking.</li> <li>• First industrial use of producer gas.</li> </ul>	<p><b>Growth of gas applications</b></p> <ul style="list-style-type: none"> <li>• Producer gas for industry and heating.</li> <li>• Water–gas shift development.</li> <li>• Municipal and industrial gas plants.</li> </ul>	<p><b>War and synthetic liquid fuels</b></p> <ul style="list-style-type: none"> <li>• Coal and biomass gasification for synthetic fuels.</li> <li>• Fischer–Tropsch process commercialization.</li> <li>• Strategic importance of syngas.</li> </ul>	<p><b>From feasibility to demonstration</b></p> <ul style="list-style-type: none"> <li>• Oil crises stimulate interest in coal gasification.</li> <li>• IGCC (Integrated Gasification Combined Cycle) emerges.</li> <li>• Large pilots and demo plants worldwide.</li> </ul>	<p><b>Toward renewable and circular carbon</b></p> <ul style="list-style-type: none"> <li>• Biomass and waste as renewable feedstocks.</li> <li>• CHP, SNG, biofuels and chemicals.</li> <li>• Advances in tar control, materials and systems.</li> </ul>	<p><b>Decarbonization and negative emissions</b></p> <ul style="list-style-type: none"> <li>• Advanced gasification: indirect, SEG, CLG.</li> <li>• Hydrogen production, BECCS and e-fuels.</li> <li>• Key role in circular carbon and net-zero pathways.</li> </ul>

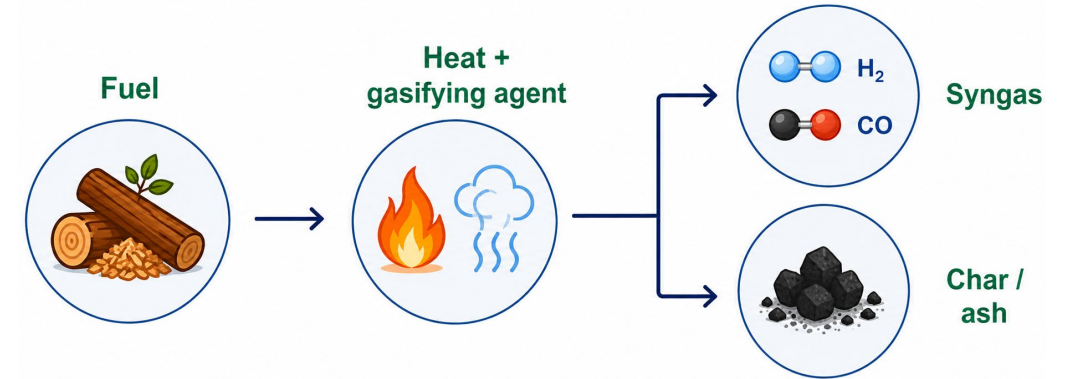
**Key message:** Gasification has evolved from local gas production to a strategic technology for clean fuels, hydrogen economy and carbon management. Innovation continues to expand its role in a sustainable energy system.

# Gasification fundamentals

Partial oxidation and thermal conversion of a carbonaceous solid into a combustible gas

## Core definition

Gasification converts a solid or liquid fuel into syngas using a limited amount of oxidant and/or steam. It operates above pyrolysis temperatures, but below complete combustion conditions.



## Main process steps

- Drying
- Devolatilisation / pyrolysis
- Partial oxidation
- Tar cracking and reforming
- Char gasification

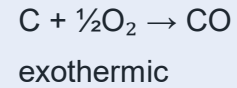
## Typical gas products

- H<sub>2</sub>
- CO
- CO<sub>2</sub>
- CH<sub>4</sub>
- C<sub>2</sub>+ hydrocarbons
- Tar vapours and particulates

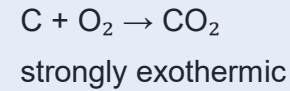
# Main reactions in gasification

The observed syngas composition is the result of competing heterogeneous and homogeneous reactions

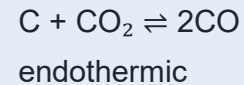
## Partial oxidation



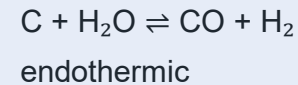
## Combustion



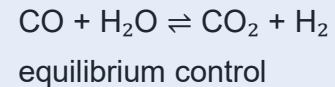
## Boudouard



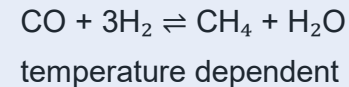
## Steam gasification



## Water–gas shift



## Methanation / reforming



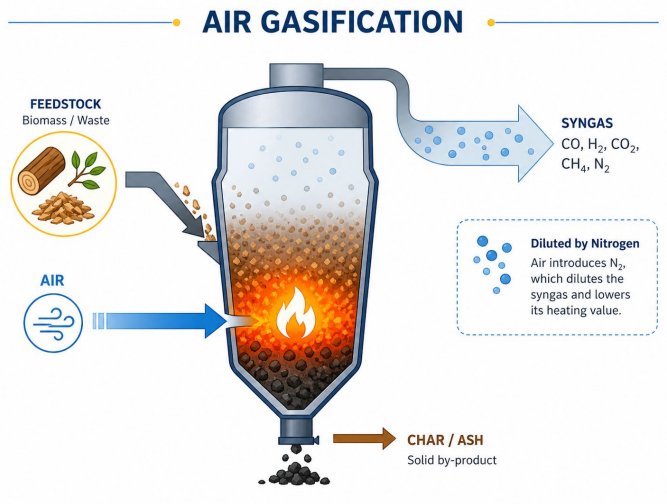
**Important: char gasification reactions are often slower than devolatilisation and gas-phase reactions; they can limit global solid conversion.**

# Gasification routes: oxidant, heat supply and syngas quality

The gasifying agent and the heat-supply strategy determine whether the process produces diluted fuel gas, synthesis gas or H<sub>2</sub>-rich gas

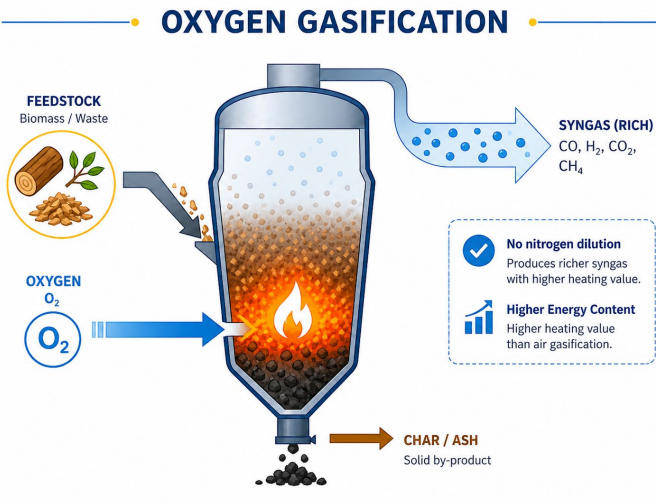
## Air gasification

- Simple and cheap
- N<sub>2</sub> dilution ≈ low LHV gas
- Suitable for direct heat/CHP
- Partly autothermal



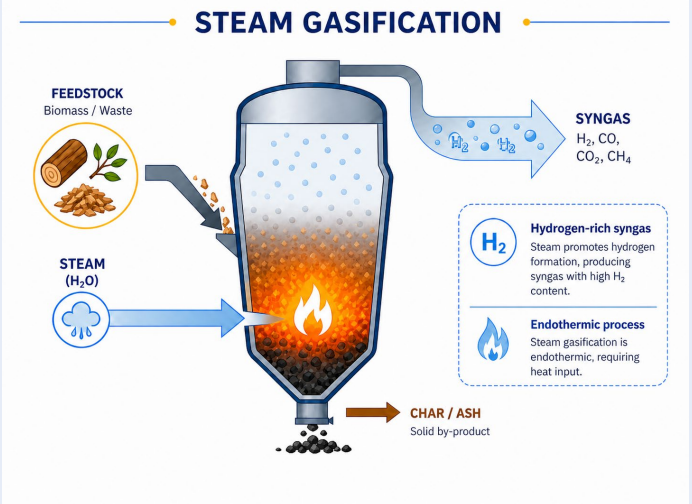
## O<sub>2</sub> / O<sub>2</sub>-steam gasification

- No N<sub>2</sub> dilution
- Higher CO + H<sub>2</sub> concentration
- Moderate LHV syngas
- Requires ASU or O<sub>2</sub> supply



## Steam / allothermal gasification

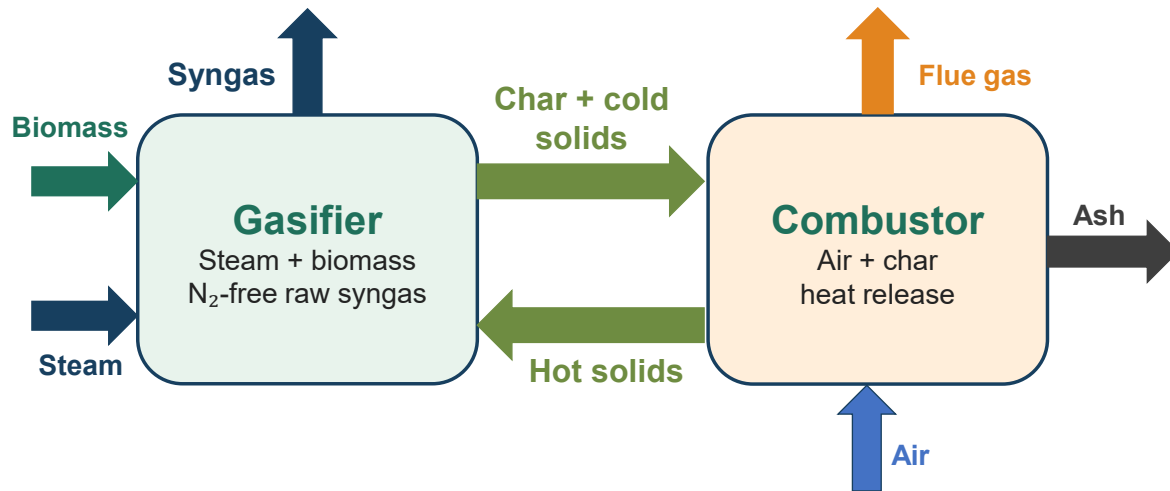
- Favours H<sub>2</sub> formation
- Supports reforming and shift
- Highly endothermic
- Requires heat and steam generation



This leads to advanced configurations where heat supply, oxygen transfer and CO<sub>2</sub> management are separated or controlled: indirect gasification, SEG and chemical looping gasification.

# Indirect gasification with a circulating heat carrier

Allothermal steam gasification separates syngas production from char combustion and heat generation



	% vol. dry
H <sub>2</sub>	40
CO	25
CO <sub>2</sub>	20
CH <sub>4</sub>	10
N <sub>2</sub>	5



Indirect gasification plant in Güssing (Austria)

## Why it is useful

Steam gasification without direct air dilution.

## Main advantage

Higher-quality syngas with no N<sub>2</sub> dilution.

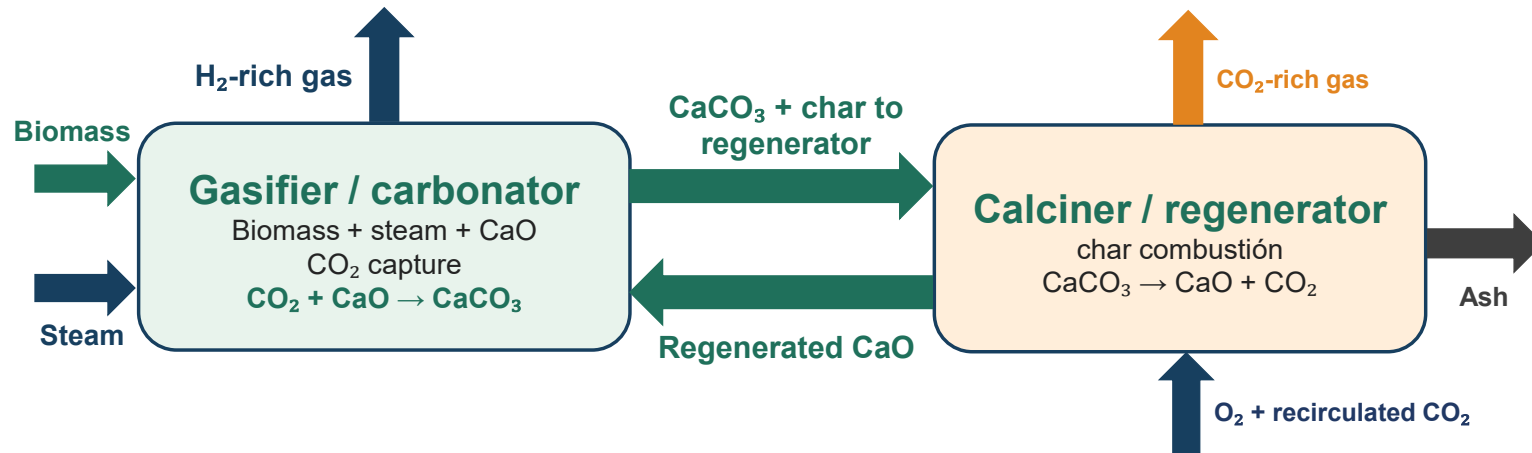
## Main challenge

Solids circulation and heat-transfer control.

**Key point:** the gasifier produces syngas, while char is combusted in a separate reactor to reheat the circulating heat carrier, typically olivine or another bed material.

# Sorption Enhanced Gasification using CaO/CaCO<sub>3</sub>

In-situ CO<sub>2</sub> capture shifts gas-phase equilibria and the sorbent is regenerated in a secondary reactor



	% vol. dry
H <sub>2</sub>	70
CO	7
CO <sub>2</sub>	7
CH <sub>4</sub>	12
N <sub>2</sub>	4

## Effect in the gasifier

CO<sub>2</sub> removal favours H<sub>2</sub> production.

## Regeneration step

CaCO<sub>3</sub> is calcined back to CaO.

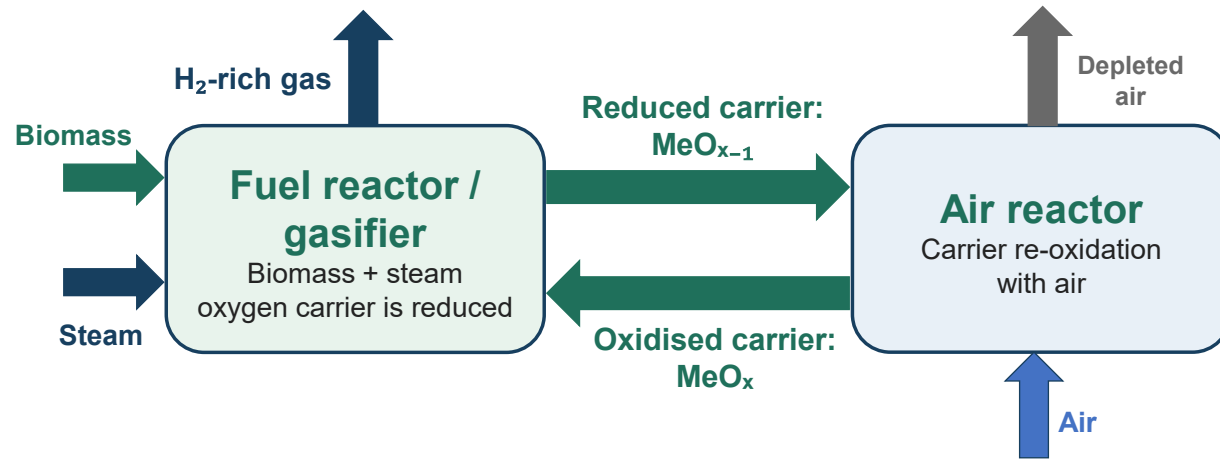
## Heat supply

Char combustion can provide regeneration heat.

**Key point:** the CaO/CaCO<sub>3</sub> loop combines gasification, CO<sub>2</sub> capture and sorbent regeneration, producing a hydrogen-enriched gas in the gasifier and a concentrated CO<sub>2</sub> stream from the calciner.

# Chemical Looping Gasification with an oxygen carrier

Lattice oxygen is transferred by a solid oxygen carrier instead of feeding air directly to the gasifier



	% vol. dry
H <sub>2</sub>	30
CO	30
CO <sub>2</sub>	22
CH <sub>4</sub>	8
N <sub>2</sub>	2



## Concept

Oxygen is supplied by a solid metal oxide.

## Main advantage

Air and syngas are never directly mixed.

## Control parameter

Oxygen carrier circulation and reactivity.

**Key point:** chemical looping controls the oxygen potential through a circulating solid carrier, enabling partial oxidation/gasification while avoiding nitrogen dilution of the syngas.

# Typical syngas composition depending on gasification technology

Advanced gasification concepts reduce nitrogen dilution and can enhance hydrogen production

Component (% vol. dry)	Air	O <sub>2</sub>	O <sub>2</sub> + steam	Indirect	SEG	CLG
H <sub>2</sub>	15	30	45	40	70	30
CO	20	40	25	25	7	30
CO <sub>2</sub>	15	20	20	20	7	22
CH <sub>4</sub>	3	4	8	10	12	8
N <sub>2</sub>	47	1	2	5	4	2

- Air gasification gives the most diluted, low-LHV gas because N<sub>2</sub> dominates.
- O<sub>2</sub> and O<sub>2</sub>+steam avoid most N<sub>2</sub> dilution and increase CO+H<sub>2</sub> concentration.
- Steam shifts the gas towards higher H<sub>2</sub>/CO ratios through reforming and WGS.
- Indirect gasification separates heat generation from syngas production.
- SEG maximises H<sub>2</sub> by capturing CO<sub>2</sub> in situ; CLG controls oxygen with a solid carrier.

## Diluted fuel gas

Air operation is simple and autothermal, but the high N<sub>2</sub> content strongly lowers gas quality.

## Synthesis-oriented gas

O<sub>2</sub> and indirect routes produce low-N<sub>2</sub> syngas with higher heating value and easier upgrading.

## H<sub>2</sub> / CO<sub>2</sub> management

SEG boosts H<sub>2</sub> and creates a CO<sub>2</sub>-rich regeneration stream; CLG tunes oxidation without air mixing.

Note: actual gas composition depends on feedstock, equivalence ratio, steam/biomass ratio, temperature, pressure, residence time and bed material/catalyst activity.

Key message: the oxygen and heat supply strategy determines whether the product is a diluted fuel gas, a synthesis gas or an H<sub>2</sub>-rich gas with CO<sub>2</sub>-capture potential.

# Main gasifier configurations I

Fixed/moving beds and bubbling fluidized beds represent two different levels of gas–solid contacting and mixing

## Fixed or moving bed gasifiers

Packed fuel bed with gas flowing upward, downward or cross-current



LOW MIXING

### Main characteristics

- Simple and robust reactor concept, often used at small to medium scale.
- Fuel particles move slowly through drying, pyrolysis, oxidation and reduction zones.
- Strong axial gradients; tar level depends strongly on updraft/downdraft configuration.

## Bubbling fluidized bed gasifiers

Gas velocity suspends the bed but solids remain mainly inside the reactor



INTENSE MIXING

### Main characteristics

- Excellent gas–solid contact and nearly uniform bed temperature.
- Very suitable for heterogeneous biomass and waste feedstocks.
- Requires bed material, distributor design, cyclone separation and agglomeration control.

Key point: increasing gas–solid mixing improves heat transfer and fuel flexibility, but also increases hydrodynamic and solids-handling complexity.

# Main gasifier configurations II

Circulating fluidized beds and entrained-flow gasifiers are used when higher throughput, conversion or syngas quality is required

## Circulating fluidized bed gasifiers

High gas velocity entrains solids; cyclone returns bed material to the reactor



### SOLIDS RECYCLE

### Main characteristics

- High throughput and better scale-up potential than bubbling beds.
- Continuous solids circulation improves heat transfer and carbon conversion.
- More complex operation: cyclone, loop seal, erosion and fines management.

## Entrained-flow gasifiers

Fine particles or slurry are co-fed with O<sub>2</sub>/steam at very high temperature



### HIGH TEMPERATURE

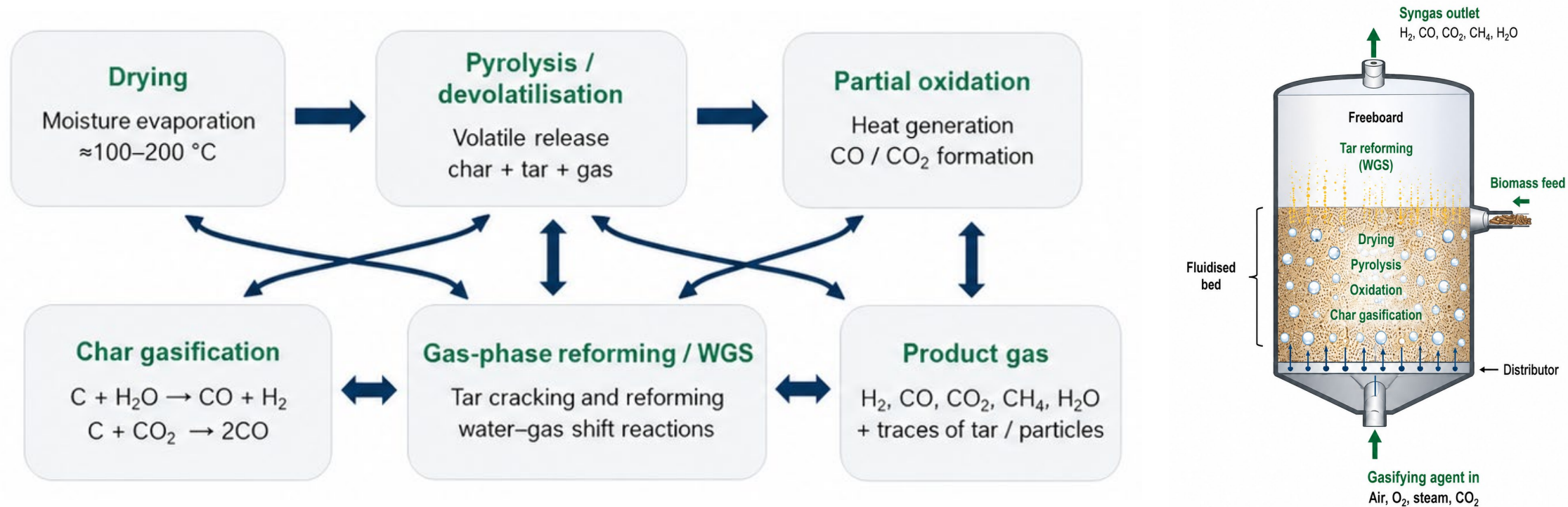
### Main characteristics

- Very short residence time and high carbon conversion at high temperature.
- Low tar formation; product gas is suitable for downstream synthesis after cleaning.
- Demanding feed preparation, oxygen supply and high-temperature ash/slag handling.

Key point: reactor selection is a compromise between feedstock flexibility, scale, tar control, carbon conversion and process complexity.

# Thermochemical stages are universal, but reactor-dependent

The same fundamental reactions occur in all gasifiers, but not necessarily as fixed sequential zones



## What remains common to all gasifiers?

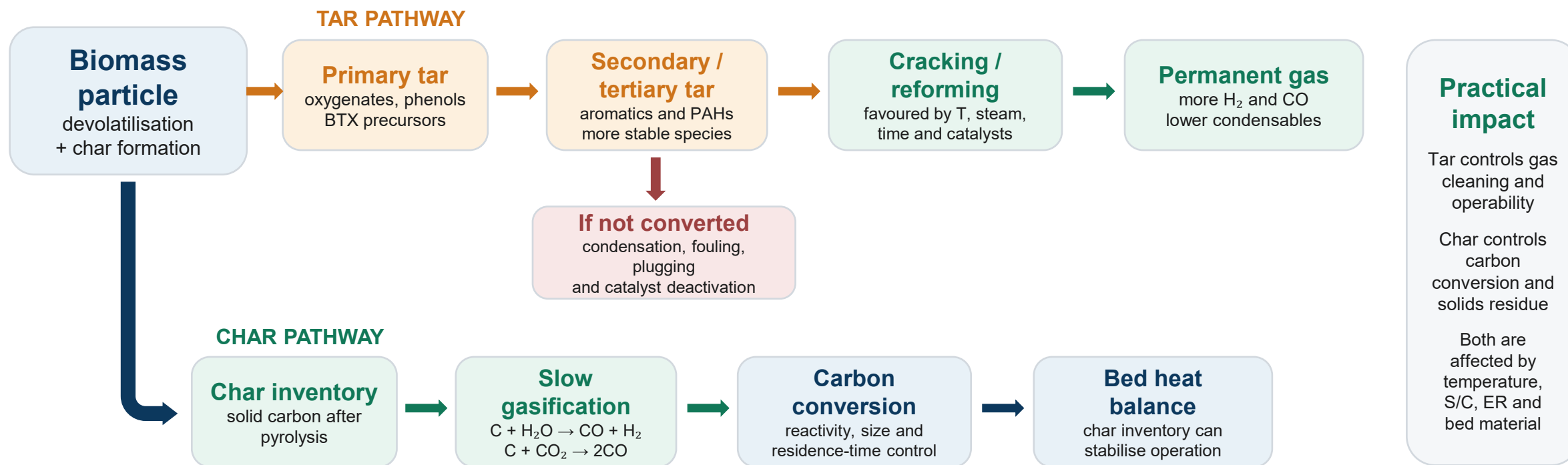
- The same main thermal and chemical steps occur: drying, devolatilisation, oxidation, char gasification and gas-phase conversion reactions.
- These phenomena are strongly coupled through heat and mass transfer.

## What changes with reactor design?

- Their spatial distribution, residence time and intensity depend on reactor hydrodynamics.
- In fixed beds, zones may be more stratified.
- In fluidised beds, reactions are highly mixed and occur simultaneously throughout the bed and freeboard.

# Tar and char formation

Tar and char are not secondary details: they often determine operability, conversion and gas cleaning needs



**Key message:** good gasification requires simultaneous control of tar formation, char conversion and contaminant release.

# Syngas cleaning and tar removal

Raw syngas usually contains contaminants that are harmful for downstream units, catalysts and synthesis processes

Raw syngas may contain particles, alkali species, H<sub>2</sub>S, HCl, NH<sub>3</sub>, tars and condensable organics

## Particles and solids

Cyclones  
Hot ceramic / candle filters  
Bag filters or polishing filtration

## Inorganic / acid contaminants

H<sub>2</sub>S, HCl, NH<sub>3</sub>, alkalis, trace metals  
Wet scrubbers  
Sorbent beds / activated carbon

## Why cleaning matters

- avoids plugging, fouling and condensation
- protects catalysts, membranes and synthesis units
- limits corrosion, emissions and downstream instability
- tailors gas quality to H<sub>2</sub>, methanol, SNG or FT routes

## Tar removal after cooling

Quench and condensation  
Water / venturi scrubbers  
Oil scrubbers or wet ESP

## Hot tar conversion

Catalytic beds: dolomite, olivine, Ni  
Thermal cracking  
Thermal plasma

**Key point:** the syngas cleaning train depends on the final use of the gas and on whether tar is removed cold or converted hot.

# From syngas to fuels, chemicals and hydrogen

Once cleaned and conditioned, syngas becomes a versatile platform intermediate for several downstream routes

## Clean and conditioned syngas

platform gas for energy, fuels and chemicals

### Hydrogen



WGS to increase H<sub>2</sub>  
CO<sub>2</sub> removal + PSA / membranes  
Refining, chemicals, mobility

### Methanol

H<sub>2</sub>/CO ratio adjustment  
Catalytic synthesis  
Basis for solvents and e-fuels

### Synthetic natural gas (SNG)

Methanation to CH<sub>4</sub>  
Gas grid or storage applications  
High methane purity after polishing

### Fischer–Tropsch fuels / SAF

Syngas → FT liquids  
Upgrading to diesel, naphtha and jet-range fuels  
Relevant route for sustainable aviation fuels

### Power, CHP and chemicals

Gas engines / turbines for heat and power  
Ammonia and other synthesis routes  
Product choice depends on gas quality and economics

**Common requirement:** clean gas, controlled H<sub>2</sub>/CO ratio and very low levels of sulfur, chlorine and tar.

# HYIELD project: waste-to-hydrogen demonstration

A European framework for converting biogenic waste streams into high-purity H<sub>2</sub>

HYIELD integrates advanced gasification, syngas cleaning and H<sub>2</sub> separation to demonstrate a waste-to-hydrogen route at industrially relevant scale.



## Why HYIELD matters

- Valorisation of difficult biogenic waste streams
- Production of clean H<sub>2</sub> from a renewable/circular carbon route
- Direct connection between gas quality and downstream H<sub>2</sub> purification

## Role of this presentation

- Context for the experimental work performed by ICB-CSIC
- Focus on bubbling fluidized bed gasification and raw gas quality
- Basis for discussing tar, sulfur species and operating variables

**Key point: HYIELD provides the application framework for linking gasification performance, syngas cleaning and high-purity hydrogen production.**

# EXPERIMENTAL MATRIX FOR TRL-5

Run	Feedstock	Bed	T (°C)	S/C	ER
1	Structurant	Olivine	650	1.5	0.14
2	Structurant	Olivine	750	1.5	0.13
3	Structurant	Olivine	850	1.5	0.20
4	Structurant	Olivine	650	2	0.12
5	Structurant	Olivine	650	1	0.15
8	Olive stone	Olivine	650	1.5	0.13
11	Sewage sludge	Olivine	650	1.5	0.14
14	Grape seeds	Olivine	650	1.5	0.15

# Feedstock characterization



Structurant



Olive stone



Sludge



Grape Seeds

## Proximate analysis

Parameter (%)	Structurant	Sludge	Grape Seeds	Olive stone
Moisture	7.7	6.5	7.8	8.61
Volatile Matter	64.4	48.0	67.7	72.96
Ash	12.8	42.1	3.1	0.42
Fixed carbon	15.2	3.4	21.5	18.01

## Ultimate analysis

Parameter (%)	Structurant	Sludge	Grape Seeds	Olive stone
C	41.6	28.0	51.7	46.66
H*	5.89	4.49	6.94	5.21
N	0.75	3.86	1.74	0.13
S	<0.1	1.8	0.1	<0.1
O**	31.16	13.25	28.62	38.87

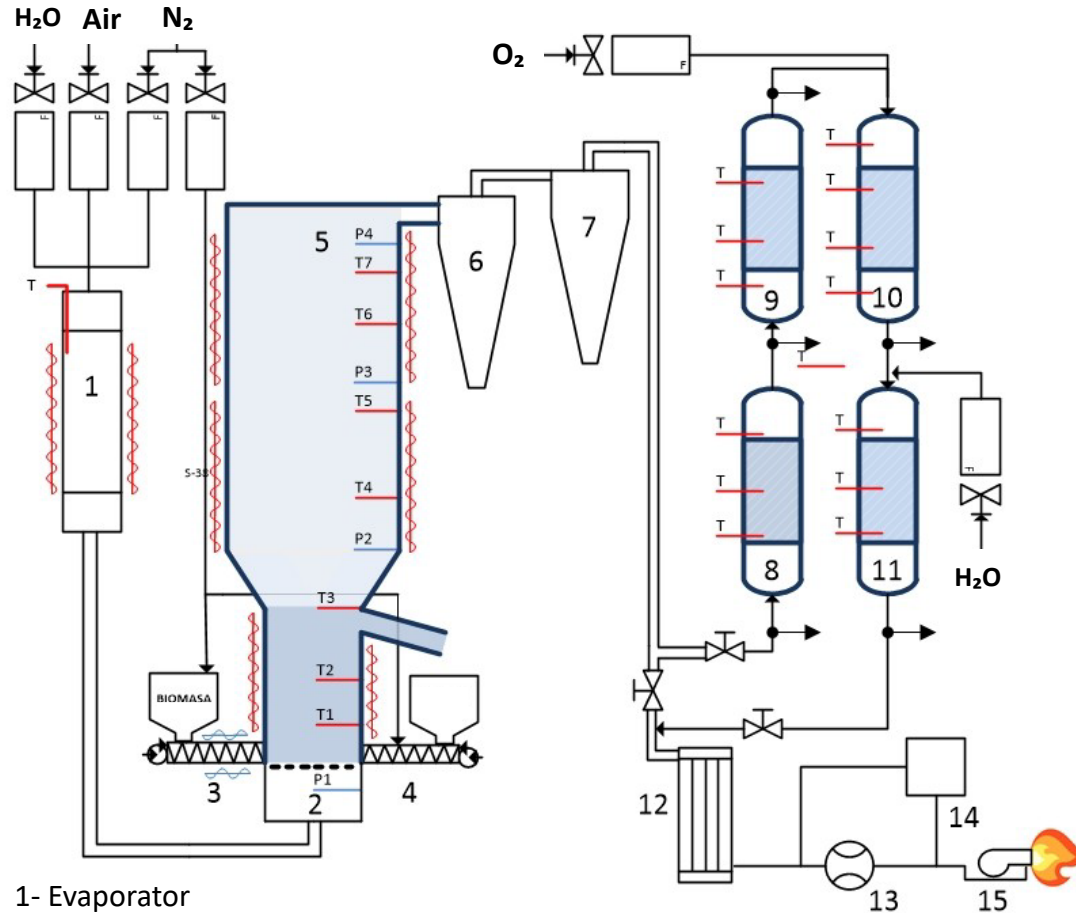
\*The H content includes the H content in the moisture.

\*\*The O content has been calculated as  $100 - C - H^* - N - S - \text{Ash} - \text{Moisture}$ .

## Heating value

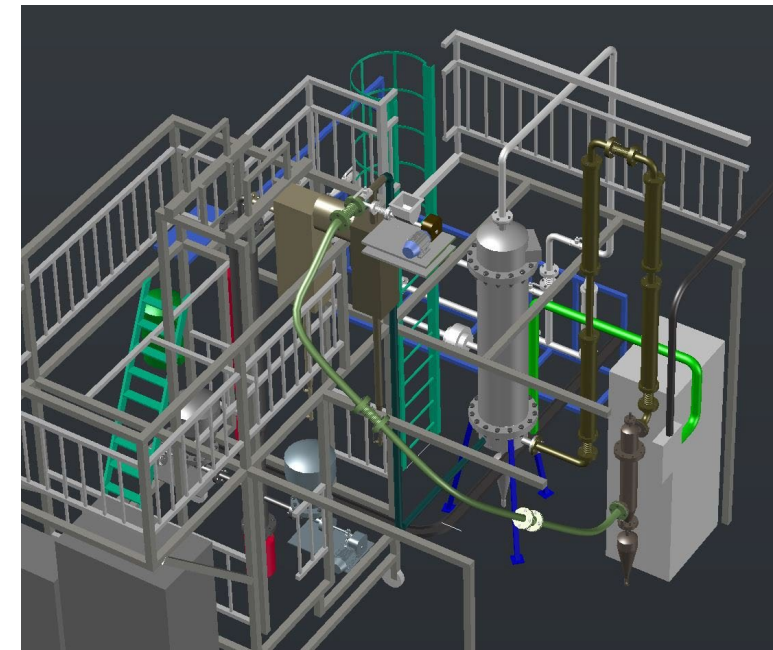
Parameter (MJ/kg)	Structurant	Sludge	Grape Seeds	Olive stone
HHV	15.96	11.93	21.75	18.77
LHV	14.72	10.99	20.32	17.35

# TRL5 bubbling fluidized bed gasifier at ICB-CSIC



- 1- Evaporator
- 2- Distributor plate
- 3- Biomass screw feeder (water-cooled)
- 4- Bed screw feeder (insulated)
- 5- Fluidized-bed gasifier
- 6 & 7- Cyclones
- 8- Chlorine removal reactor

- 9- Sulphur removal reactor
- 10- Tar reforming reactor
- 11- WGS reactor
- 12- Condenser
- 13- Flow meter
- 14- Online gas analyzer
- 15- Flare stack

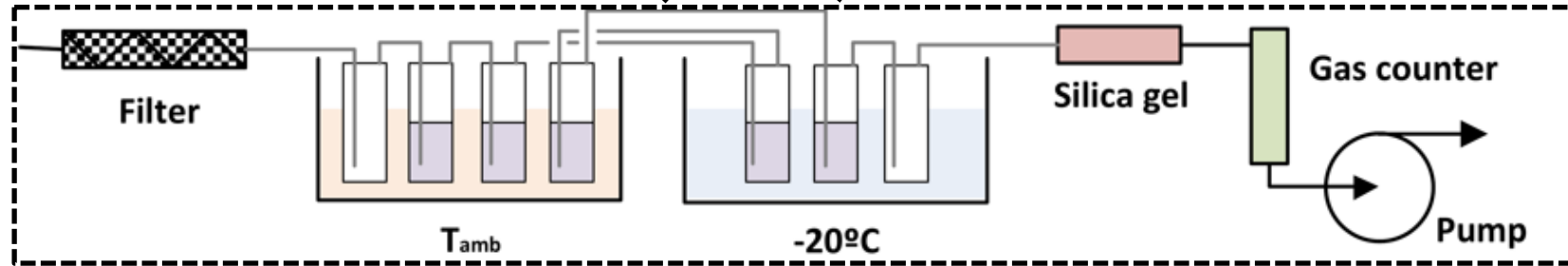


# Tar Sampling and Quantification Methods

- Standardized cold sampling train downstream of the gasifier
- Particle filter + impingers at  $T_{amb}$  and  $-20\text{ }^{\circ}\text{C}$

## Tar sampling system

- Isopropanol used as solvent
- Gas flow controlled by pump and gas counter

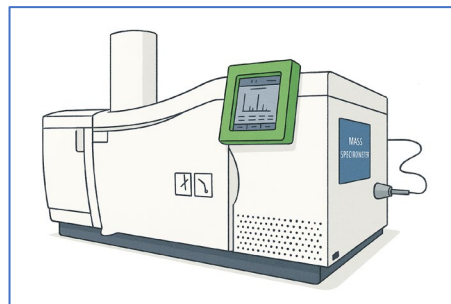


## Collectable tar

- 23 representative compounds (BTX, phenols, PAHs)



GC-MS

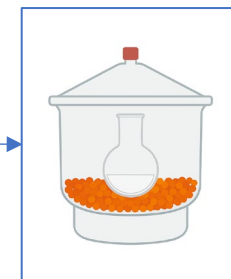


## Gravimetric tar

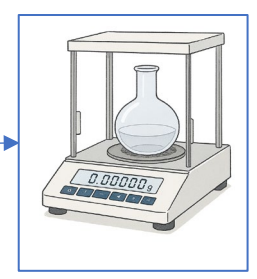
Rotary Evaporator



Drying 24 h (Silica Gel)



Analytical Balance

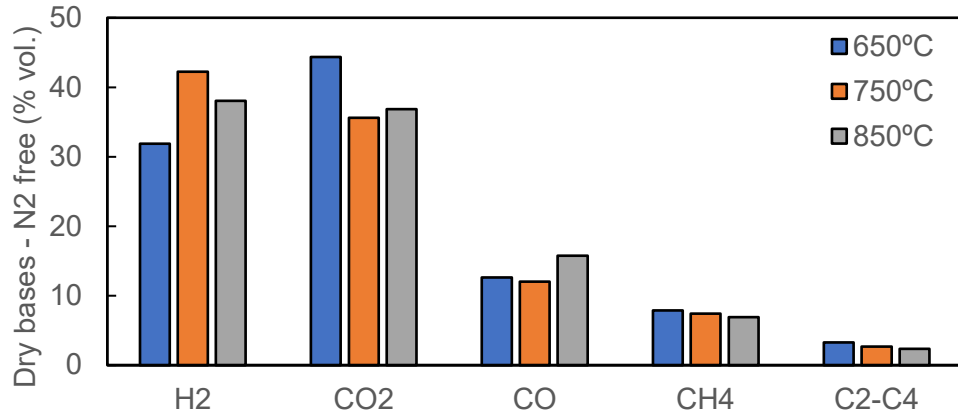


# Temperature effect

## Operating Conditions

- Bubbling fluidized bed gasifier
- Structurant biomass
- Constant S/C ratio

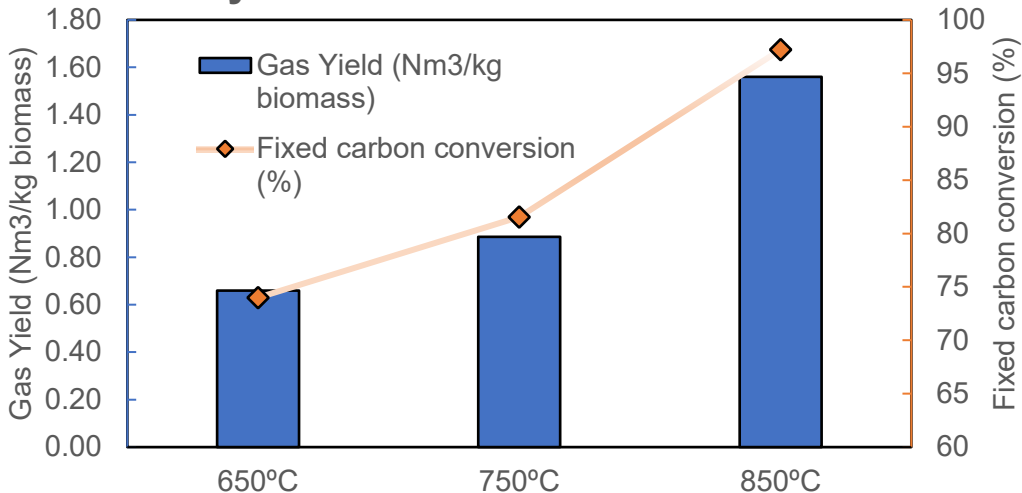
### Gas composition



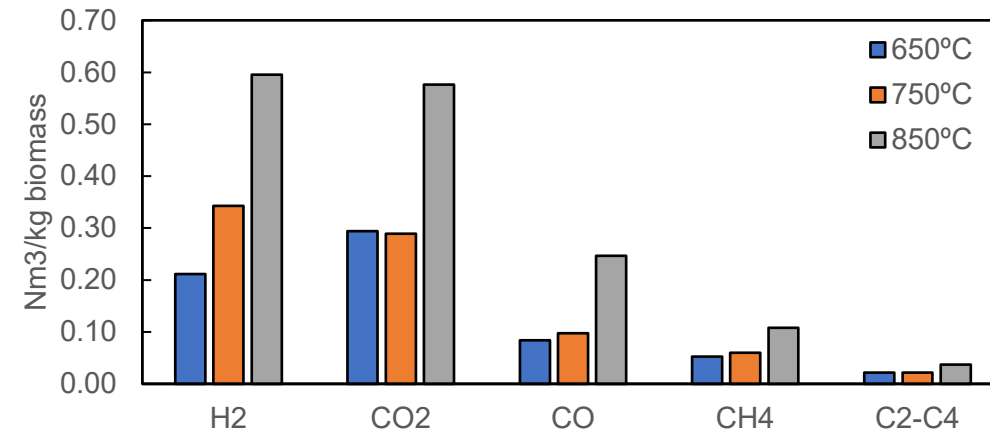
### Main trends

- The H<sub>2</sub> concentration in the product gas increases from 650 °C to 750 °C, but slightly decreases at higher temperature. (Reverse water–gas shift reaction)
- Light hydrocarbons (CH<sub>4</sub> and C<sub>2</sub>–C<sub>4</sub>) decrease with increasing temperature due to enhanced cracking and reforming.
- Higher temperature significantly increases the total amount of gas produced, strongly affecting the individual gas yields.
- Despite the lower H<sub>2</sub> molar fraction at 850 °C, the highest individual H<sub>2</sub> production is achieved due to the increased gas yield.

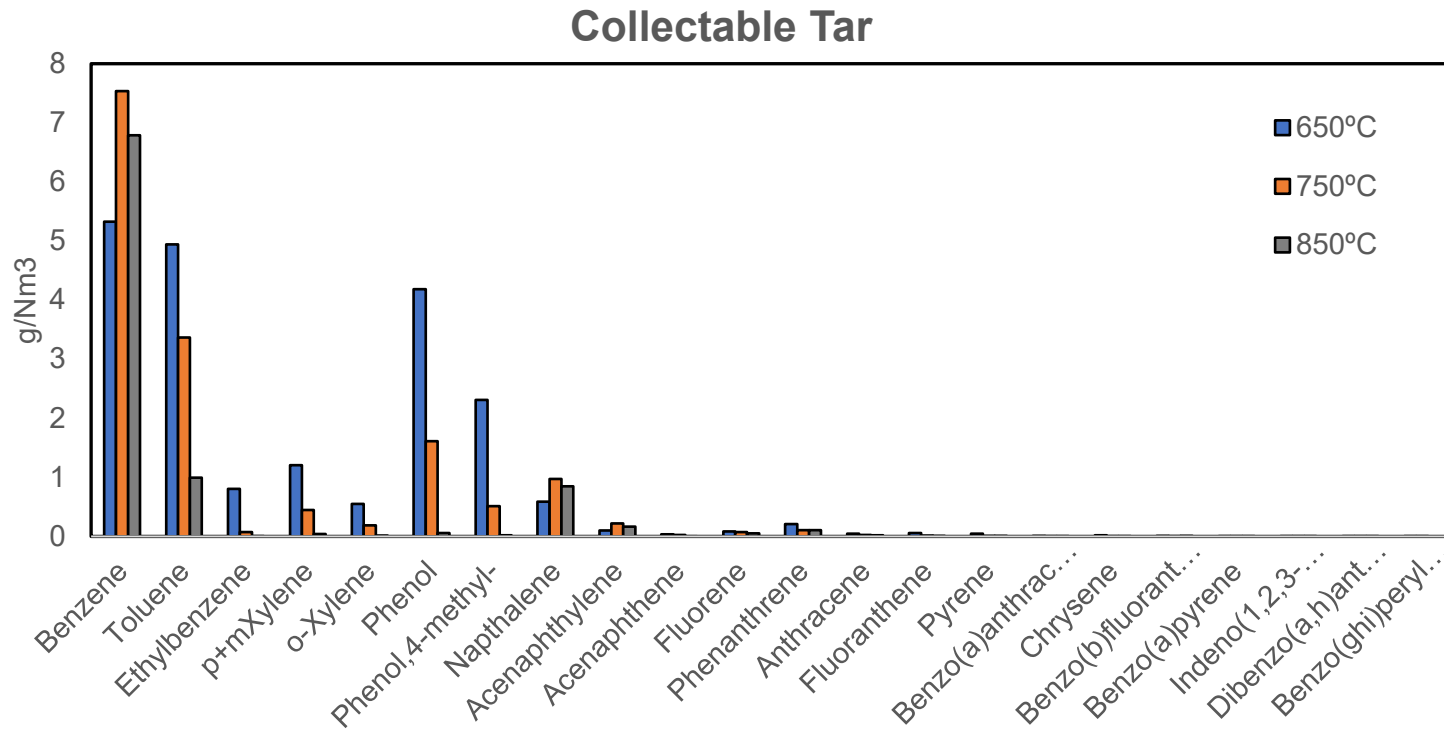
### Gas yield VS Fixed carbon conversion



### Individual gas yield



# Temperature effect



- ❖ **650 °C:** Maximum tar production, dominated by phenols and BTEX.
- ❖ **750 °C:** Phenols decrease; BTEX remains but in lower amounts; PAHs start to decline.
- ❖ **850 °C:** Minimum tar; heavy compounds (PAHs) almost disappear.

	Collectable tar		
	650°C	750°C	850°C
<b>TOTAL (g/Nm<sup>3</sup>)</b>	20.54	15.12	9.16
	Gravimetric tar		
	650°C	750°C	850°C
<b>TOTAL (g/Nm<sup>3</sup>)</b>	35.16	6.85	2.39

	Sulfur compounds (ppmv)		
	650°C	750°C	850°C
<b>COS</b>	7.53	6.55	11.53
<b>H<sub>2</sub>S</b>	516.05	594.60	544.41
<b>CS<sub>2</sub></b>	0.00	0.00	0.00
<b>CH<sub>4</sub>S</b>	20.84	0.00	0.00

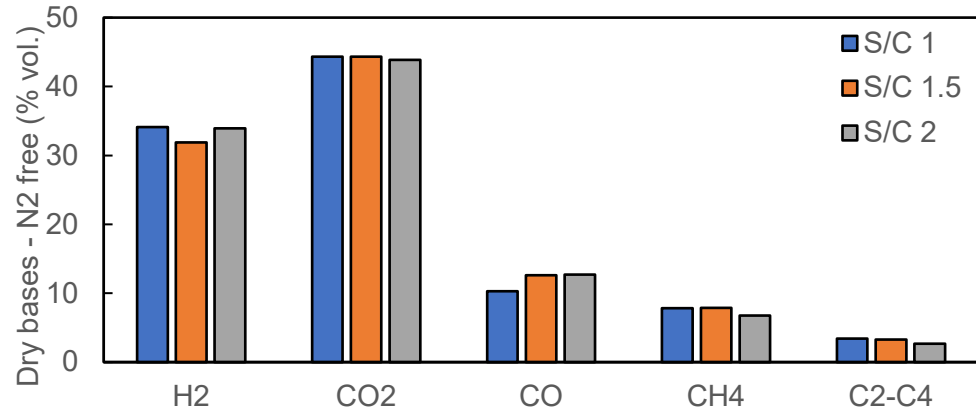
- The main **sulfur compound** detected is H<sub>2</sub>S which remained relatively stable at around 500 ppm.

# Steam to carbon ratio (S/C) effect

## Operating Conditions

- Bubbling fluidized bed gasifier
- Structurant biomass
- Constant temperature

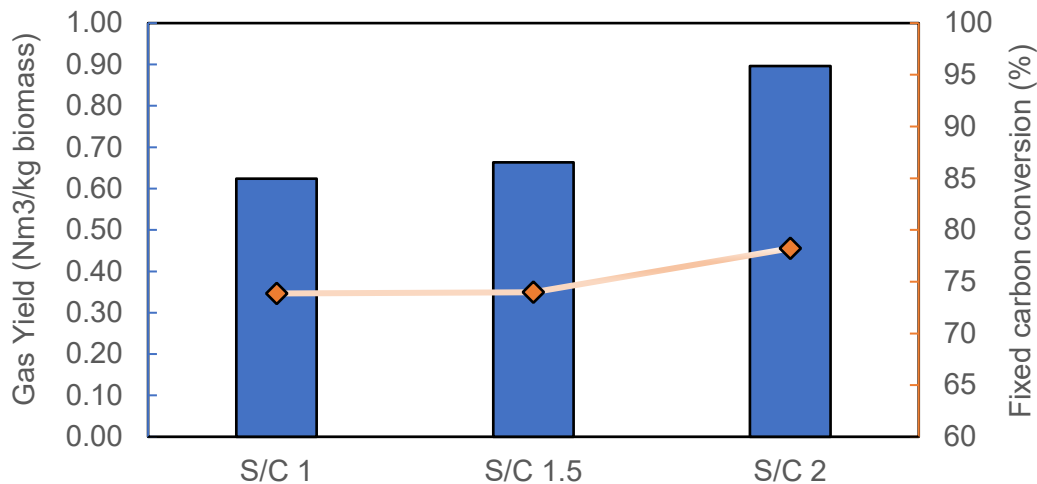
### Gas composition



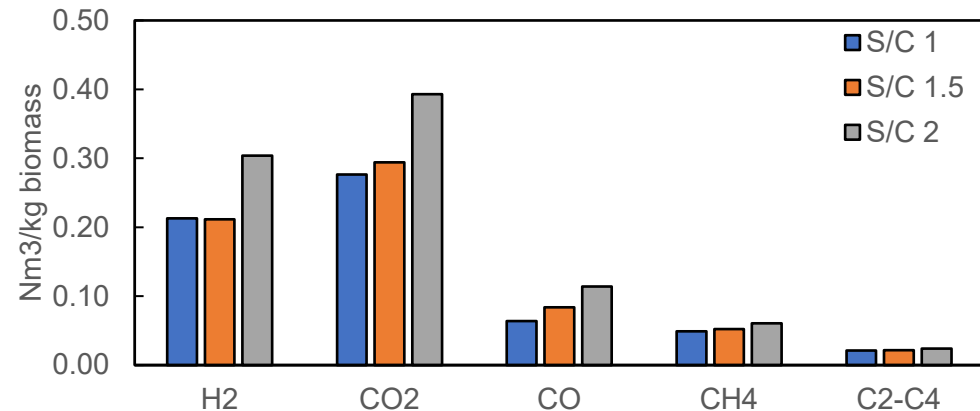
## Main trends

- Increasing S/C promotes cracking and reforming reactions, reducing CH<sub>4</sub> and C<sub>2</sub>-C<sub>4</sub> hydrocarbons while increasing CO production.
- At 650 °C, the water-gas shift reaction is kinetically limited and does not progress sufficiently to convert the additional CO produced by reforming into H<sub>2</sub>, resulting in CO accumulation, and decreasing H<sub>2</sub> molar fraction.
- Only above a threshold S/C value (≈2.0), reforming and char gasification are fully activated, leading to higher carbon conversion, increased gas yield and a clear rise in individual H<sub>2</sub> production.

### Gas yield VS Fixed carbon conversion

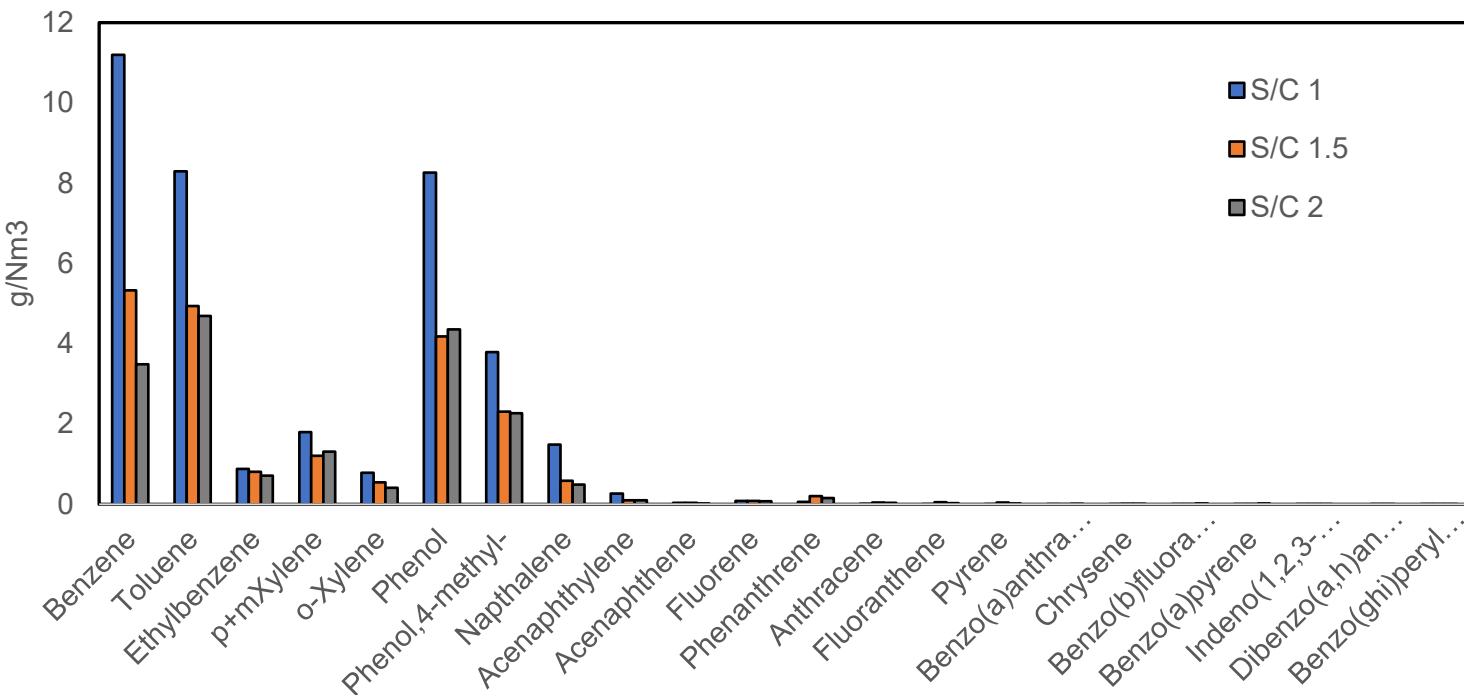


### Individual gas yield



# Steam to carbon ratio (S/C) effect

Collectible Tar



- ❖ **S/C 1.0:** Highest tar production, dominated by phenolic compounds and BTEX.
- ❖ **S/C 1.5:** Strong reduction of total tar due to enhanced cracking and reforming.
- ❖ **S/C 2:** Minimum tar content, with heavy tar compounds largely suppressed.

	Collectible tar		
	S/C 1	S/C 1.5	S/C 2
<b>TOTAL (g/Nm<sup>3</sup>)</b>	37.00	20.54	18.26
	Gravimetric tar		
	S/C 1	S/C 1.5	S/C 2
<b>TOTAL (g/Nm<sup>3</sup>)</b>	37.27	35.16	21.50

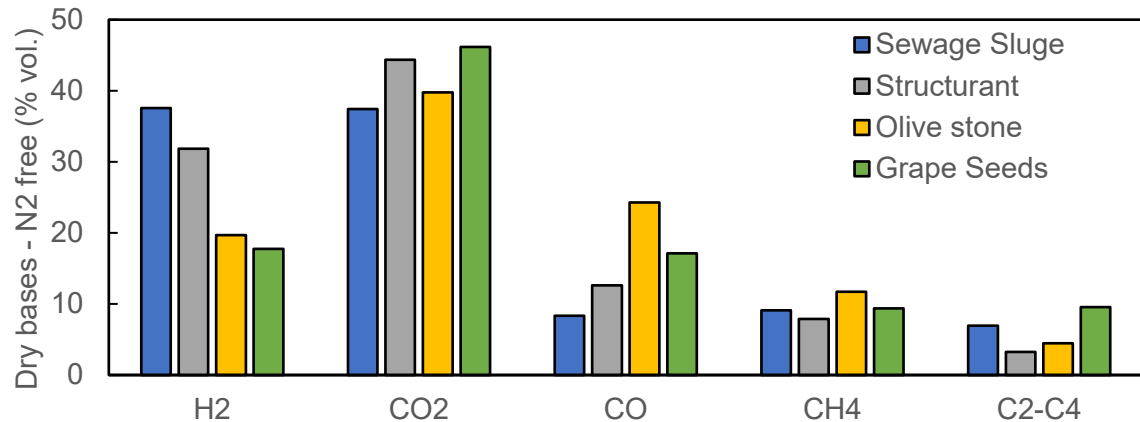
	Sulfur compounds (ppmv)		
	S/C 1	S/C 1.5	S/C 2
<b>COS</b>	9.48	7.53	3.02
<b>H<sub>2</sub>S</b>	509.47	516.05	276.31
<b>CS<sub>2</sub></b>	0.00	0.00	0.20
<b>CH<sub>4</sub>S</b>	10.73	20.84	1.69

- H<sub>2</sub>S is the main sulfur species detected in all cases.
- At high S/C (2.0), H<sub>2</sub>S concentration decreases probably due to dilution effects.

# Feedstock effect

Operating Conditions	Structurant	Olive Stone	Grape Seeds	Sewage Sludge
Temperature (°C)	645	654	658	651
Biomass Flow (kg/h)	3.07	4,31	3,21	3.14
Olivine Flow (kg/h)	7.54	5.78	6.03	4.89
H <sub>2</sub> O mass Flow (kg/h)	3	4,2	4.5	2
S/C	1.56	1.42	1,83	1.52
ER	0.15	0.13	0.15	0.14

## Gas composition



## Main trends

### Sewage sludge

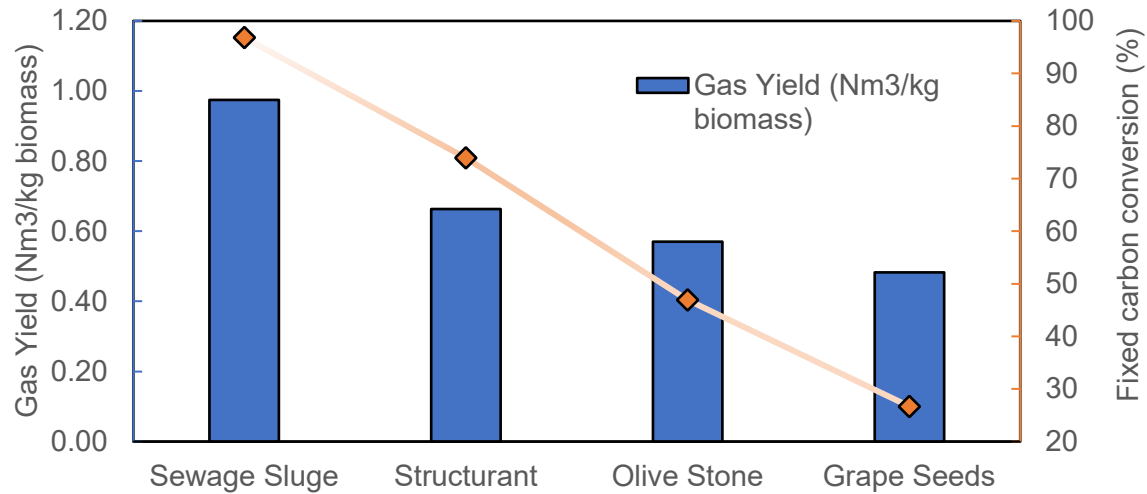
- Shows higher H<sub>2</sub> concentration
- Has very low fixed carbon content (~3.1 wt.%). Limited gas–solid reactions lead to low CO formation and gas dominated by devolatilisation products.
- High CH<sub>4</sub> and C<sub>2</sub>–C<sub>4</sub> concentrations indicate limited reforming at 650 °C.
- Partial reforming of volatiles and tar, even if limited, can still generate significant H<sub>2</sub>.

### Structurant, olive stone and grape seeds

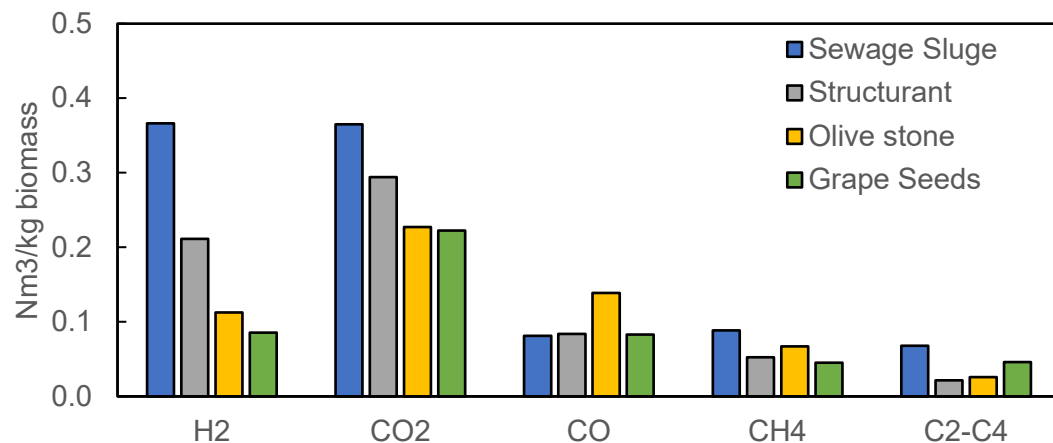
- Among lignocellulosic biomasses, structurant shows the highest H<sub>2</sub> concentration together with the lowest CH<sub>4</sub> and C<sub>2</sub>–C<sub>4</sub> contents.
- Proximate and ultimate analyses indicate a higher ash content in structurant.
- Ash components may exert a mild catalytic effect, enhancing reforming of methane, light hydrocarbons and tar precursors.
- As reforming reactions produce proportionally more H<sub>2</sub> than CO, H<sub>2</sub> concentration increases while CO decreases.

# Feedstock effect

Gas yield VS Fixed carbon conversion



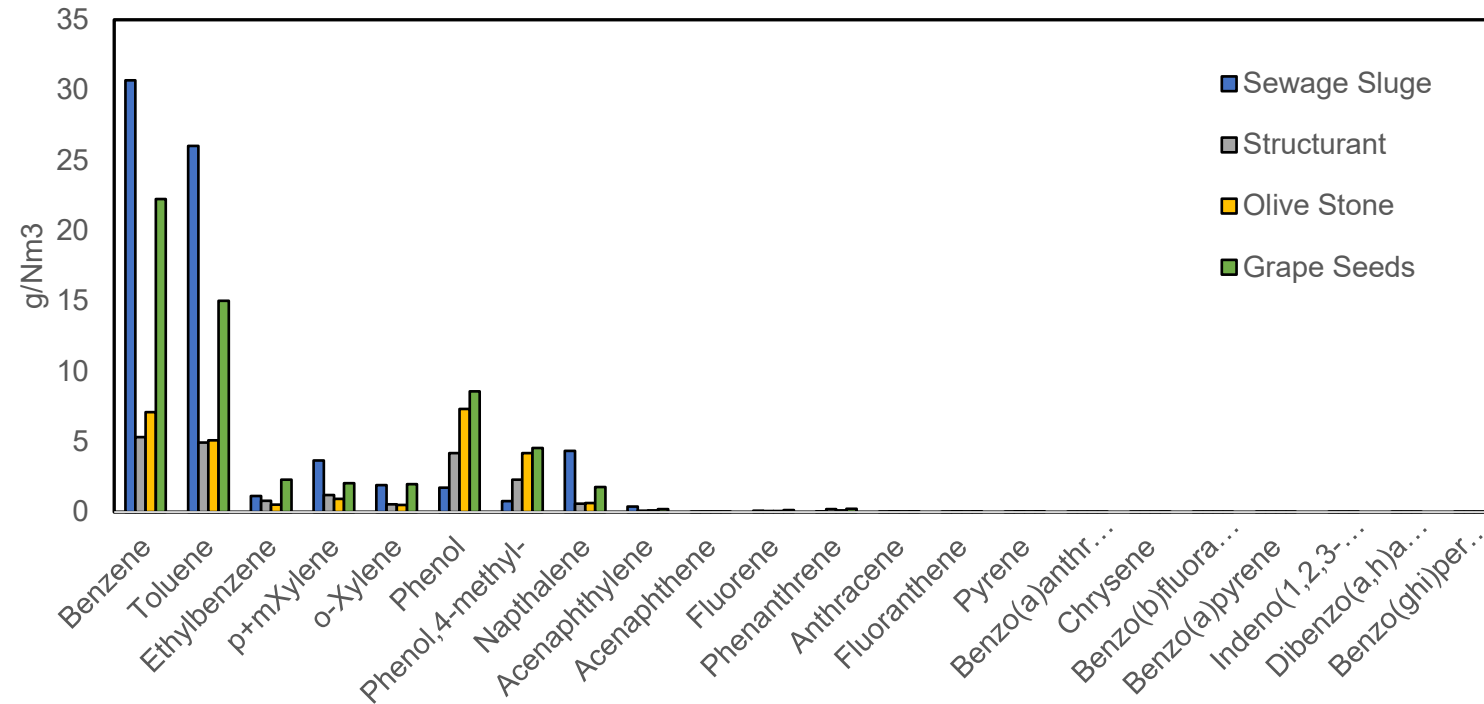
Individual gas yield



- Sewage sludge shows the highest total gas yield, despite its very low fixed carbon content. High gas yield is mainly associated with devolatilisation and partial reforming of large amounts of tar.
- Among lignocellulosic biomasses, structurant achieves the highest fixed carbon conversion.
- Higher carbon conversion results in higher gas yield and the highest H<sub>2</sub> production among lignocellulosic feedstocks.

# Feedstock effect

Collectible Tar



- Sewage sludge shows the highest collectable tar content, mainly dominated by the BTEX fraction.
- Lignocellulosic biomasses show higher phenolic contents, associated with lignin-derived tar.
- Among lignocellulosic feedstocks, structurant presents the lowest collectable and gravimetric tar contents.
- Grape seeds exhibit particularly high tar formation, indicating limited tar conversion at 650°C.

Collectible tar			
Structurant	Olive Stone	Grape Seeds	Sewage Sludge

<b>TOTAL (g/Nm³)</b>	20.54	26.79	59.41	70.92
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Gravimetric tar			
Structurant	Olive Stone	Grape Seeds	Sewage Sludge

<b>TOTAL (g/Nm³)</b>	35.16	66.73	124.82	33.56
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Sulfur compounds (ppmv)			
Structurant	Olive Stone	Grape Seeds	Sewage Sludge

<b>COS</b>	7.53	2.36	34.90	9.61
<b>H<sub>2</sub>S</b>	516.05	101.02	52.43	6480.74
<b>CS<sub>2</sub></b>	0.00	0.00	0.00	8.80
<b>CH<sub>4</sub>S</b>	20.84	1.67	23.30	108.40

- Sewage sludge shows significantly higher sulfur release than lignocellulosic biomasses.
- H<sub>2</sub>S is the dominant sulfur species detected in all cases.
- Higher sulfur concentration in sewage sludge is consistent with its higher sulfur content in the elemental analysis.

# Conclusions

- Gasification is a flexible platform for converting biomass and biogenic waste into syngas for H<sub>2</sub>, fuels and chemicals.
- Raw gas quality is governed by operating conditions and feedstock properties: temperature, S/C ratio, ER, bed material, ash and reactor hydrodynamics.
- Conclusions obtained from the experimental results:
  - Experimental temperature effect: increasing T from 650 to 850 °C raised gas yield from 0.66 to 1.56 Nm<sup>3</sup>/kg biomass and fixed-carbon conversion from ~74 to ~97%.
  - Higher temperature strongly reduced tar: collectable tar decreased from 20.5 to 9.2 g/Nm<sup>3</sup> and gravimetric tar from 35.2 to 2.4 g/Nm<sup>3</sup>.
  - Steam addition promoted reforming and tar conversion, but at 650 °C the WGS reaction was kinetically limited; H<sub>2</sub> molar fraction did not increase linearly with S/C.
  - Feedstock strongly affected gas quality: structurant showed the cleanest lignocellulosic behaviour, whereas sewage sludge produced high H<sub>2</sub> but much higher tar and sulfur release.
  - For waste-to-hydrogen routes, gasification performance and syngas cleaning must be designed together to protect downstream H<sub>2</sub> purification.

# Thank you for your attention!!!

## Questions?

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