Energy recovery from lignocellulosic biomass by hydrothermal carbonization and anaerobic digestion: A circular economy concept

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Urban Bioeconomy: from Biowaste to Biofuels and Bioproducts of Industrial Interest

$2.2·10^8$ t MSW year^{-1}

≈ 10% lignocellulosic biomass

Biowaste

47 % composting and recycling

28% energy valorization

25% landfill

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Urban pruning waste

One the most abundant energy resource on the planet

Industrial level

Home level

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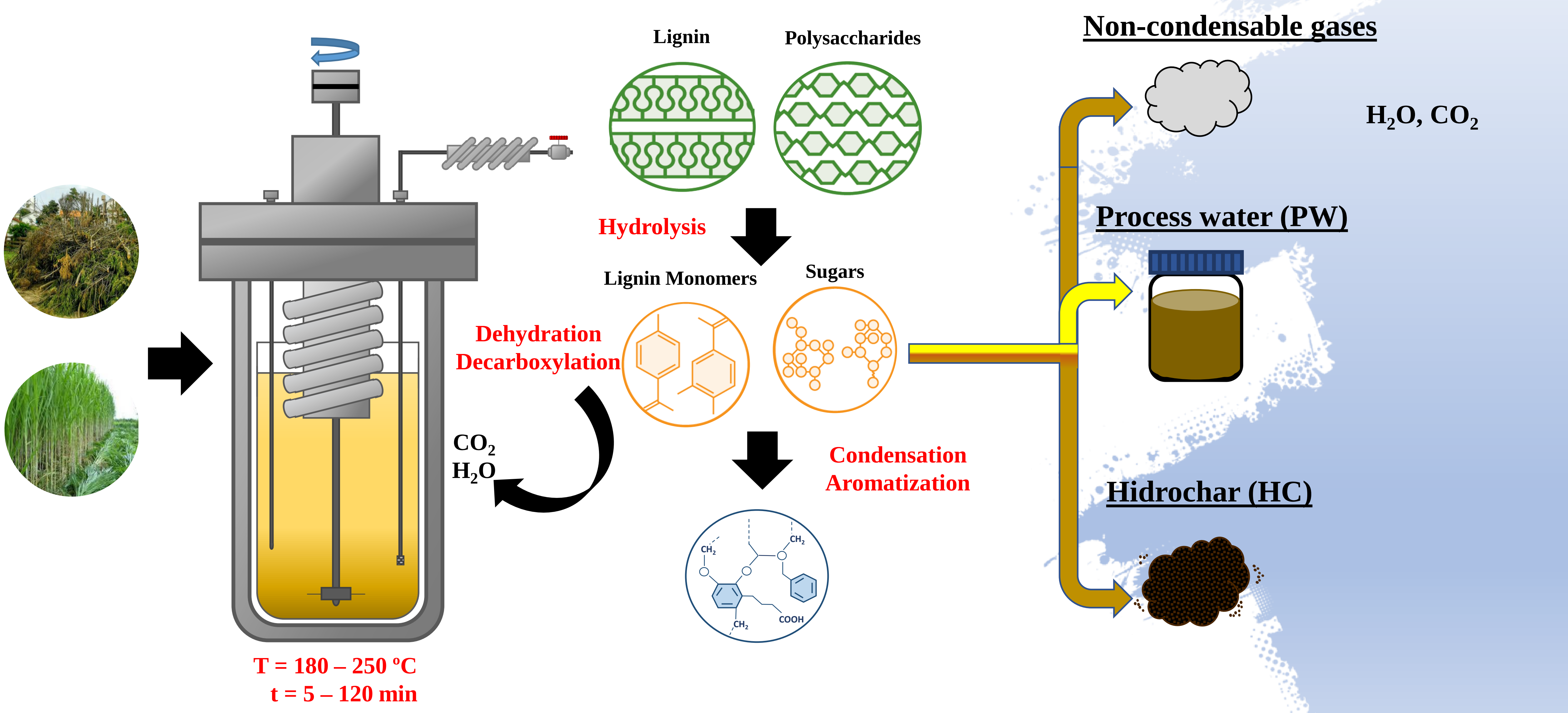

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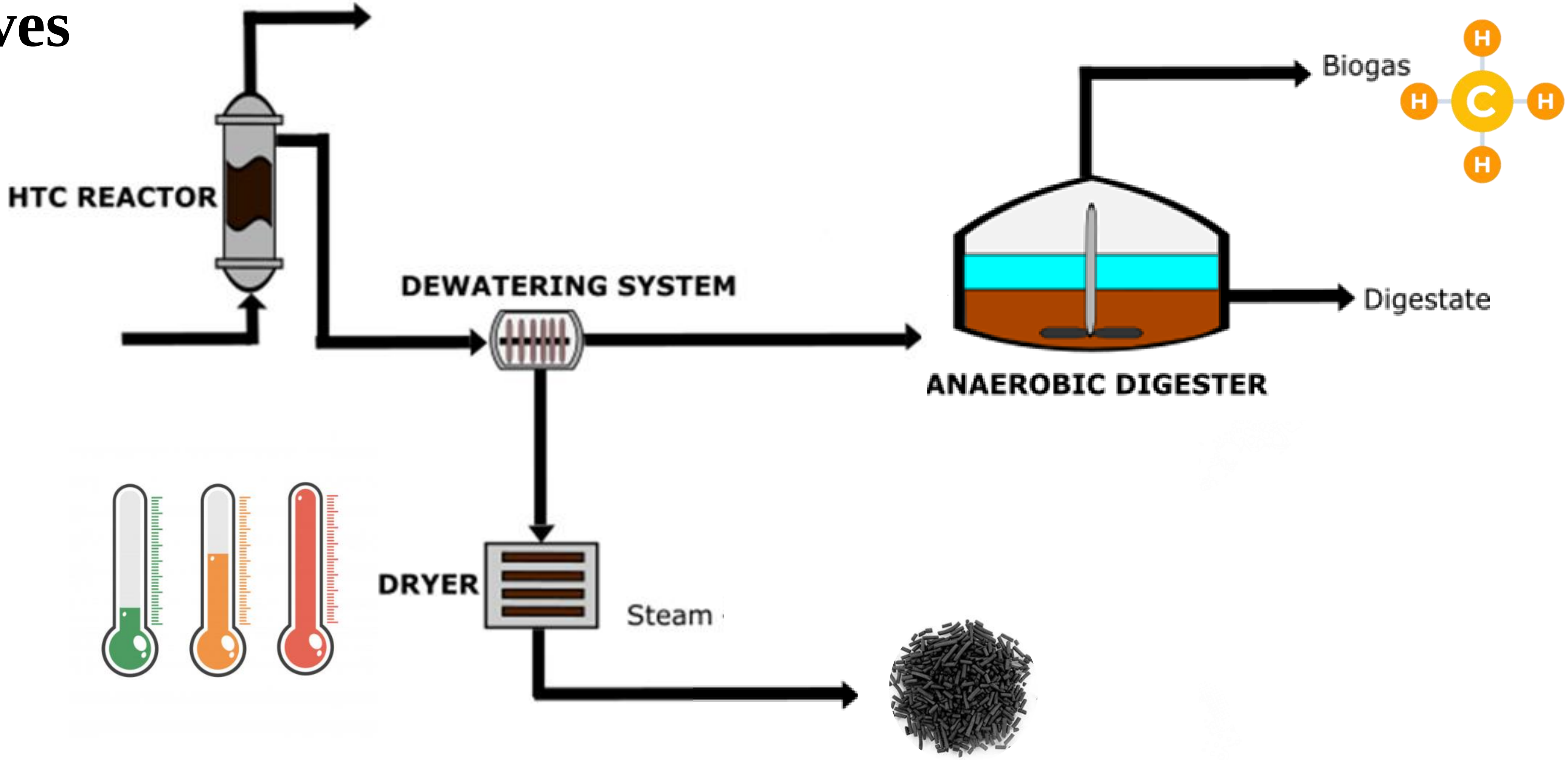
Objectives



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Urban Pruning Waste

Characteristics	UPW
Moisture (%)	4.76 ± 0.2
C (%)	46.9 ± 1.1
H (%)	6.1 ± 0.4
N (%)	0.9 ± 0.1
S (%)	0.4 ± 0.2
O* (%)	40.6 ± 0.1
Volatile matter (d.b.%)	76.5 ± 0.1
Ash (d.b.%)	5.1 ± 0.1
Fixed carbon (d.b.%)	18.4 ± 0.1
HHV (MJ kg^{-1})	19.7 ± 0.1
H/C	1.55
O/C	0.65
NPK	0.9/0.1/0.5
Ca (mg g^{-1})	10.13
Al (mg g^{-1})	0.12
Na (mg g^{-1})	0.03
Mg (mg g^{-1})	0.77
Fe (mg g^{-1})	0.10
K (mg g^{-1})	4.86
P (mg g^{-1})	0.93

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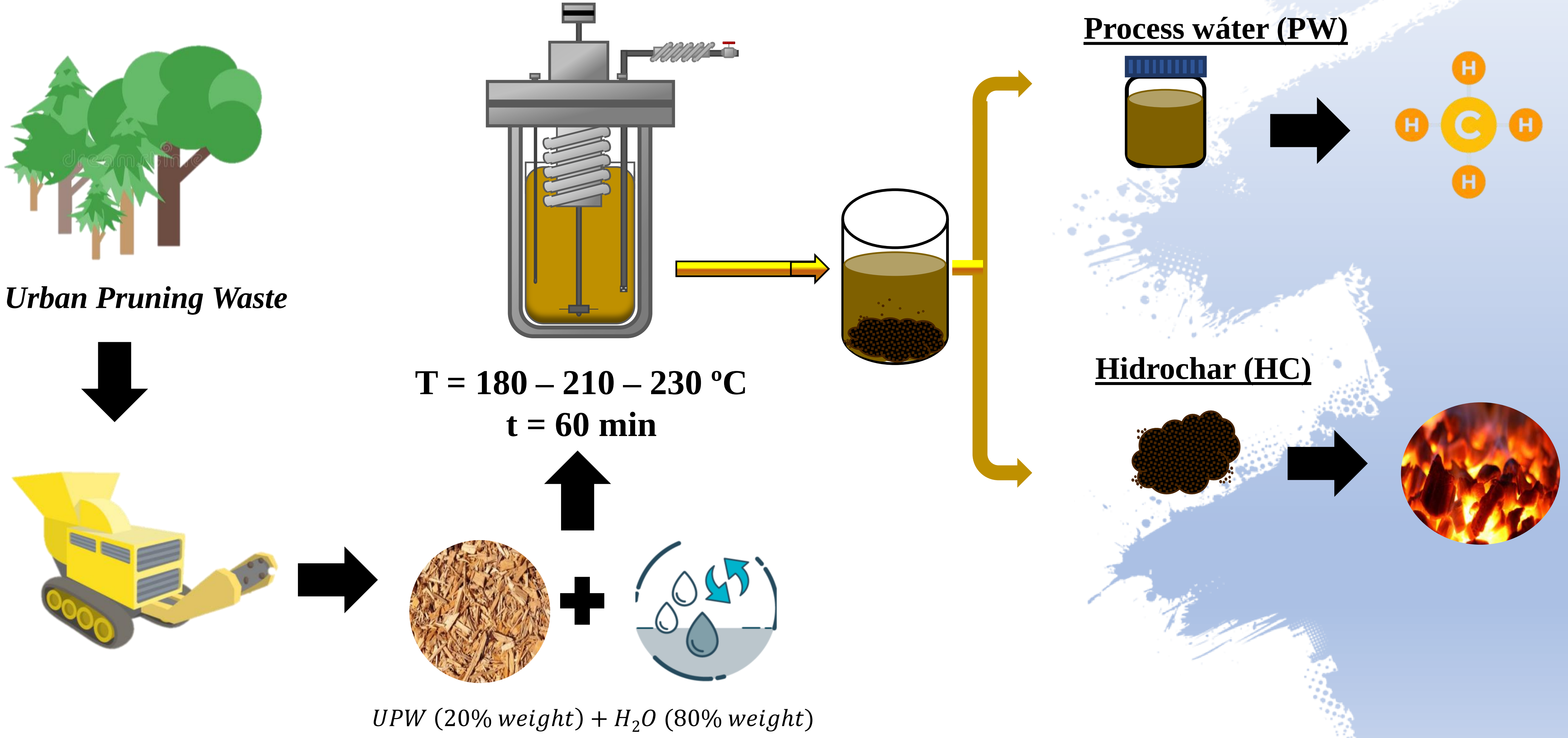

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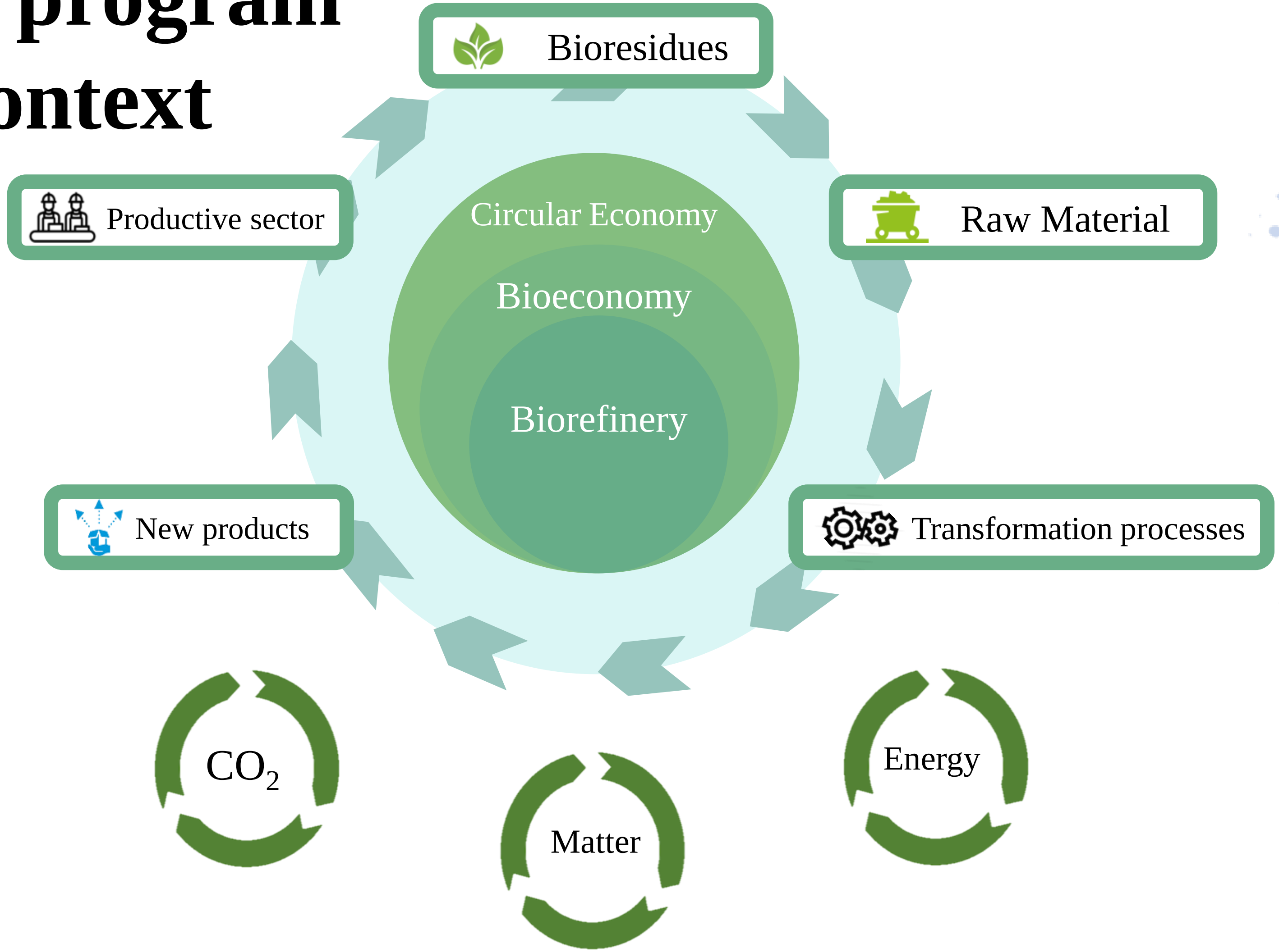
BIO3 program context



Objective 3

Hydrothermal carbonization of biowaste

Objective 7

Anaerobic digestion of process water from hydrothermal carbonization

Materials and methods

HTC reactor

Anaerobic digestion

Thermogravimetric analysis (TGA)

Results

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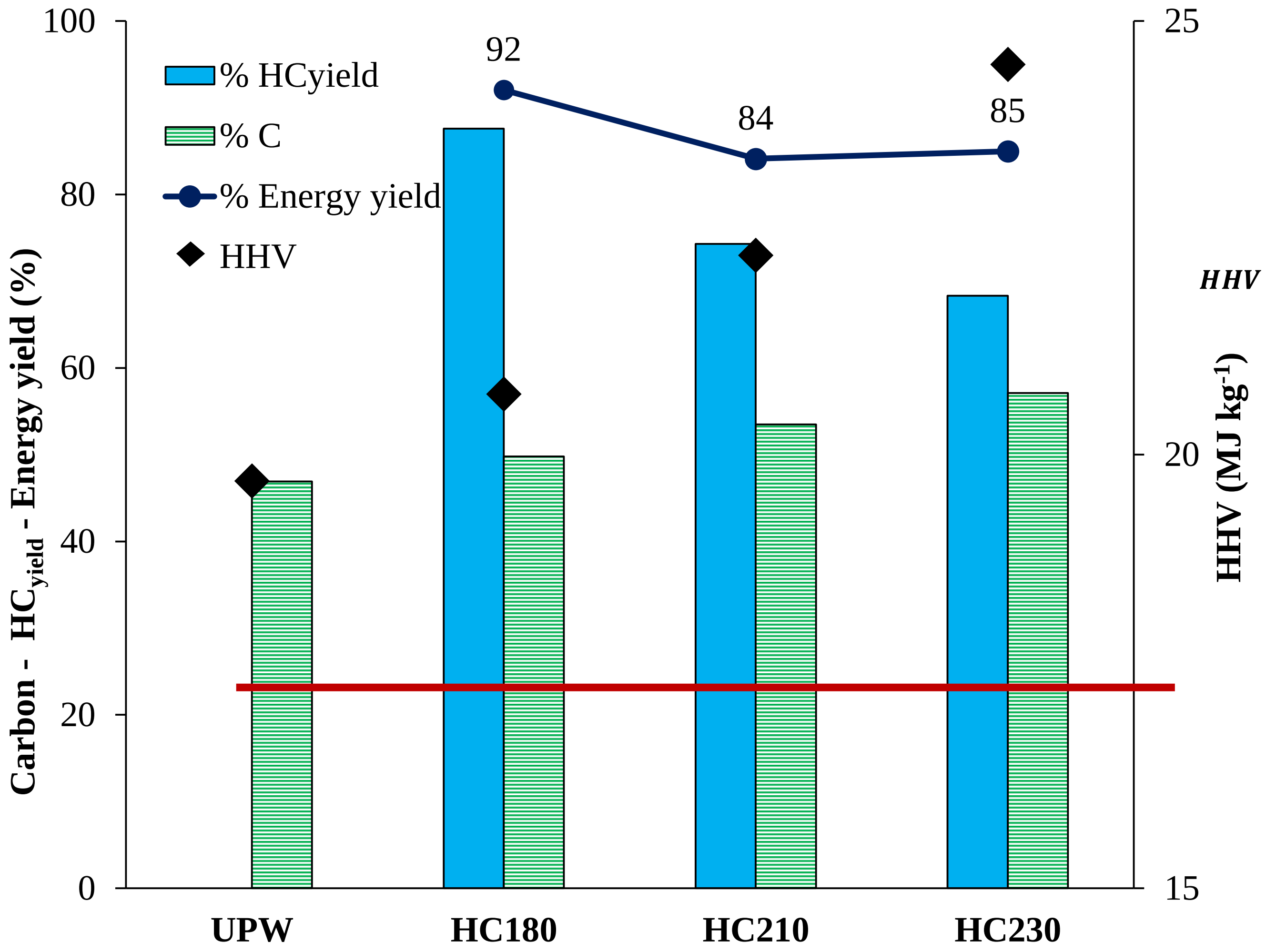
Energy and elemental analysis



$$HC_{yield} = \frac{M_{HC}}{M_{UPW}} \cdot 100\%$$

$$Carbon\ (\%) = \frac{\%C_{HC}}{\%C_{UPW}} \cdot 100\%$$

$$\boldsymbol{HHV\ (MJ\ kg^{-1}) = 0,3491 \cdot \%C + 1,1783 \cdot \%H + 0,1005 \cdot \%S - 0,0151 \cdot \%N - 0,0211 \cdot \%Ash}$$

$$Energy_{yield}\ (MJ\ kg^{-1}) = HHV_{HC} \cdot Y_{HC}$$

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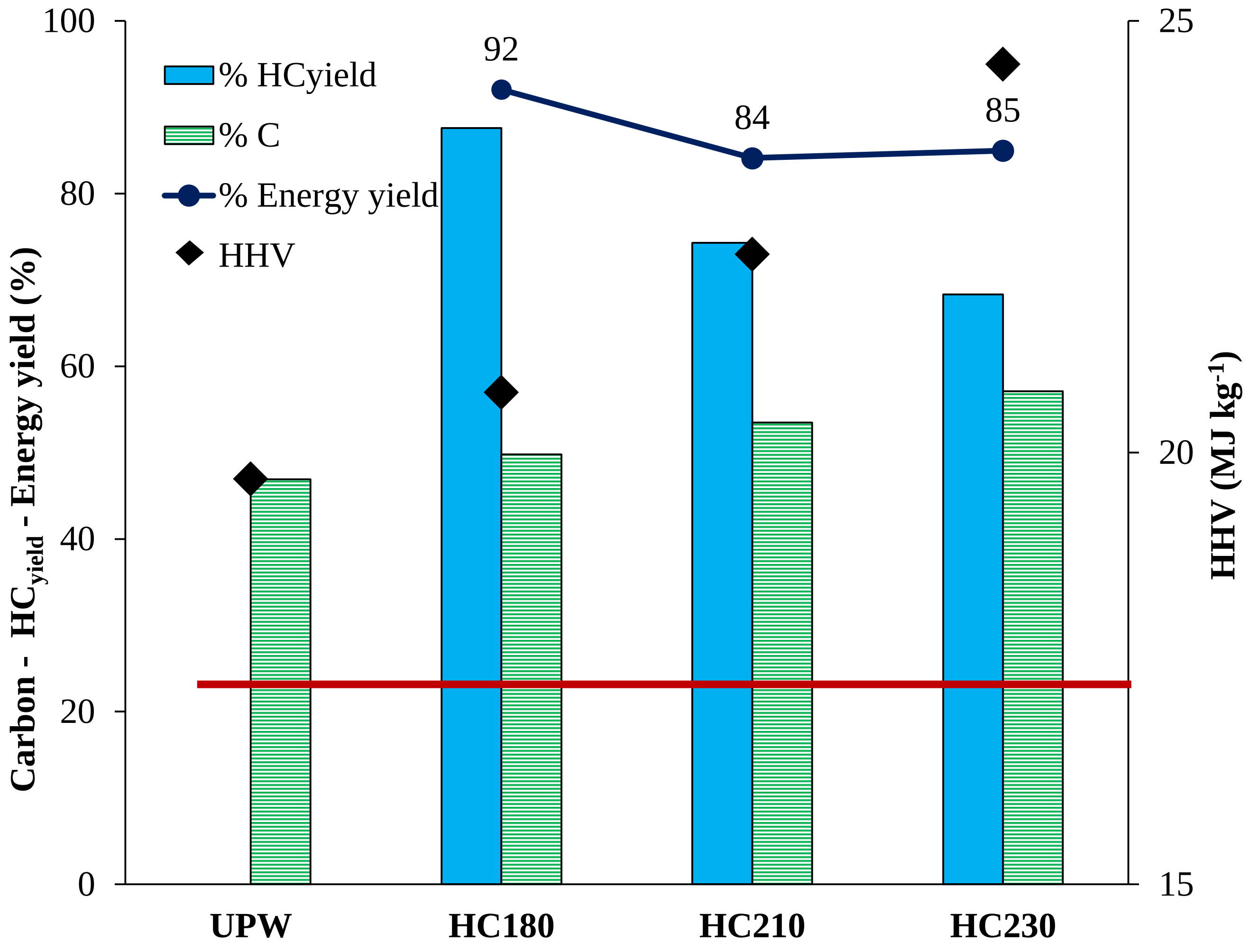
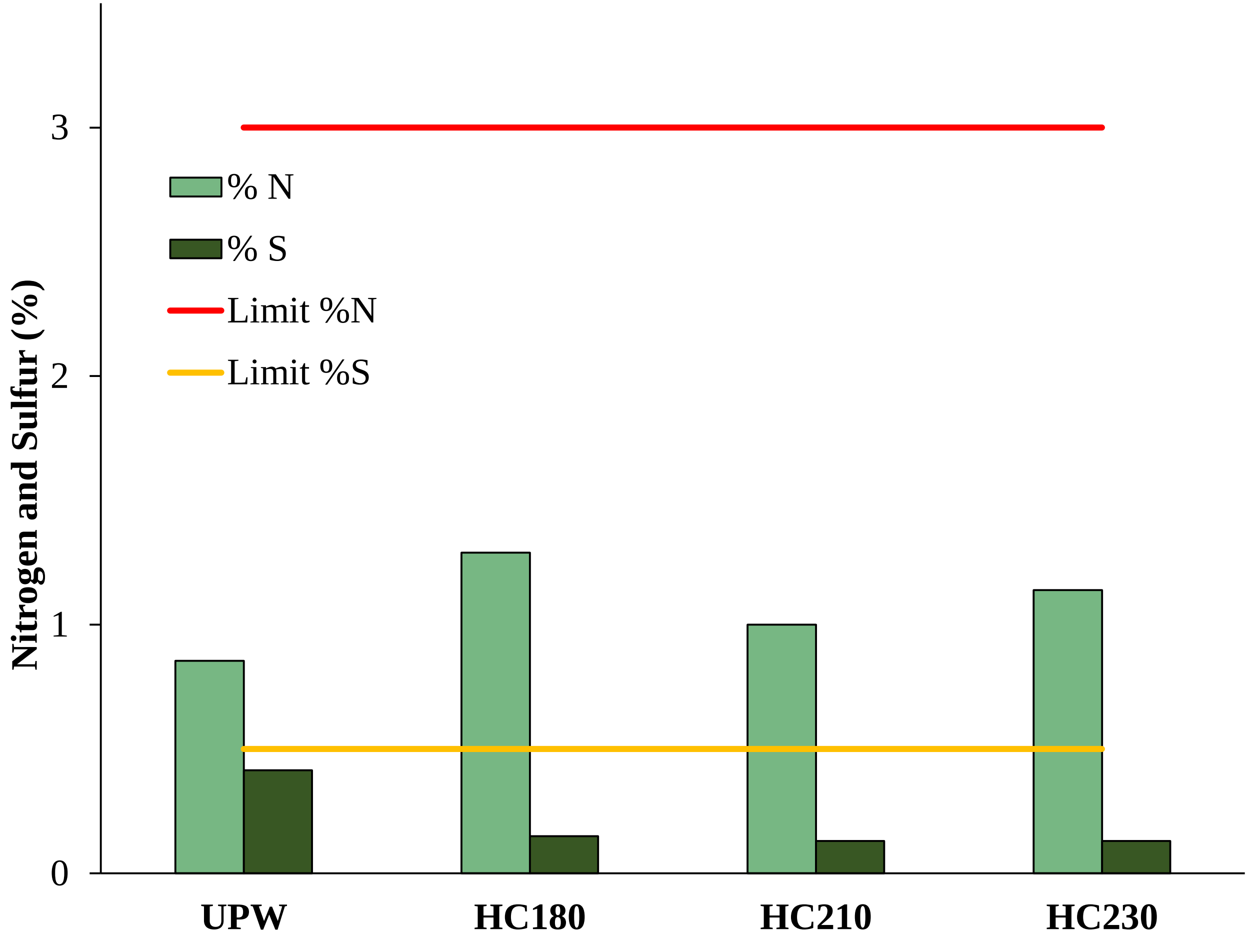
Energy and elemental analysis



ISO 17225
Graded thermally treated and densified biomass fuels

	UPW	HC180	HC210	HC230
HHV > 17 MJ kg^{-1}	✓	✓	✓	✓
Nitrogen < 3%				
Sulfur < 0.5%				
Volatile matter < 75%				

Nitrogen and Sulfur content



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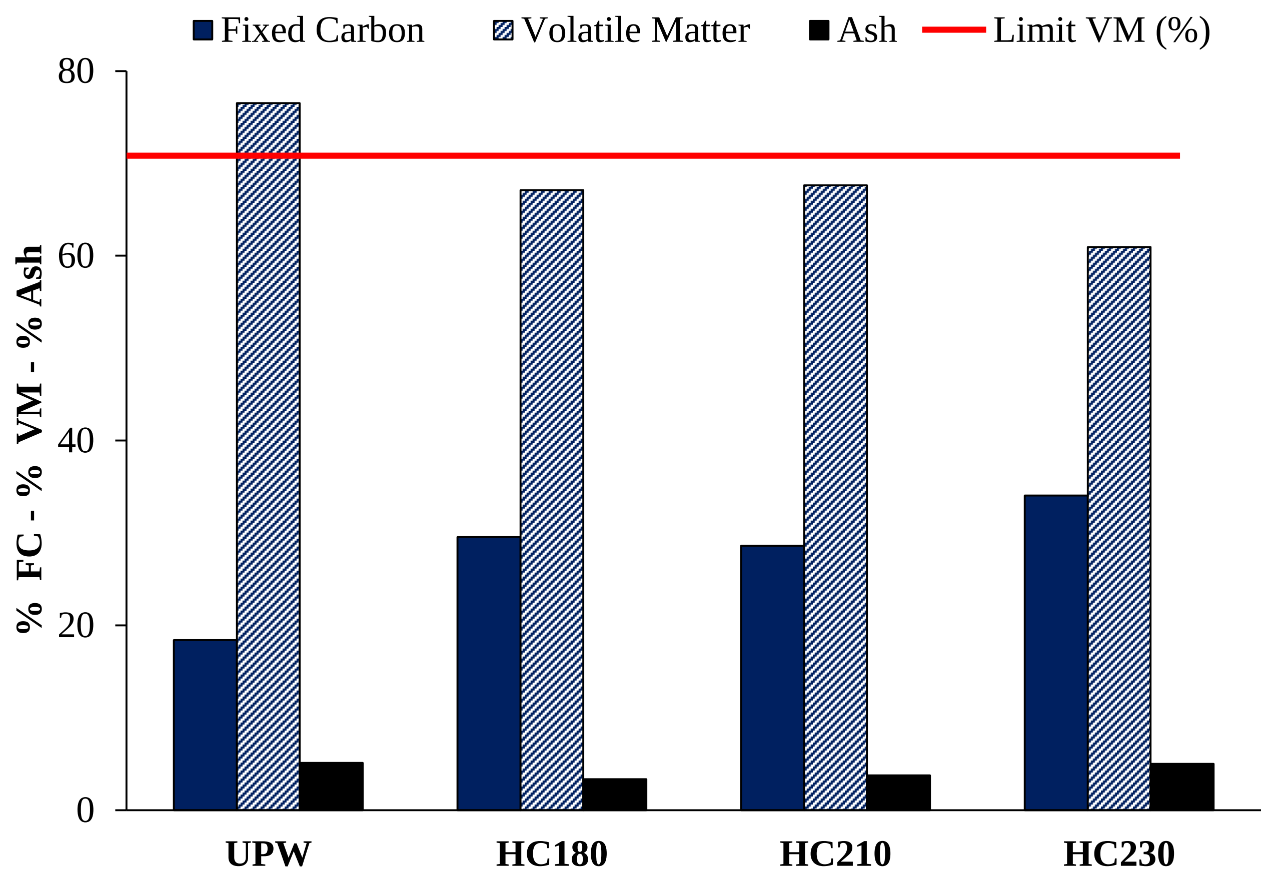
Proximal analysis



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Volatile matter < 75%	✗	✓	✓	✓

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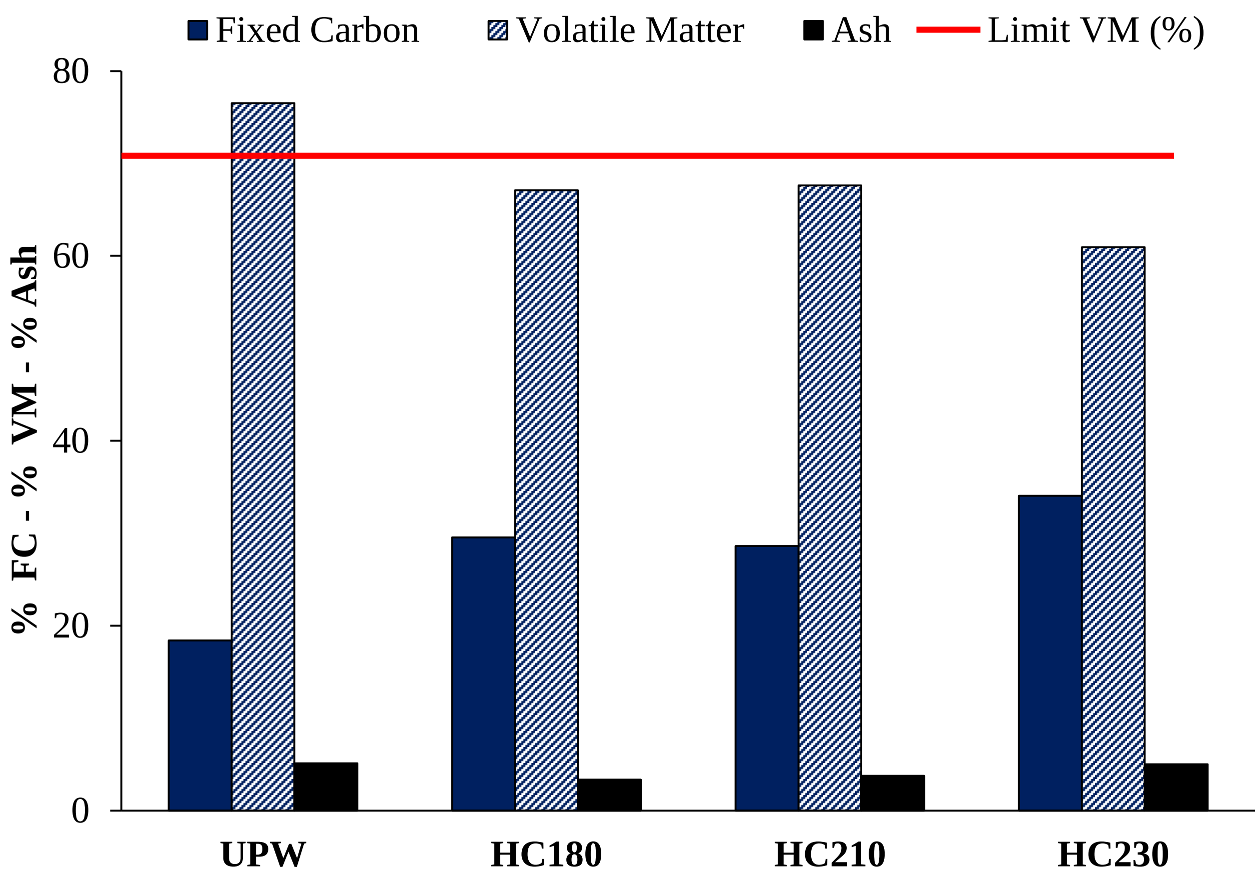
Proximal analysis



Ash content ↓ **5 – 35%**

$$Alkali\ (kg\ GJ^{-1}) = \frac{1 \cdot 10^6}{HHV\ (kJ\ kg^{-1})} \cdot \frac{\%\ Ash}{100} \cdot \left(\frac{\%K_2O + \%Na_2O}{100}\right)$$

	UPW	HC180	HC210	HC230
Alkali(kg GJ^{-1})	0.30	0.09	0.07	0.07

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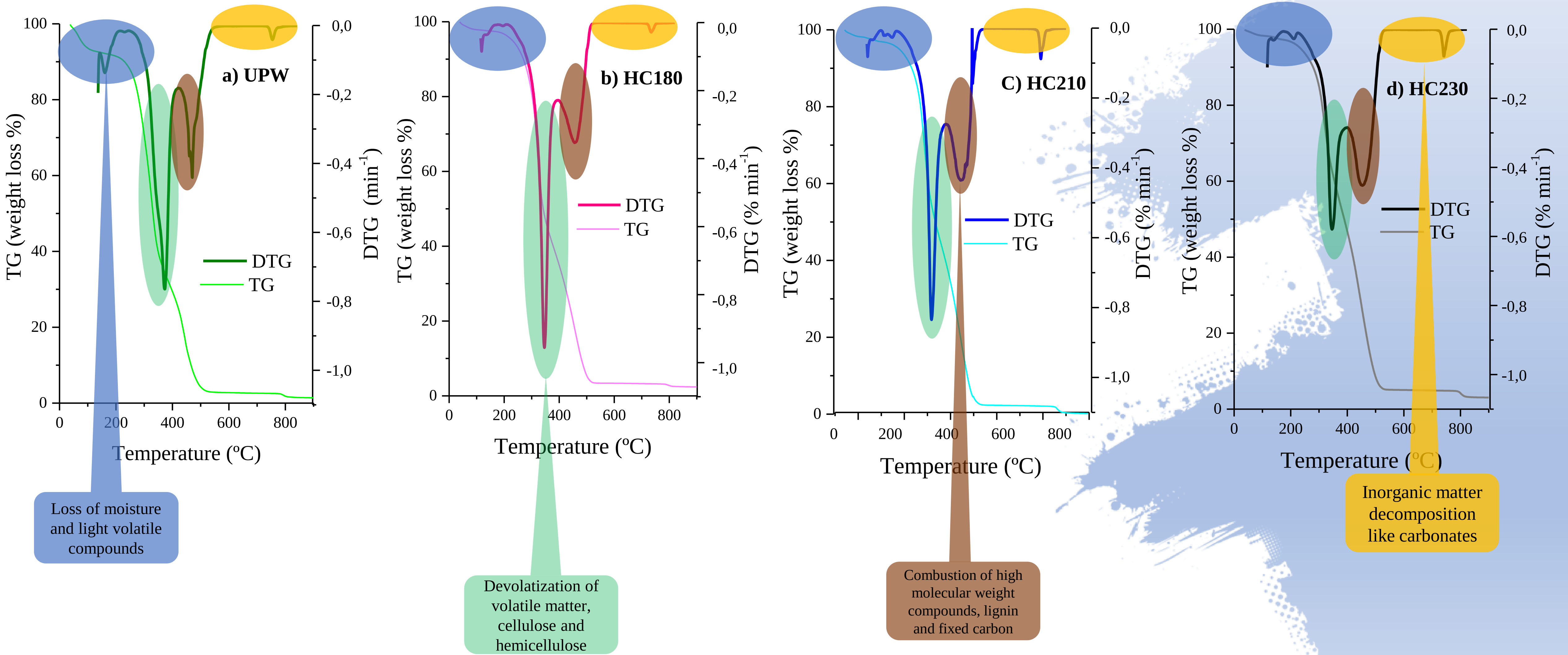
Thermogravimetric and differential TG profiles



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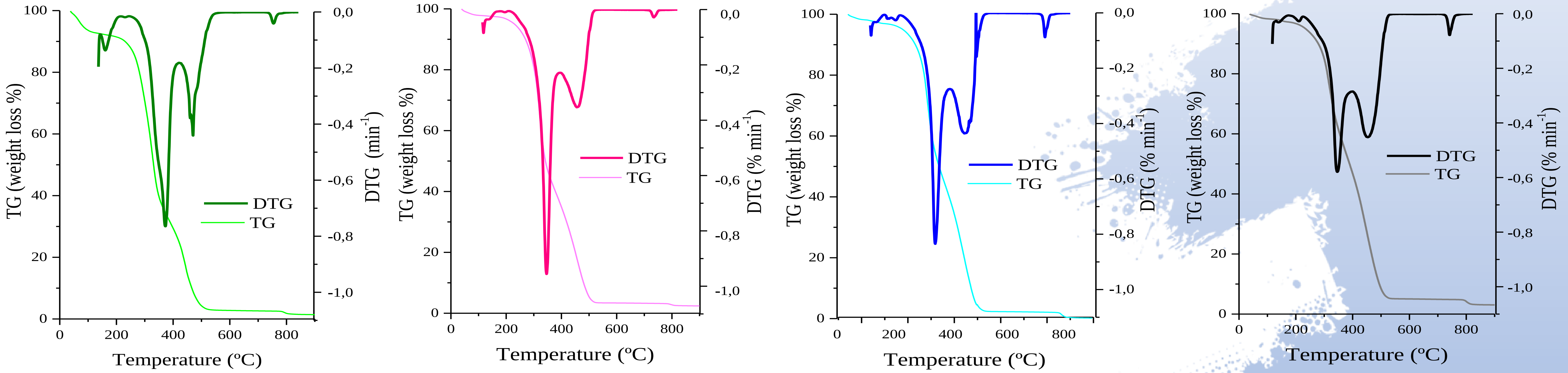

	UPW	HC180	HC210	HC230
T_i (ºC)	239	242	251	254
T_m (ºC)	326	325	318	313
T_b (ºC)	533	528	528	536
CCI·10^{-7} (min^{-2} $ºC^{-3}$)	7.8	8.0	8.4	9.6
Z_i (% min^3)	8.6	10.6	11.4	11.6
H_j (% min^4)	0.2	0.3	0.4	0.4

HC stability in the combustion ↑

$$CCI\ (min^{-2} \cdot {}^{o}C^{-3}) = \frac{(dw/dt)_{max} - (dw/dt)_{mean}}{T_i^2 \cdot T_b}$$

$$Z_i = \frac{(dw/dt)_{max}}{t_i \cdot t_{max}}$$

$$H_j = \frac{(dw/dt)_{max}}{t_b \cdot t_{max} \cdot \Delta t_{1/2}}$$

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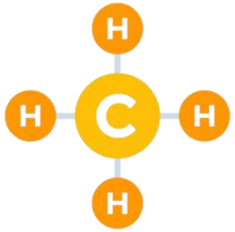
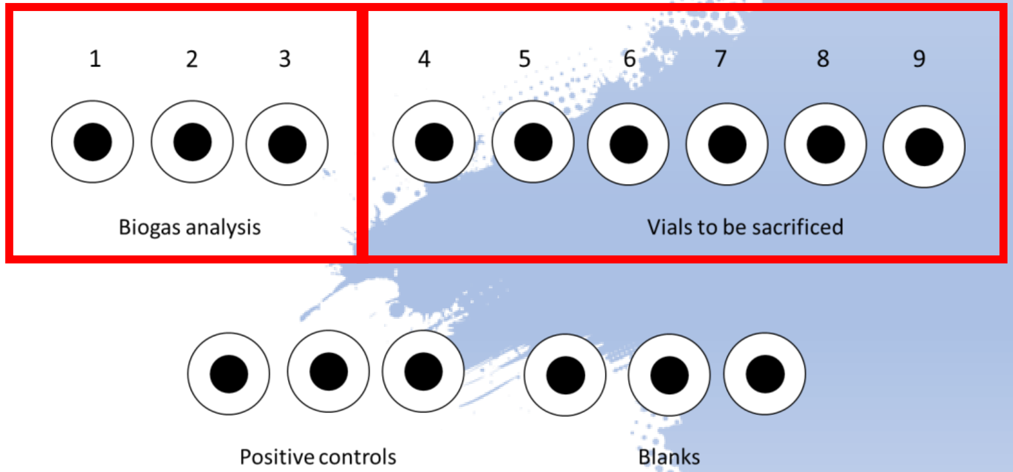
Process water characteristics

	PW180	PW210	PW230
pH	3.5 ± 0.1	3.4 ± 0.1	3.5 ± 0.1
COD (g L^{-1})	51.1 ± 1.3	39.3 ± 0.5	44.9 ± 2.4
TOC (g L^{-1})	21.1 ± 0.1	17.0 ± 0.1	18.4 ± 0.1
TAGV (g L^{-1})	1.5 ± 0.0	0.9 ± 0.0	0.2 ± 0.0
TS (g L^{-1})	30.7 ± 0.3	19.3 ± 0.3	21.6 ± 0.4
VS (g L^{-1})	27.0 ± 0.4	16.1 ± 0.2	18.5 ± 0.3



Biomethane potential test

ISR = 2
- 15 g VS L^{-1} granular anaerobic sludge
- 7.5 g VS L^{-1} substrate



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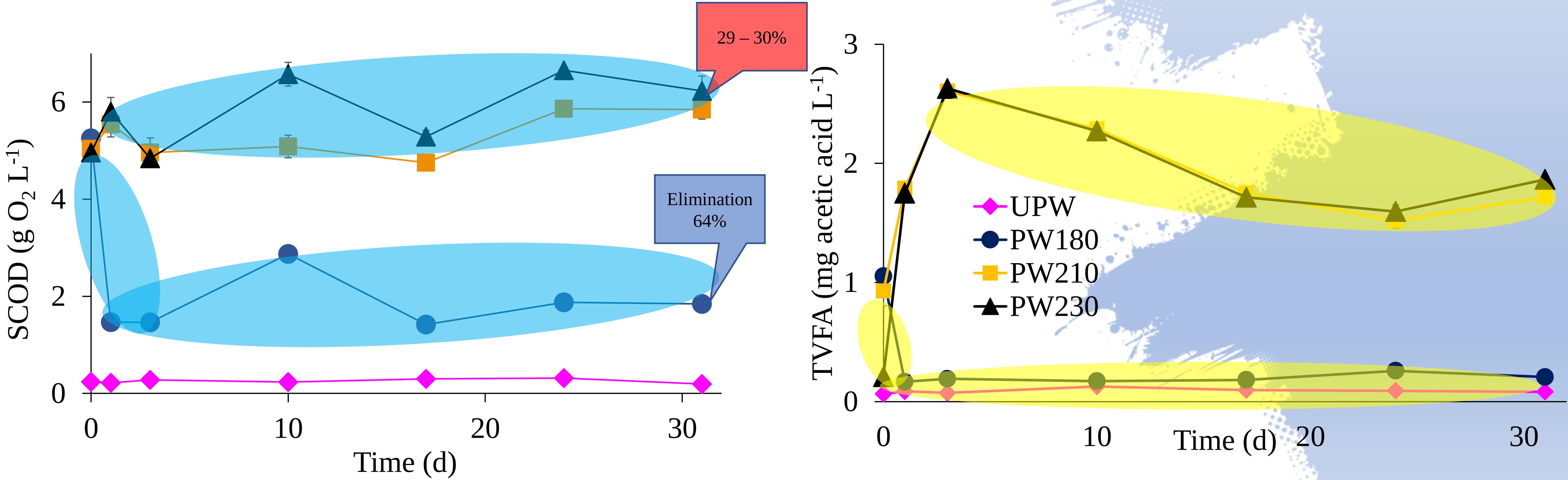
- ✓ pH (7.5 – 7.8)
- ✓ Alkalinity (> 2.5 g $CaCO_3$ L^{-1})
- ✓ Total ammonia nitrogen (1700 mg L^{-1}< inhibition values)

➡ **Adequate for the AD process**

Time-course of total soluble chemical oxygen demand (COD) and volatile fatty acids (VFA)



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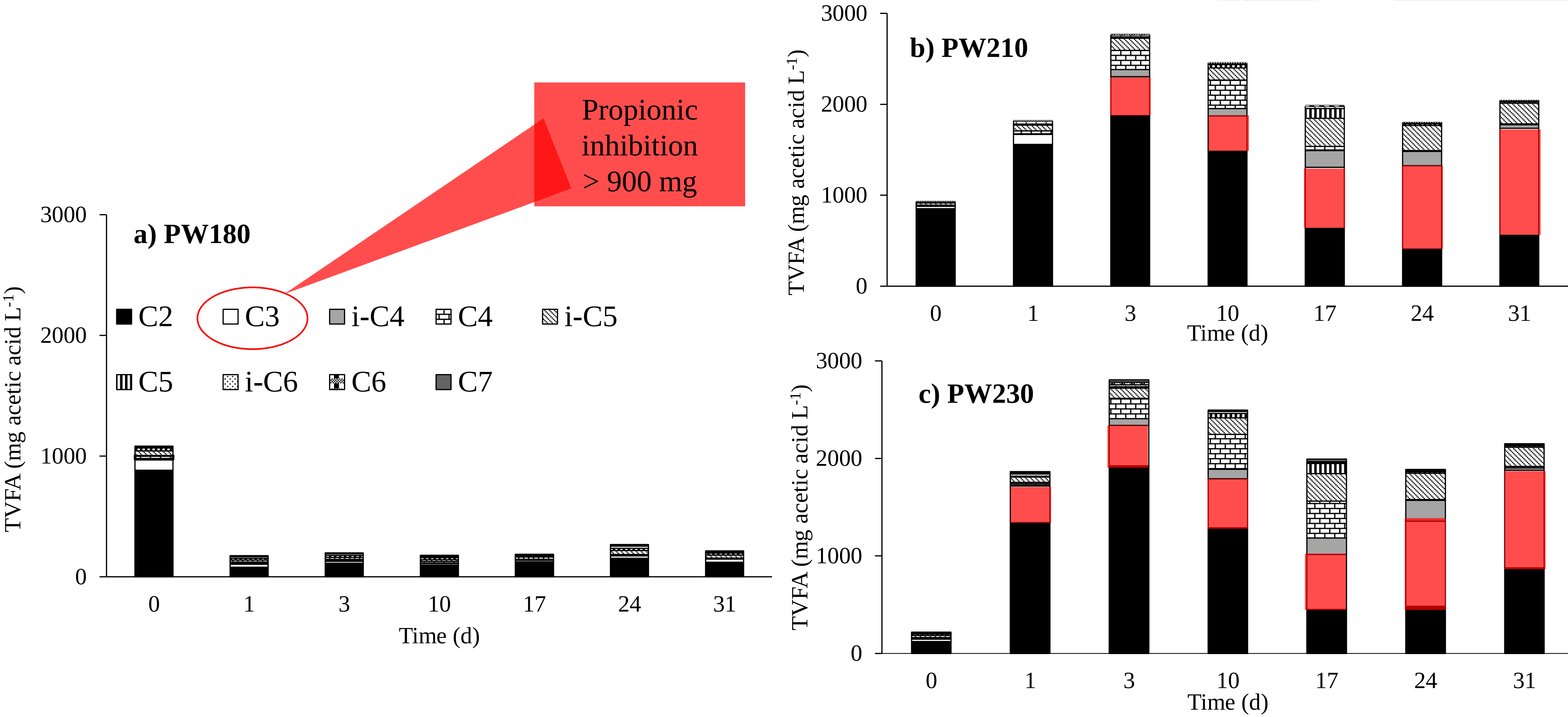
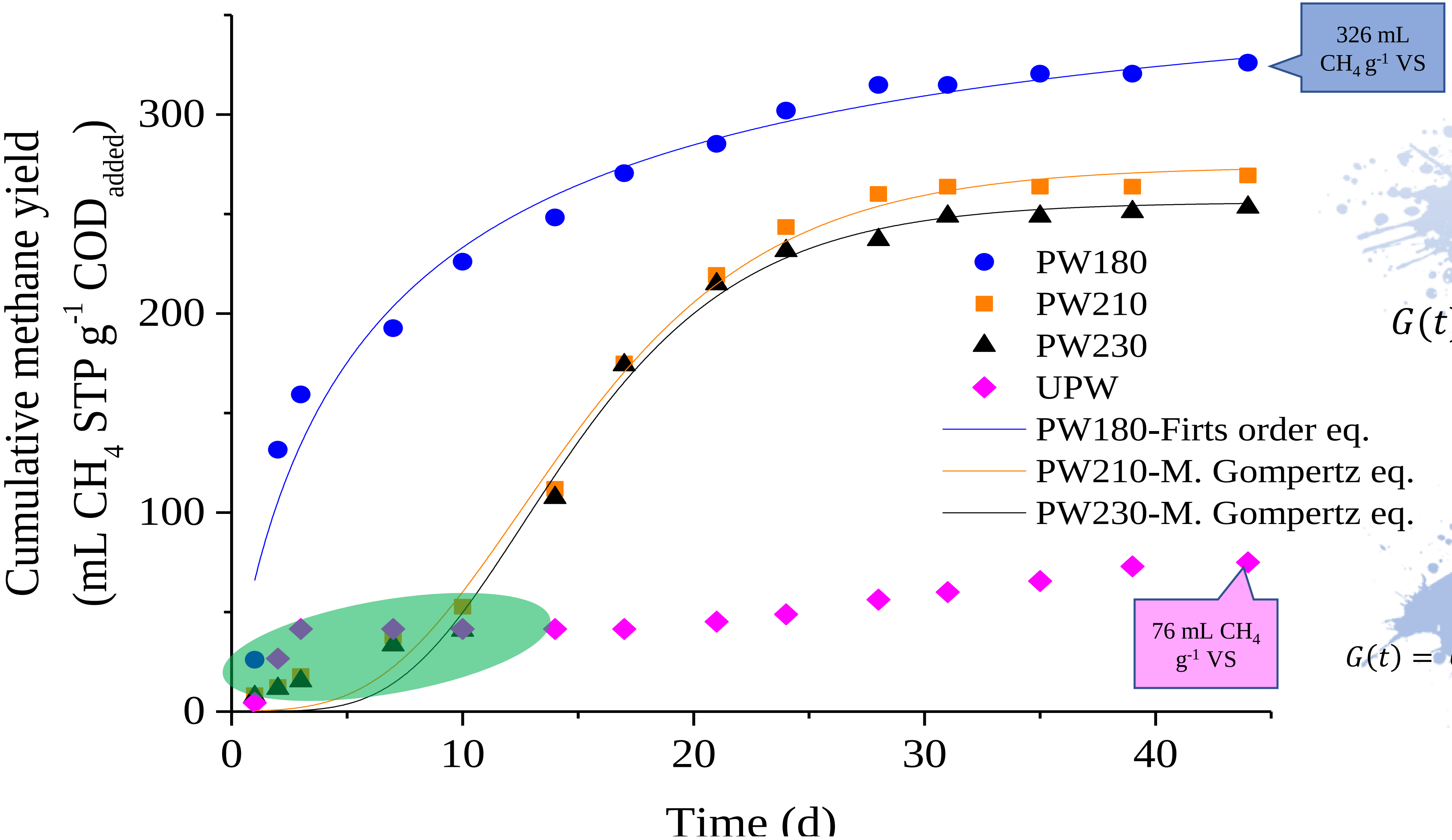


Cumulative methane yield



First order equation

$$G(t) = Gmax\,[1 - exp\,(-k \cdot t)]$$

Modified Gompertz equation

$$G(t) = Gmax \cdot exp[-exp\,(\frac{\mu}{Gmax} \cdot (\lambda - t) \cdot e^{1} + 1)]$$

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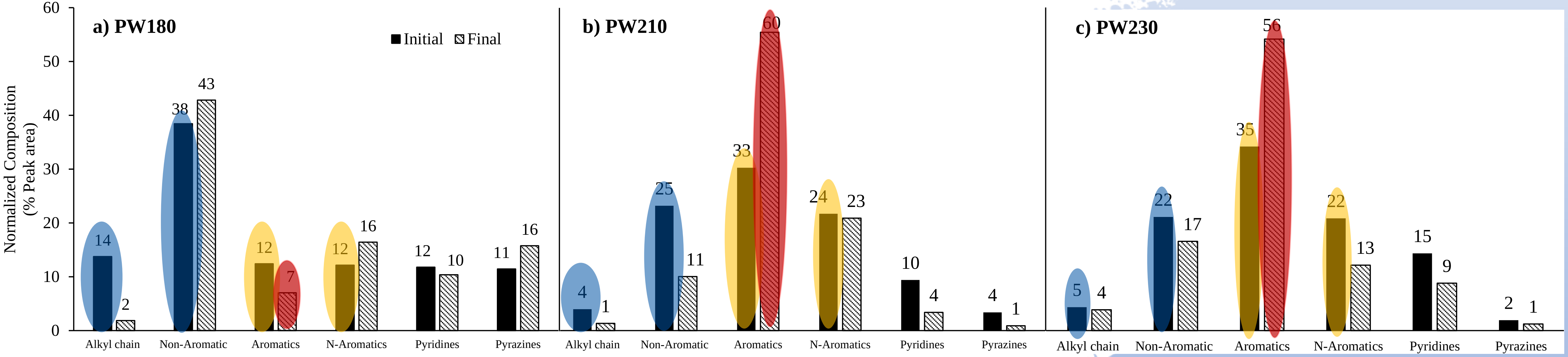
Recalcitrant compounds



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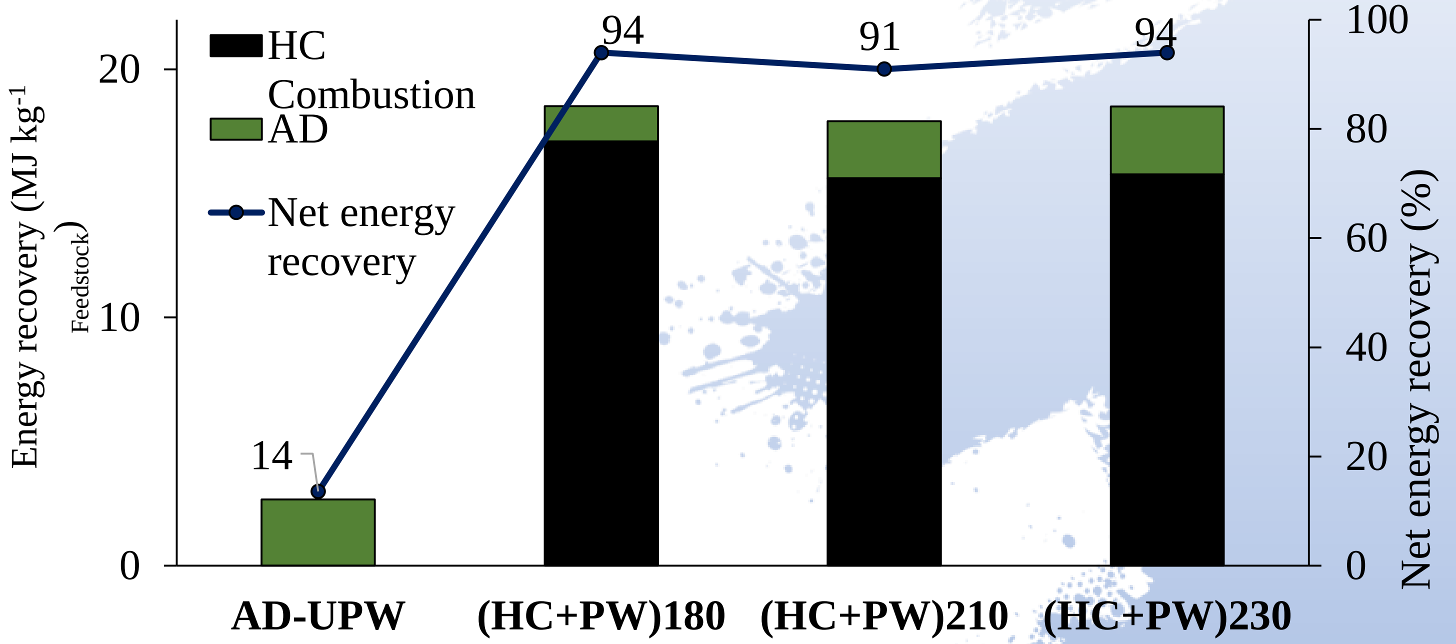
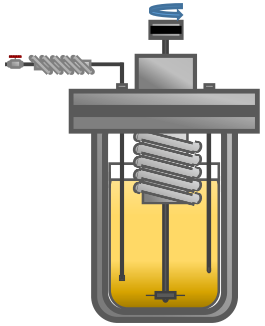
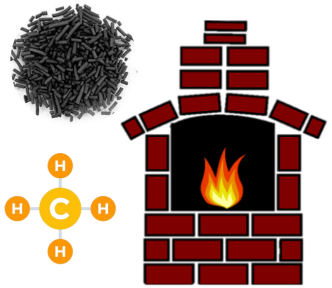
Energy recovery

HC

CH_4







	Energy Input (MJ $t^{-1}_{feddstock}$)	Energy Output (MJ $t^{-1}_{feddstock}$)		
	HTC reactor	**Energy HC**	**Energy CH_4**	**Total output**
HTC180	1311	3627	1414	**5041**
HTC210	1819	3315	2295	**5610**
HTC230	1662	3348	2734	**6082**

Conclusions

- ✓ The HC presents better physicochemical properties than the raw material like higher carbon content (50 – 57%), HHV values (21 – 25 MJ kg^{-1}) and low ash (< 5%), nitrogen (< 1.3%) and sulfur (< 0.2%).

- ✓ The HCs show high stability that together with low ash content prevent fouling and slagging in the boilers.

- ✓ The AD of the PW at low temperatures have higher organic matter elimination yields (up to 65%), while the higher temperatures affect negatively the removal of organic compound due the high recalcitrant organic compounds content.

- ✓ The energy balance shows the possibility of integrating these two processes with high energy recovery yields (91 – 94%).

- ✓ The energy obtain for the combustion of HCs and methane is 3 times greater than the energy required to carry out the entire proposed process

- ✓ Coupling thermochemical and biological processes (HTC + AD) could open new avenues to produce renewable energy with higher energy recovery's and higher organic matter removal and promote the development of a circular economy with zero waste.

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Thank you

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“The earth is a fine place and worth fighting for”

Ernest Hemingwag