Food Waste Biorefinery as Sustainable and Alternative Energy Sources

SEEEP PhD Summer School 2022

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Global Food Waste Status

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- **1/3** of produced food = **4.4 Gt** CO_2/year

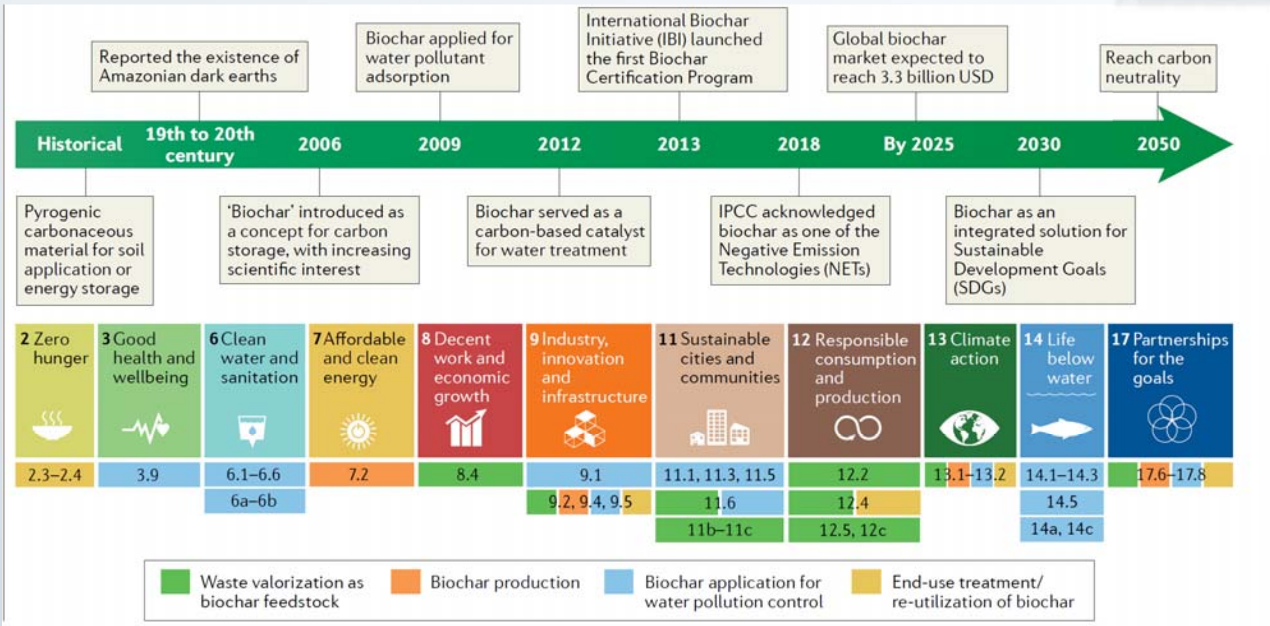
Food Waste

Thermochemical Treatment

- **Energy substitution**
- **Soil amendment**
- **Adsorbent/Catalyst support**
- **CO_2 adsorption, etc.**

Waste-derived Biochar for Sustainable Development

- **Biochar:**
  - A type of partially combusted **biomass**
  - A promising and carbon-negative solution
- Engineered biochar:
  - Contribute to at least **11 of 17 Sustainable Development**



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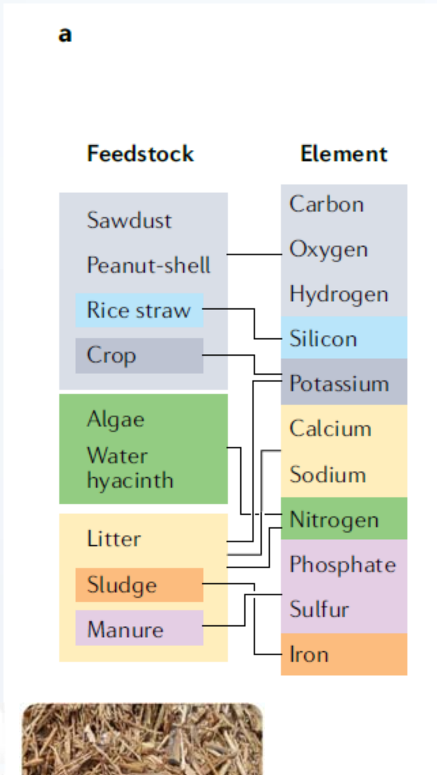
Engineered Biochar – Feedstock Properties

- **Feedstocks:**
  - Major composition:
    - **C, H, and O** for biochar carbon structure and functional groups
  - Other elements:
    - **Alkali and alkaline earth metals (AAEMs):** facilitate deoxygenation
    - **Fe:** metal chelation, redox activity, electron mediation, sorption, etc.
    - **S:** catalytic degradation
    - **Si:** metal sorption
    - **N:** redox reaction or sorption
    - **P:** metal ion precipitation



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Engineered Biochar – Pyrolysis Temperature

- Increase pyrolysis temperature:
  - Carbon:
    - From aliphatic and amorphous to aromatic and graphitic
  - Other elements:
    - From mineral salts to oxides or even elemental form

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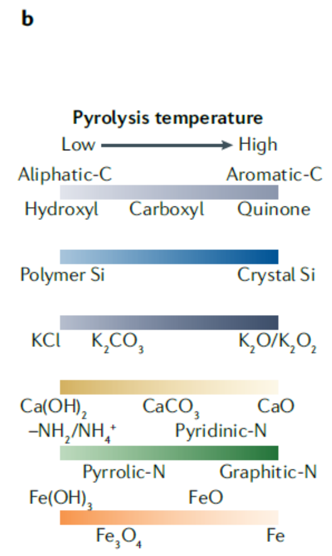

c

Reactive moieties	Application
Carbon surface	Sorption, carbon stability
O-moiety	Nutrient recycling, metal chelation, redox activity electron mediation, sorption, catalytic degradation
Carbon defects	Redox activity, catalytic degradation
OH^-	Precipitation
CO_3^{2-}	Precipitation
Aromatic-C	Electron mediation, catalytic degradation
Mn mineral	Redox activity
Ca mineral	Nutrient recycling, cation exchange
NH_4^+/NO_3^-	Nutrient recycling
Doped N	Catalytic degradation
PO_4^{3-}	Nutrient recycling, precipitation
SO_4^{2-}	Precipitation
Doped S	Catalytic degradation
Fe hydroxide	Metal chelation, redox activity, electron mediation, sorption
Fe(0)	Redox activity, electron mediation, catalytic degradation

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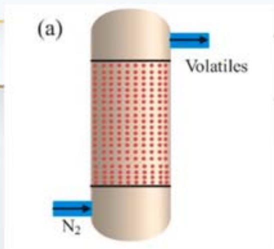
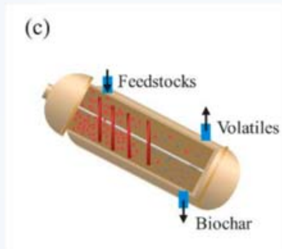
Engineered Biochar – Typical Reactors

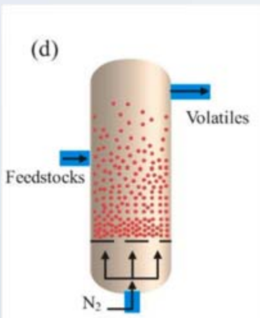


Fixed Bed
- Small-scale production
- Poor heat & mass transfer

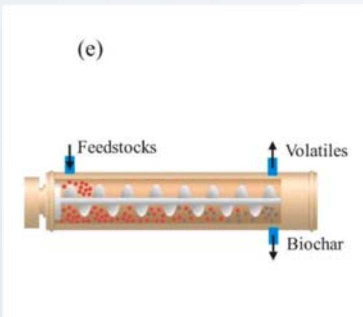
Earthen Kiln
- Traditional method
- Difficult to control with long residence time



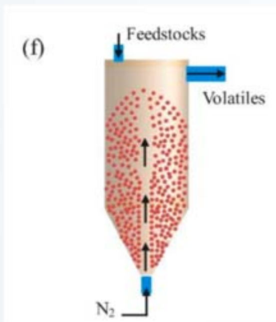
Rotary Kiln
- Simple design and operation
- Low heat efficiency



Fluidized Bed
- Good heat transfer with gas-solid uniformity
- Complex operation and expensive



Auger Reactor
- Adjustable pyrolysis speed with good heat transfer
- Complex design



Spouted Bed
- Good heat transfer with gas-solid uniformity
- Feasible for irregular shape
- Low biochar yield

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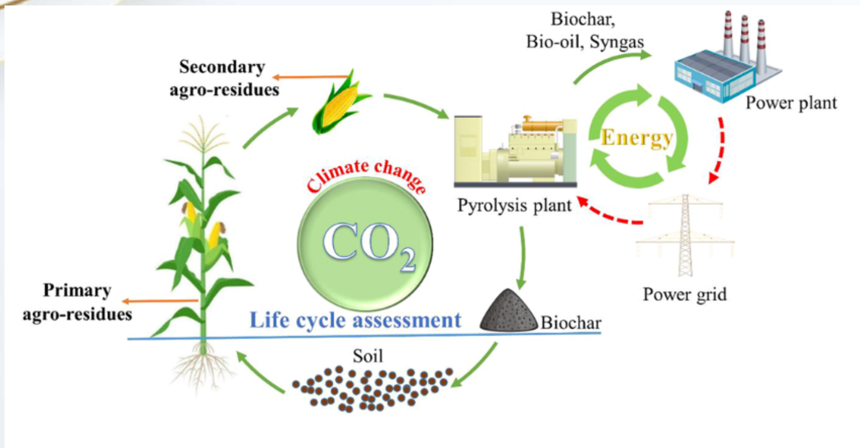
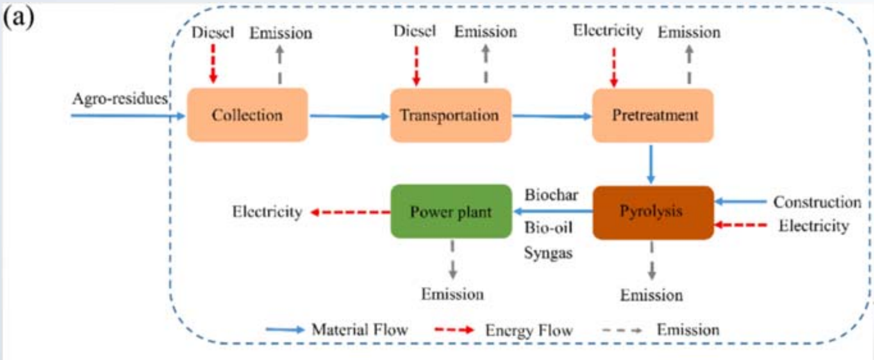
Biochar – A Net Carbon Management Strategy (1)

- **Pyrolysis of biomass**
  - Produce & customize **fit-for-purpose engineered biochar**
  - Co-generation of renewable energy



Biochar as an alternative energy source



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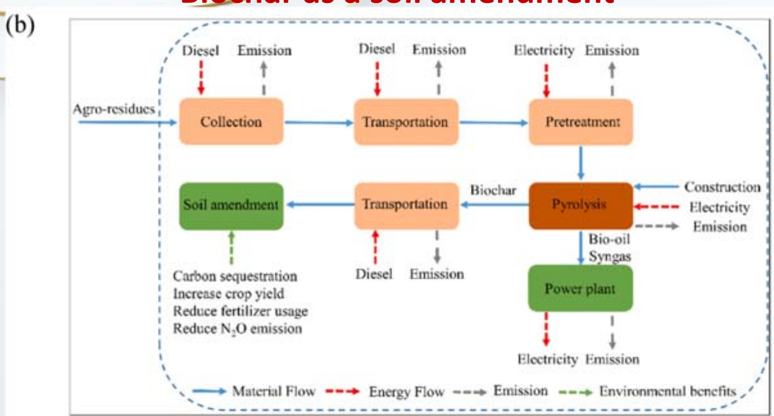
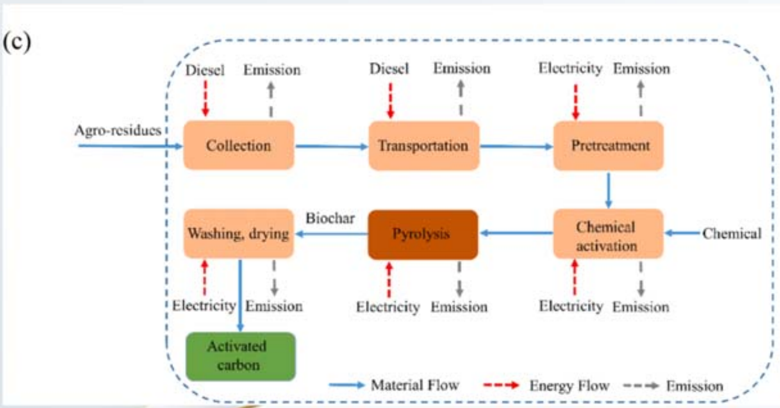
Biochar – A Net Carbon Management Strategy (2)

Biochar as a soil amendment



Biochar as an adsorbent (substitute of activated carbon)



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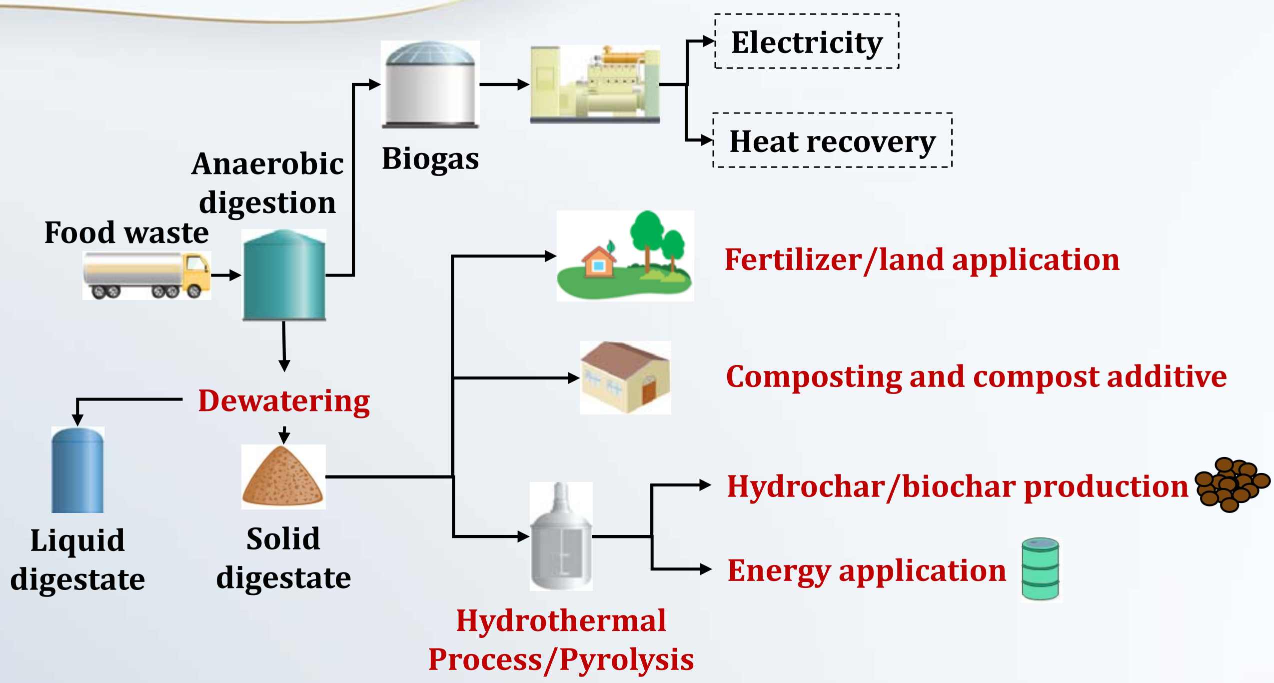
Generation of Food Waste Digestate



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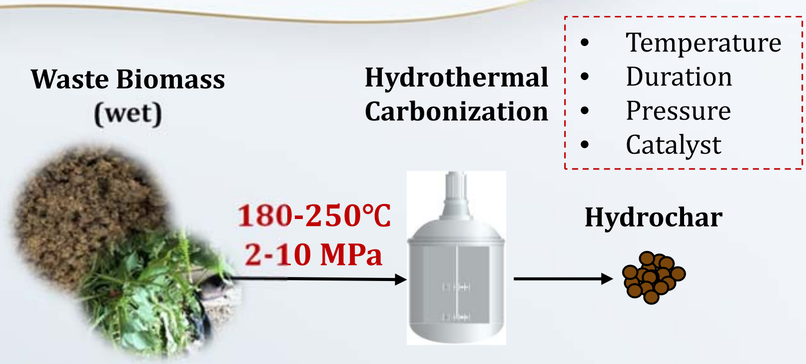
Hydrothermal Carbonization for Wet Biomass



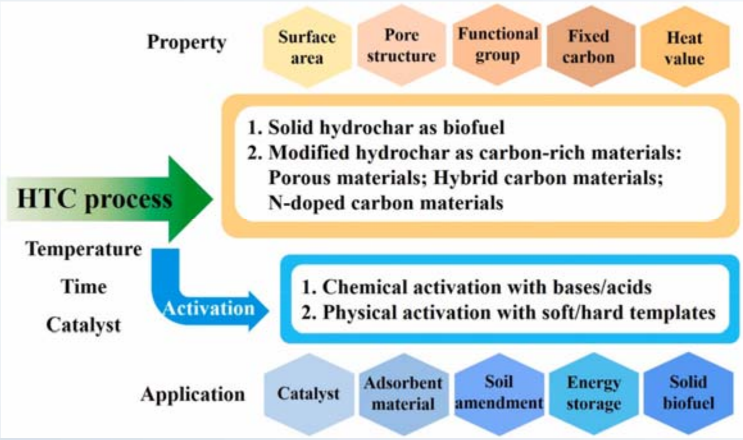
- ✓ **Carbon neutrality**
  - No pre-drying
  - Nutrient recovery
  - Carbon stabilization
- ✓ **Energy densification**
- ✓ **Easy handling**
  - Volume reduction
  - Better dewaterability
  - Sanitation
- ✓ **Organic pollutants decomposition**, etc.

Bench-scale Hydrothermal Reactor

Industry-scale Hydrothermal Reactor

He, M., Zhu, X., Dutta, S., Khanal, S. K., Lee, K. T., Masek, O., & **Tsang, D. C. W.*** (2022). Catalytic co-hydrothermal carbonization of food waste digestate and yard waste for energy application and nutrient recovery. ***Bioresource Technology***, *344, 126395.* ***[Journal Cover]***

Multifunctional Hydrochar



Cao, Y., He, M., Dutta, S., Luo, G., Zhang, S., & **Tsang, D. C. W.*** (2021). Hydrothermal carbonization and liquefaction for sustainable production of hydrochar and aromatics. ***Renewable & Sustainable Energy Reviews***, *152, 111722.*

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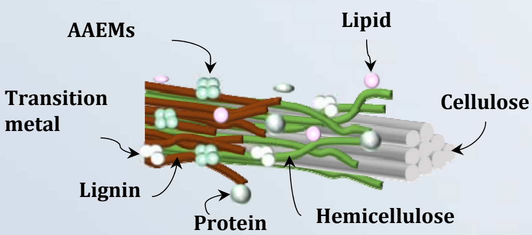
Digestate-derived Hydrochar

Feedstock	HTC conditions	HHV [MJ/kg]	Ash content [wt.%]	Reference
Food waste digestate	Raw feedstock	15.2	26.3	(Zhang et al., 2021)
	180 ℃; 60 min	13.3	45.0	
	200 ℃; 60 min	13	54.2	
Sewage sludge digestate	Raw feedstock	14.4	36.7	(Aragón-Briceño, 2020)
	250 ℃; 30 min (2.5% loading rate)	15.4	51.2	
	250 ℃; 30 min (10% loading rate)	15.8	48.4	
	250 ℃; 30 min (30% loading rate)	16.5	48.5	
Food waste digestate	Raw feedstock	13.2	30.5	Our study
	250 ℃; 120 min (10% loading rate)	13.9	47.7	

Conceptual structure:
Digestate or sludge biomass



Poor energy performance because:

- High moisture content
- Less recalcitrant carbon
- Less degradable bacterial cells
- Nutrient & protein-rich
- High ash content

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Co-HTC of Food Waste Digestate and Wet Yard Waste

Feedstock	Proximate analysis (wt.%)			Composition (wt.%)		
	VM	FC	Ash	Hemicellulose	Cellulose	Lignin
Food waste digestate	65.7	3.8	30.5	9.4	7.2	12.2
Brown yard waste (Fallen leaves)	74.1	13.3	12.6	6.1	21.0	**30.2**

Feedstock	HTC conditions	HHV [MJ/kg]	Ash content [wt.%]	Reference
Food waste digestate	Raw feedstock	13.2	30.5	Our study
	250 ℃; 120 min (10% loading rate)	13.9	47.7	
Yard waste	Raw feedstock	16.7	12.6	
	250 ℃; 120 min (10% loading rate)	20.7	20	
FWD + YW (1:1)	250 ℃; 120 min (10% loading rate)	18.9	33.4	

Improvement by co-HTC with lignocellulosic biomass is limited

Role of Lignin:

- Solid particle bridging
- Interlock bulking particles
- Energy barrier → less volatile carbon

Ash content ↓

Energy value ↑

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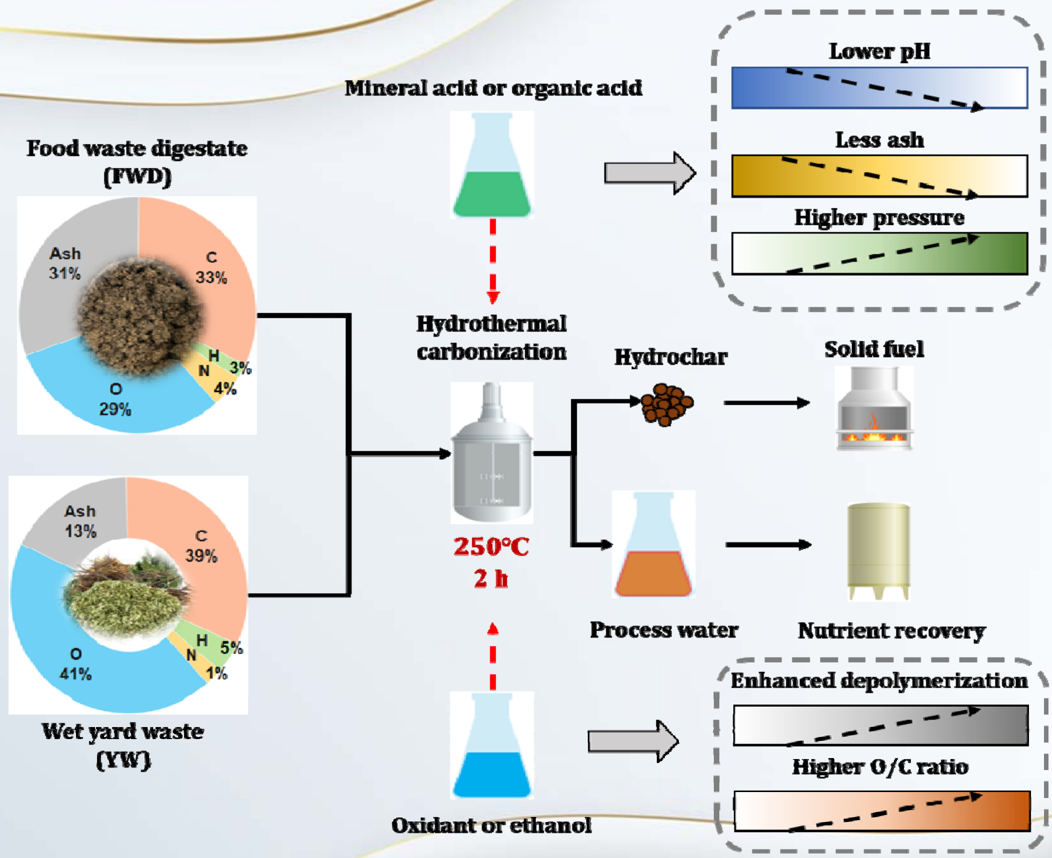
Catalytic Co-HTC for Energy Recovery



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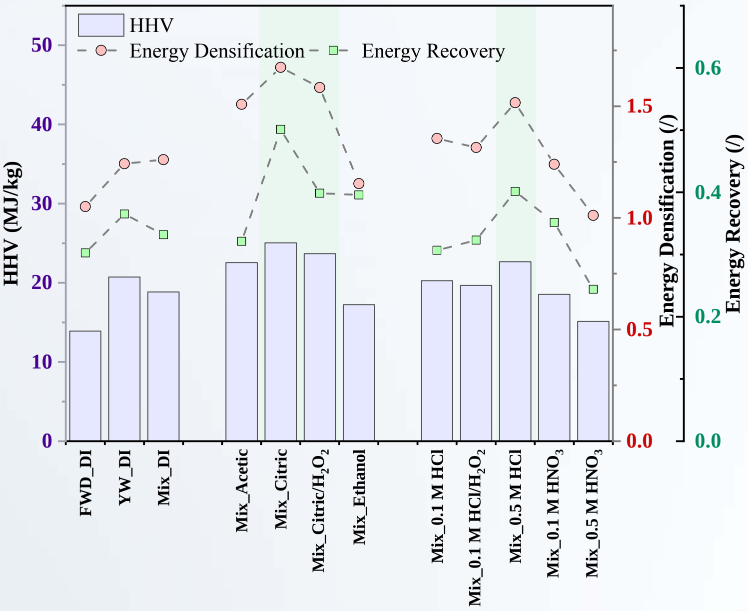
Energy Properties of Catalytic Co-HTC Hydrochar

Sample	DTG_m (% min^{-1})	DTG_{mean} (% min^{-1})	CCI (10^{-7} $\%^2$ min^{-2} ℃$^{-3}$)	R_w (10^3)
FWD_DI	8.6	1.2	2.2	9.3
YW_DI	11.4	1.8	9.6	11.9
Mix_DI	9.6	1.6	3.8	9.6
Mix_Acetic	9	1.6	5.9	9.3
Mix_Citric	9.2	1.8	15	13.2
Mix_Citric/H_2O_2	9	2	16.2	12.9
Mix_Ethanol	8.4	1.4	2.9	8.5
Mix_0.1 M HCl	9.8	1.6	6.2	10.3
Mix_0.1 M HCl/H_2O_2	9	1.6	4.2	9.6
Mix_0.5 M HCl	15.6	1.8	14.2	18.1
Mix_0.1 M HNO_3	13.6	1.6	5.4	17.3
Mix_0.5 M HNO_3	7.6	1.4	2.2	6.8



CCI: Comprehensive combustion index
R_w: Combustion stability index

Acid-catalytic HTC:
Combustion performance
Energy recovery & HHV ↑

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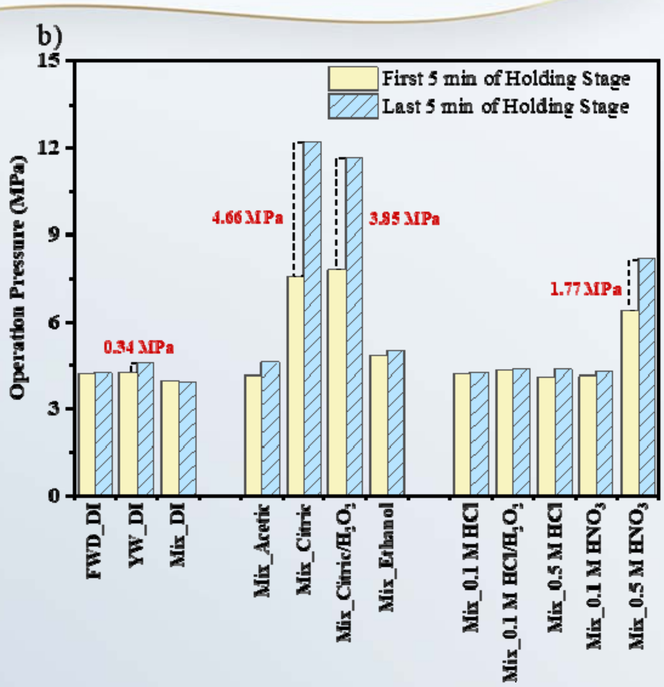
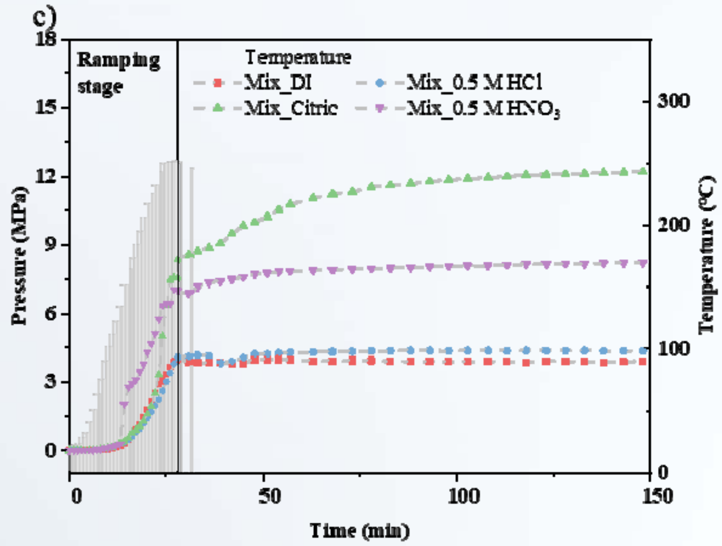
Operating Pressure of Catalytic Co-HTC Hydrochar





- Saturation pressure of water at 250 ℃ = 4.0 MPa
- Thermal decomposition:
  - Citric acid → CO_2 (175−250 ℃)
  - HNO_3 → NO_2

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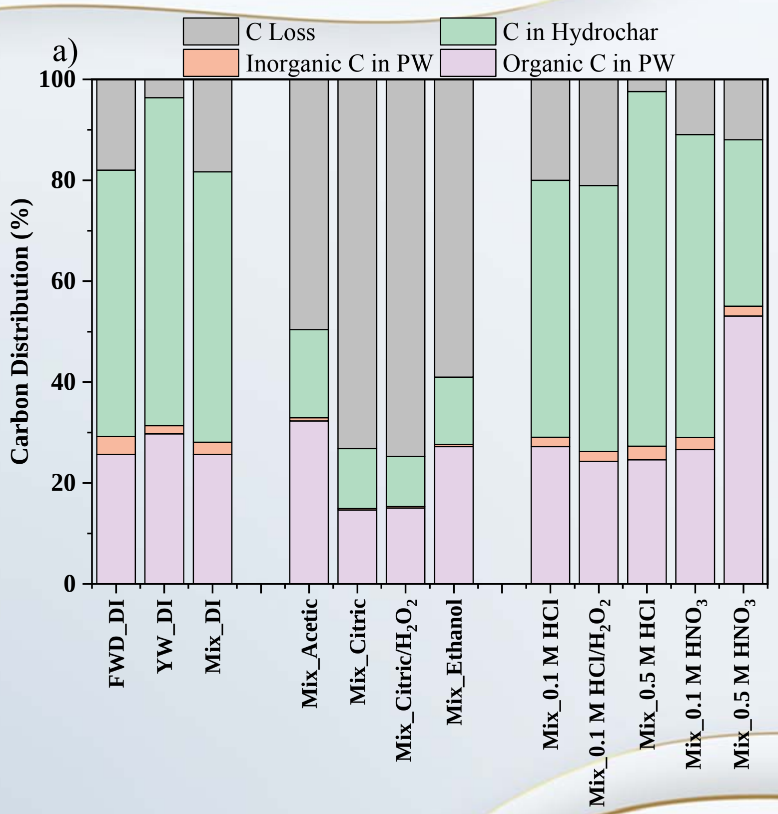
Carbon Balance of Catalytic Co-HTC Hydrochar



Labile carbon

→ Gaseous products (*e.g.,* CO_2, VOCs)

→ Higher pressure but higher C loss

YW_DI: **3.6%** C loss

Mix_DI: **18.0%** C loss

…

Mix_Citric: **74.0%** C loss

Mix_0.5 M HCl: 2.4% C loss

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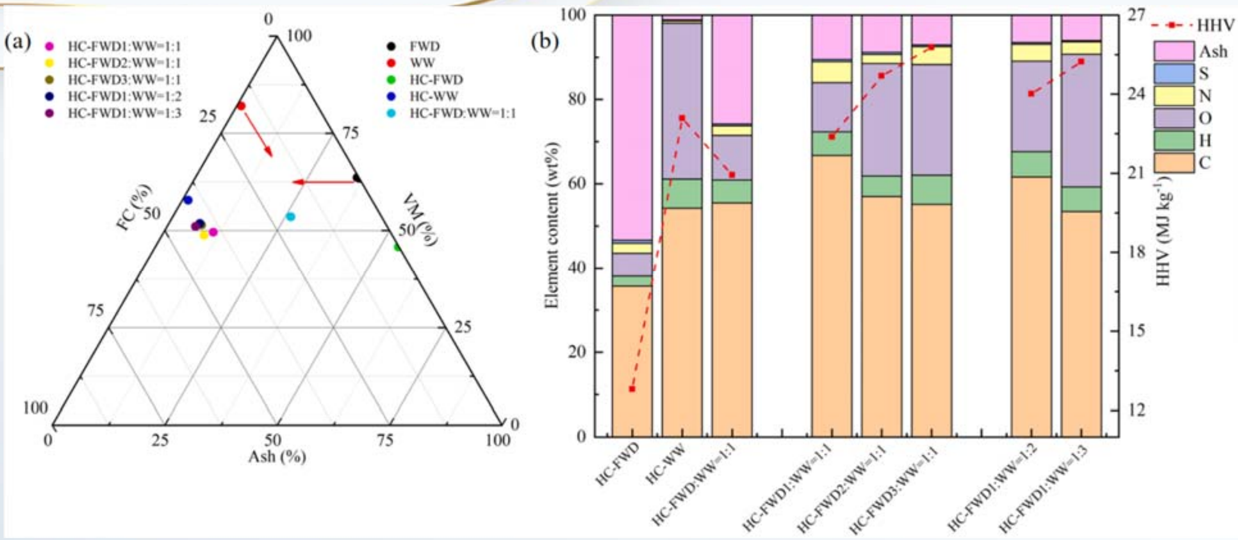
Acid Pretreatment & Co-HTC

Food waste digestate ❯ 1 M HCl solution; 8 h 1-3 times ❯ Washed by DI water Dried at 60 ℃ ❯ Co-HTC with wet yard waste

Acid demineralization → Lower ash content → Improve energy performance

Zhu, X., He, M., Xu, Z., Luo, Z., Gao, B., Ruan, R., Wang, C.-H., Wong, K.-H., & **Tsang, D. C. W.*** (2022). Combined acid pretreatment and co-hydrothermal carbonization to enhance energy recovery from food waste digestate. ***Energy Conversion and Management***, *266, 115855.*

Acid Pretreatment for Enhanced Energy Recovery



One time of acid pretreatment
- Remove ash
- Promote depolymerization

→ Effectively increase carbon content

Repeat 2-3 times of acid pretreatment
- Hinder dehydration & decarboxylation
- Remove dissolved carbon

→ A decrease of carbon content

3 times of acid pretreatment + co-HTC

→ HC-FWD3:WW=1:1 (HHV = 25.8 MJ kg^{-1};~3-fold of HC-FWD)

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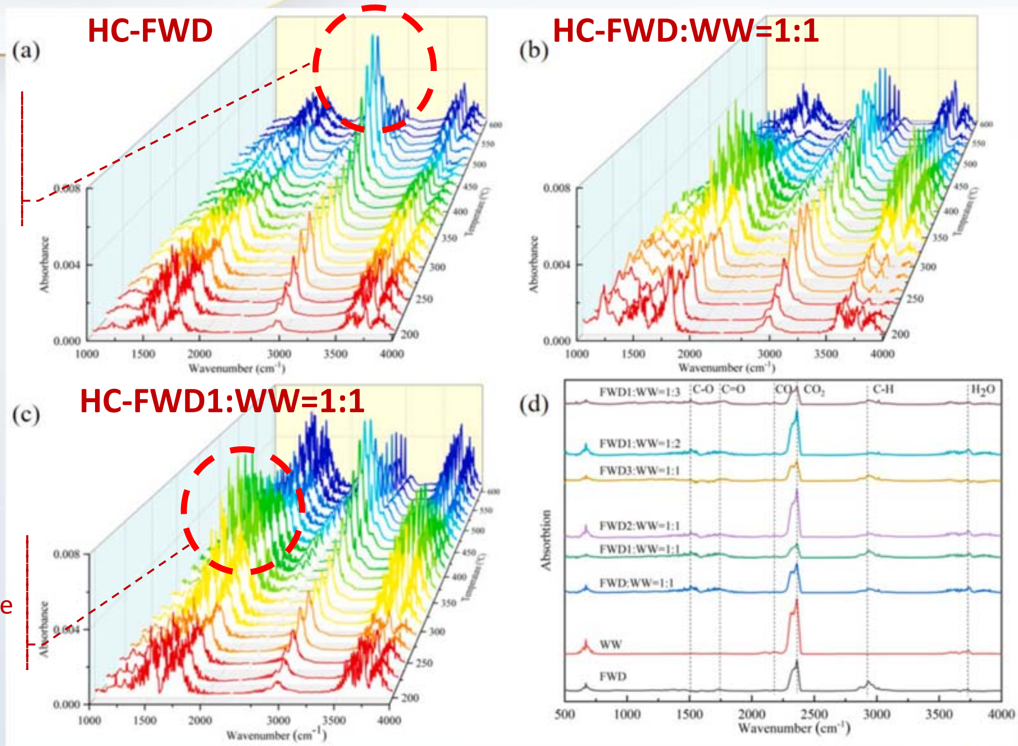
Acid Pretreated Hydrochar – Evolved Gas Analysis

C-H stretching at 500 ℃
- Abundant combustible organics
- Contributor of combustion process

Peak at 300-400 ℃
- Decomposition of cellulose from yard waste



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Acid Pretreated Hydrochar – Combustion Kinetics

Combustion kinetic parameters of the hydrochar.

($kJ\ mol^{-1}$)	α	HC-FWD	HC-WW	HC-FWD: WW = 1:1	HC-FWD1: WW = 1:1	HC-FWD2: WW = 1:1	HC-FWD3: WW = 1:1	HC-FWD1: WW = 1:2	HC-FWD1: WW = 1:3
FWO	0.1	129.61	80.03	141.68	87.82	81.77	63.93	41.48	38.22
	0.2	138.00	108.14	124.57	155.66	108.14	100.11	124.58	116.44
	0.3	138.51	106.42	136.31	131.22	107.75	101.55	128.51	112.57
	0.4	130.88	108.87	143.93	120.30	108.16	102.61	121.58	109.34
	0.5	133.85	112.42	128.94	121.39	112.53	106.29	123.08	111.08
	0.6	144.43	117.01	117.65	126.74	116.16	109.51	125.08	112.33
	0.7	154.96	120.78	109.98	128.62	115.69	110.00	123.19	111.95
	0.8	169.09	125.45	107.07	125.54	115.95	111.23	121.40	113.26
	0.9	163.88	128.70	119.26	119.59	120.35	113.09	120.12	112.98
	Average (E_a)								
KAS	0.1	121.51	71.06	133.05	78.94	73.07	55.32	33.08	29.22
	0.2	128.47	97.53	114.50	145.35	97.84	89.82	114.35	105.91
	0.3	128.46	95.21	125.78	120.28	96.82	90.63	117.64	101.42
	0.4	120.51	97.13	133.05	108.81	96.66	91.14	110.17	97.68
	0.5	123.22	100.21	117.71	109.45	100.57	94.37	111.24	98.97
	0.6	133.59	104.42	106.07	114.46	103.85	97.22	112.89	99.84
	0.7	143.87	107.86	98.02	116.00	103.07	97.37	110.66	99.08
	0.8	157.61	112.24	94.75	112.55	102.97	98.23	108.44	99.97
	0.9	151.28	115.20	106.51	106.15	106.90	99.64	106.65	99.23
	Average (E_a)								

Lower E_a → Less energy required to start combustion

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HTC Process Water Recirculation

Process water of catalytic HTC process:

- High concentration of intermediates
- Residual catalyst

He, M., Cao, Y., Xu, Z., You, S., Ruan, R., Gao, B., Wong, K.-H., & **Tsang, D. C. W.*** (2022). Process water recirculation for catalytic hydrothermal carbonization of anaerobic digestate: Water-Energy-Nutrient Nexus. ***Bioresource Technology***, *361, 127694.*

Possible Key Pathways of HTC Process for FWD

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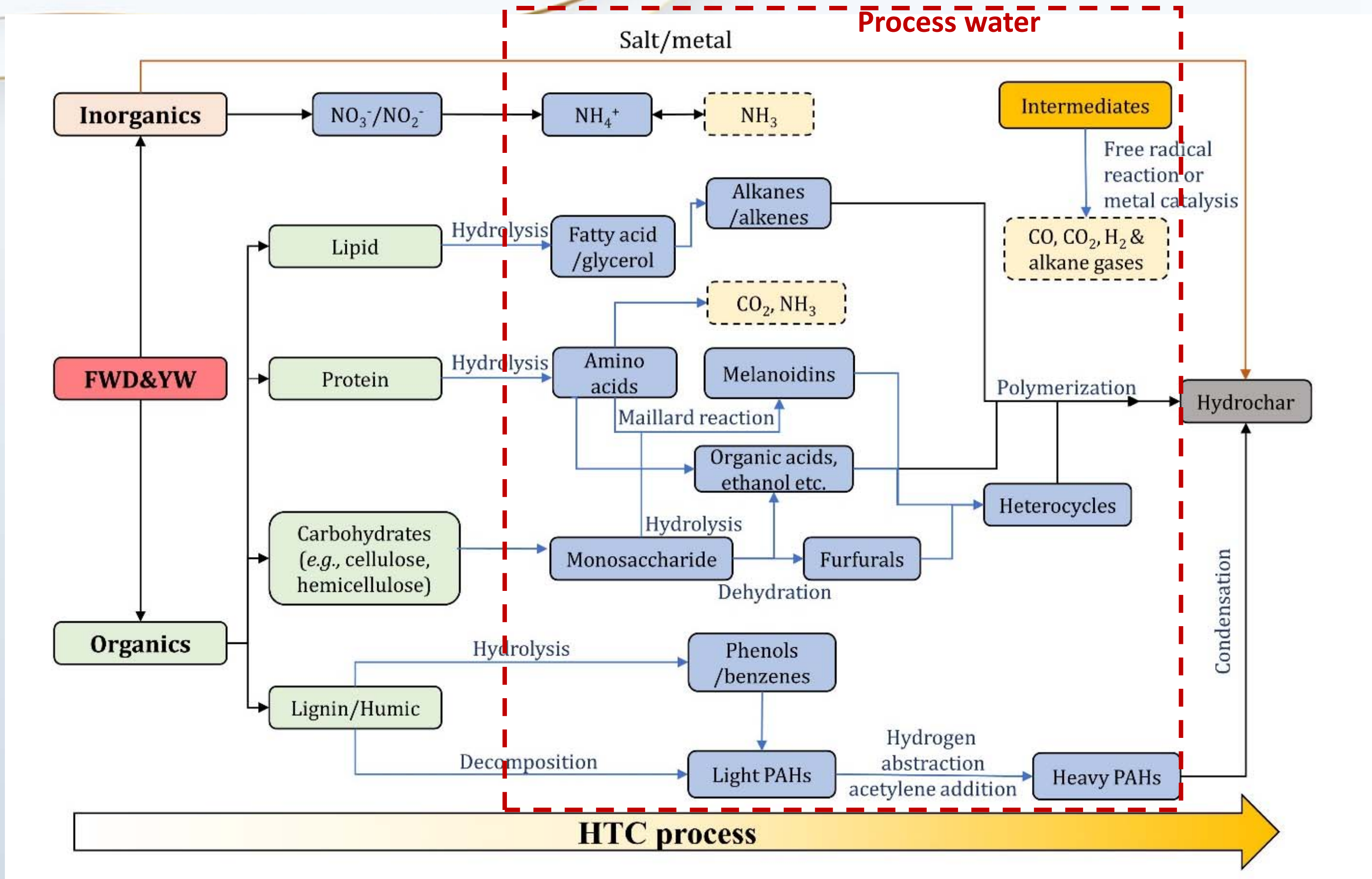

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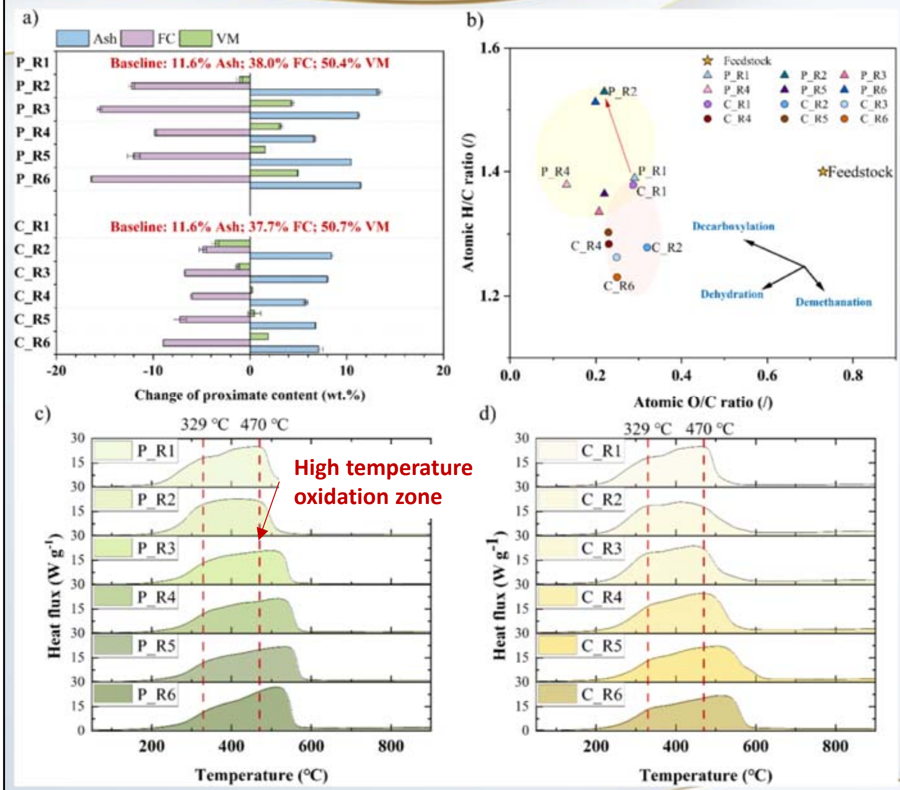


Recirculate process water:

Lower fixed carbon and higher volatile matter

- Presence of AAEMs
  - Weaken the aromatization and stability of hydrochar
  - More activated radicals for accelerated hydrolysis

Increase the recirculation cycles:

No significant change on hydrochar ultimate and proximate properties

- Affected by PW pH
- Due to the formation of hydrophilic shell

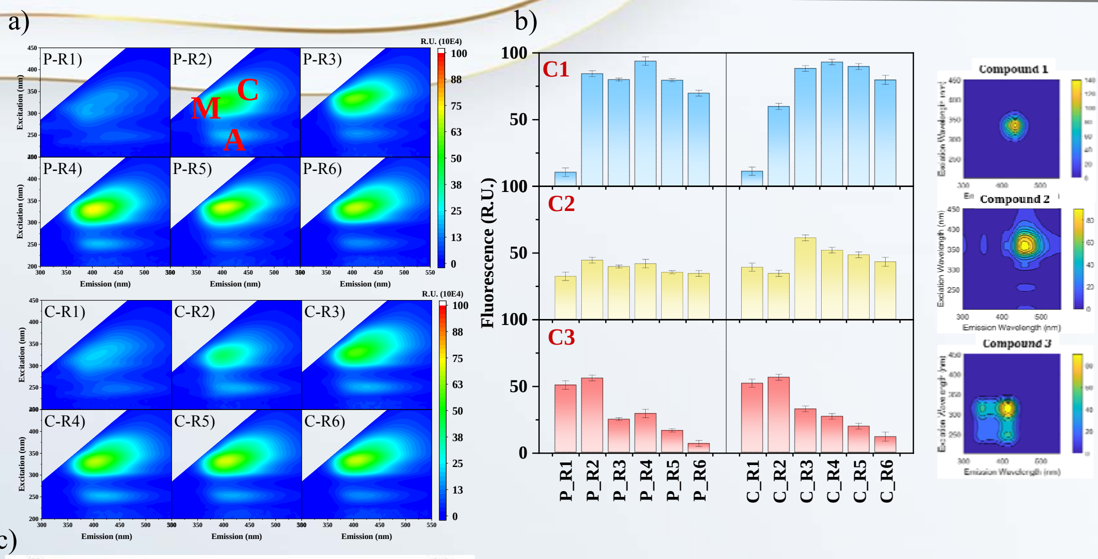
Recirculate process water:

Delay of combustion HTO zone

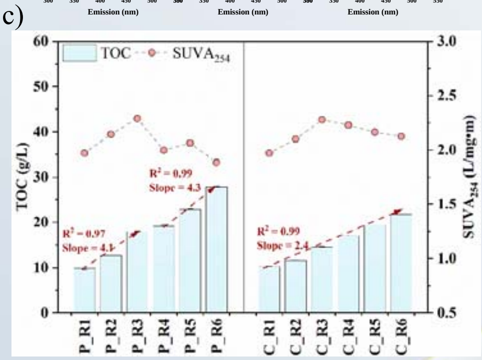
- Accumulation of ash
  - More resistant to combustion

He, M., Cao, Y., Xu, Z., You, S., Ruan, R., Gao, B., Wong, K.-H., & **Tsang, D. C. W.*** (2022). Process water recirculation for catalytic hydrothermal carbonization of anaerobic digestate: Water-Energy-Nutrient Nexus. ***Bioresource Technology***, *361*, 127694.

Intermediates Accumulation by Process Water Recirculation



c)



- **Increase recirculation times:**
  - Accumulation of humic acid-like substance
  - C1: Breakdown compounds of lignin
  - C2: UVA humic-like substances, larger molecular size and aromaticity
  - C3: presence of aromatic hydrocarbons in process water

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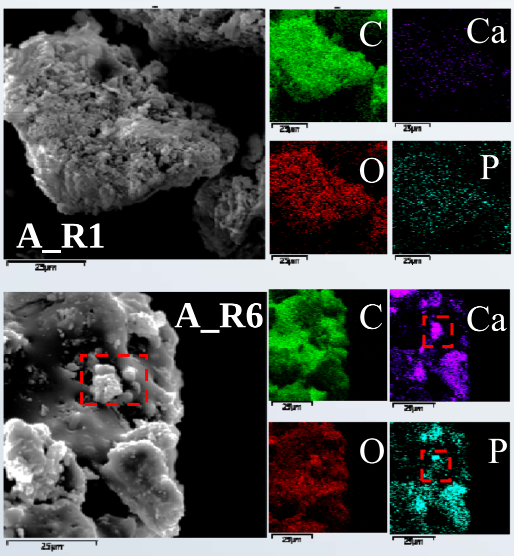
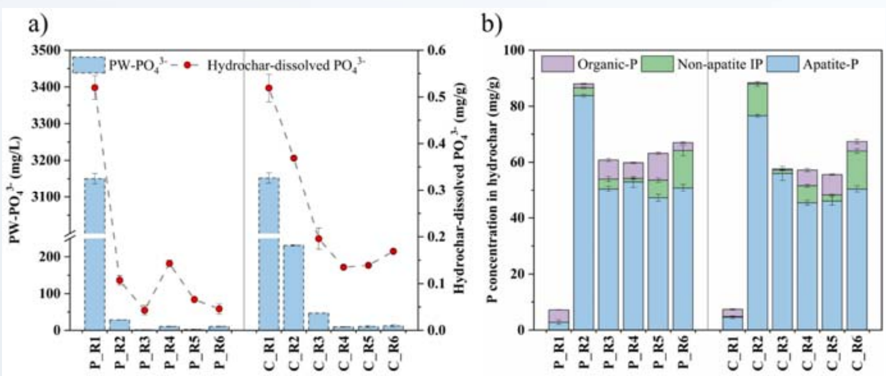
Process Water Recirculation for Nutrient Recovery

Accumulated Ca could precipitate with phosphate ion – Ca-P deposit (apatite phosphorus)





Increase the recirculation cycles:

Achieve > 93% P recovery

→ Ca-P deposit (e.g., hydroxyapatite, a slow-release fertilizer)

He, M., Cao, Y., Xu, Z., You, S., Ruan, R., Gao, B., Wong, K.-H., & **Tsang, D. C. W.*** (2022). Process water recirculation for catalytic hydrothermal carbonization of anaerobic digestate: Water-Energy-Nutrient Nexus. ***Bioresource Technology***, *361, 127694.*

Partnership for Successful Application

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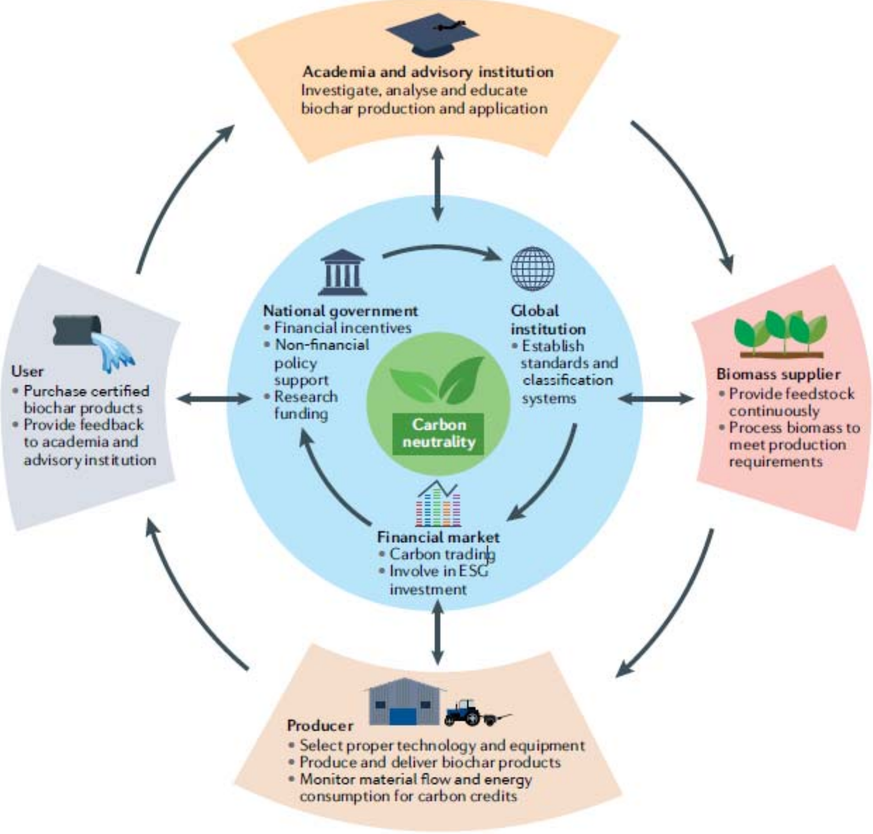

Primary stakeholders:
- National and regional government
- Global institutions
- Financial markets

Secondary stakeholders:
- Academia and advisory institutions
- Biomass supplier
- Biochar producers
- Biochar users

He, M., Xu, Z., Hou, D., Gao, B., Cao, X., Ok, Y. S., Rinklebe, J., Bolan, N. S., & **Tsang, D. C. W.*** (2022). Waste-derived biochar for water pollution control and sustainable development. ***Nature Reviews Earth & Environment***, *3, 444-460.*

Take-home Messages

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- Biochar performance in the climate-energy-carbon nexus is governed by its properties: **engineered by feedstocks and production conditions**
- Pyrolyzing waste biomass (e.g., food waste) into biochar as an alternative energy source is a promising technology for **net carbon management**
- **Sustainable management of FWD** is essential to close the resource loop and actualize circular economy
- Acid catalytic co-HTC of FWD with wet lignocellulosic biomass (e.g., wet yard waste) exhibited overall superior energy recovery and combustion performance **with minimal carbon loss**
- Combining acid pretreatment and co-HTC can enhance the fuel properties with **enhanced thermal stability and pyrolysis gas products**
- Recirculating HTC process water could valorize Ca-rich FWD into **multifunctional hydrochar** for both energy and nutrient recovery


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