Performance of Anaerobic Digestion with Hydrothermally Treated Municipal Sludge

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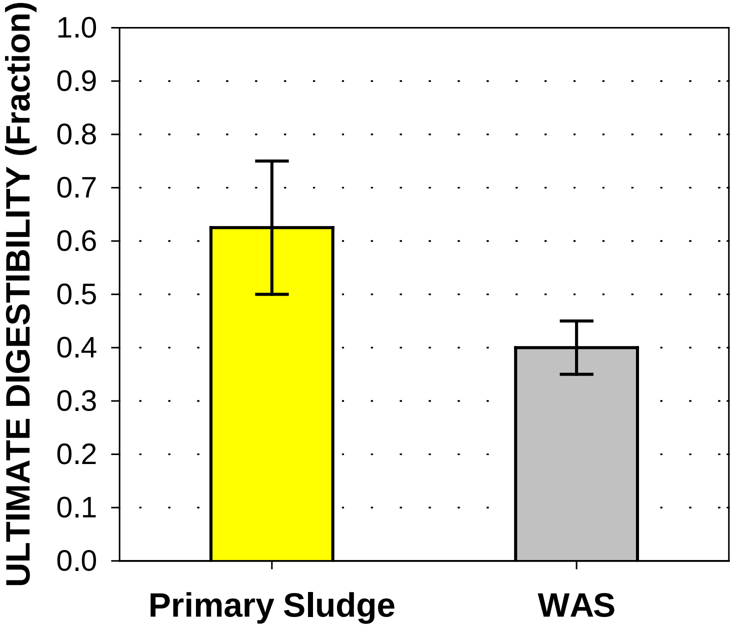
Wastewater Treatment Plant Residuals: Primary (PS) vs. Waste Activated Sludge (WAS)

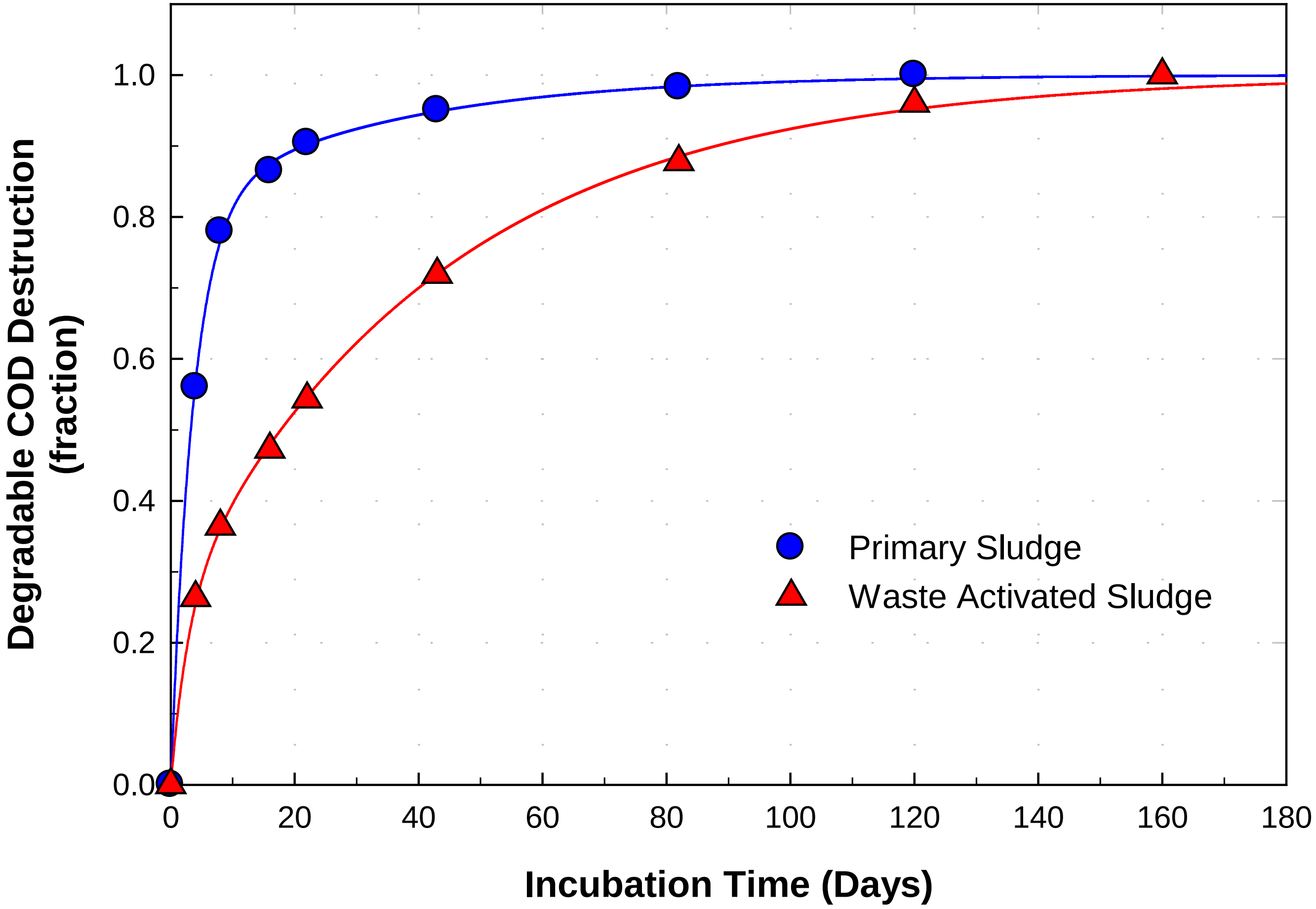
- Extent of Digestibility & Methane Production



Methane Production
(m^3 @ STP/tonne COD fed):
- PS: 175 – 263
- WAS: 123 – 158

Thus, on average:
PS/WAS = 1.6

- Kinetics



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Introduction & Motivation

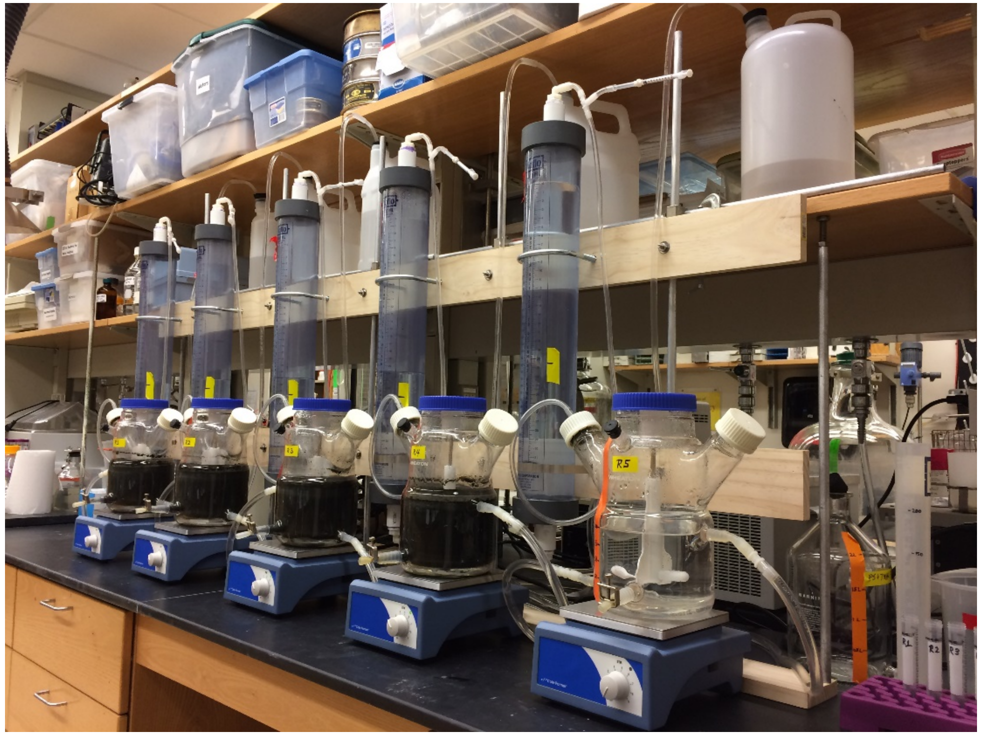
Hydrolysis, which converts insoluble, particulate organic matter to soluble organics, is usually the rate-controlling step, strongly hindering anaerobic digestion (AD) performance.

Among the various pretreatment methods, hydrothermal (HT) treatment is very effective in accelerating sludge solubilization. HT has been widely tested as a pretreatment process (HT+AD). Alternatively, HT can be used as an inter-stage process (Pre-AD+HT+post-AD). However, the effect of HT as an inter-stage process on the AD performance has not been well explored and documented.

To the best of our knowledge, there is no study that compares the effect of pre- and inter-stage HT at 155^{o}C on sewage sludge mixture (i.e., primary and waste activated sludge) in terms of volatile solids destruction and biogas production using both batch tests and semi-continuously fed digesters, the latter representing conditions of real AD applications.

Project Objectives

- ❑ Compare the effect of pre- and inter-stage HT at 155^{o}C on the ultimate biodegradability of sewage sludge mixture (i.e., primary and waste activated sludge) through <u>batch biochemical methane potential (BMP) test</u>
- ❑ Compare four AD configurations, e.g., AD, HT-AD, AD-AD and AD-HT-AD, in terms of methane yield, as well as organic matter and solids destruction in <u>semi-continuously fed digesters</u>



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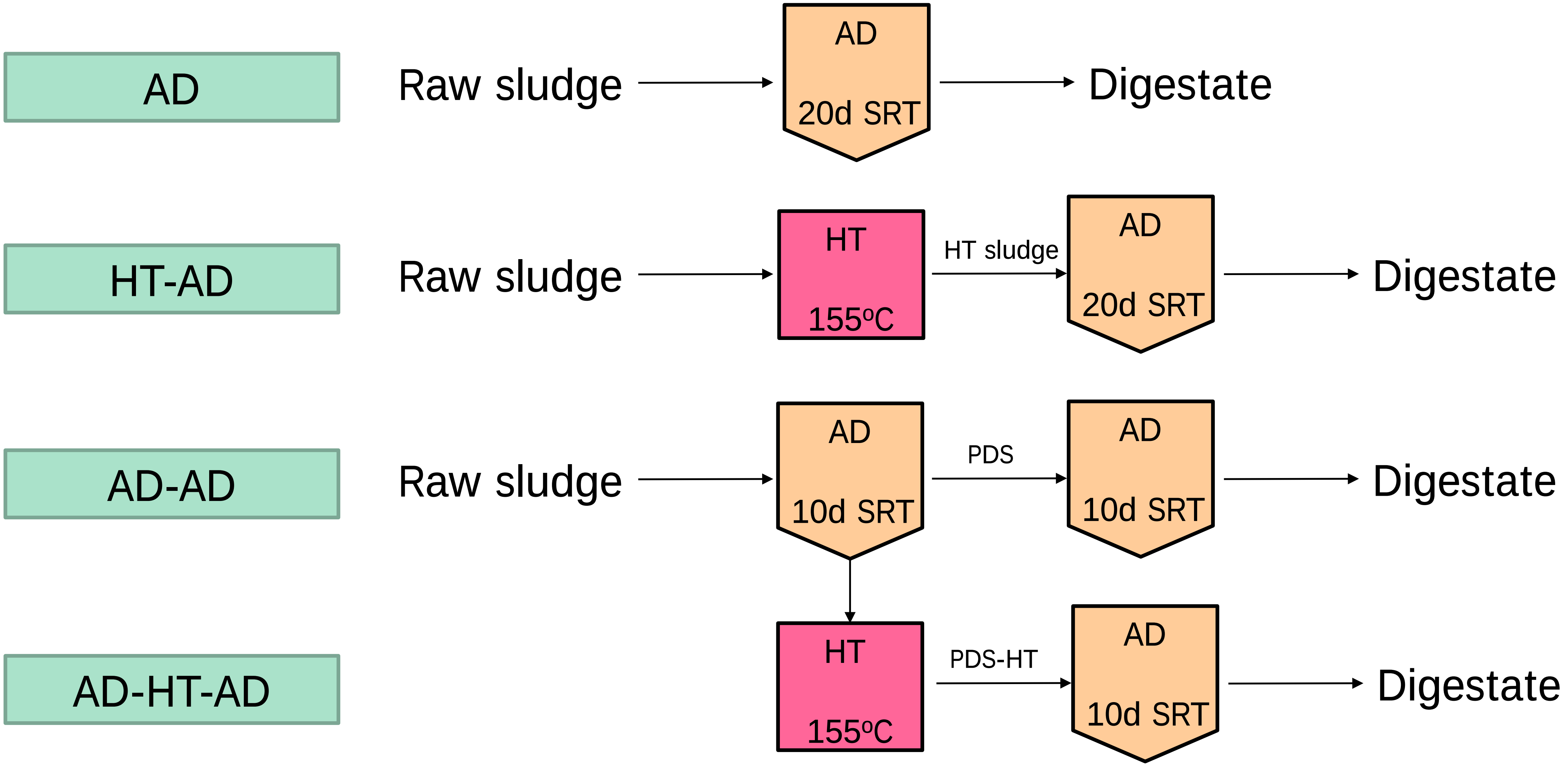
Four AD-HT Configurations



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Effect of HT on Solubilization and VFAs Formation

HT sludge: raw sludge with pre-stage HT
PDS: pre-digested sludge
PDS-HT: PDS with inter-stage HT

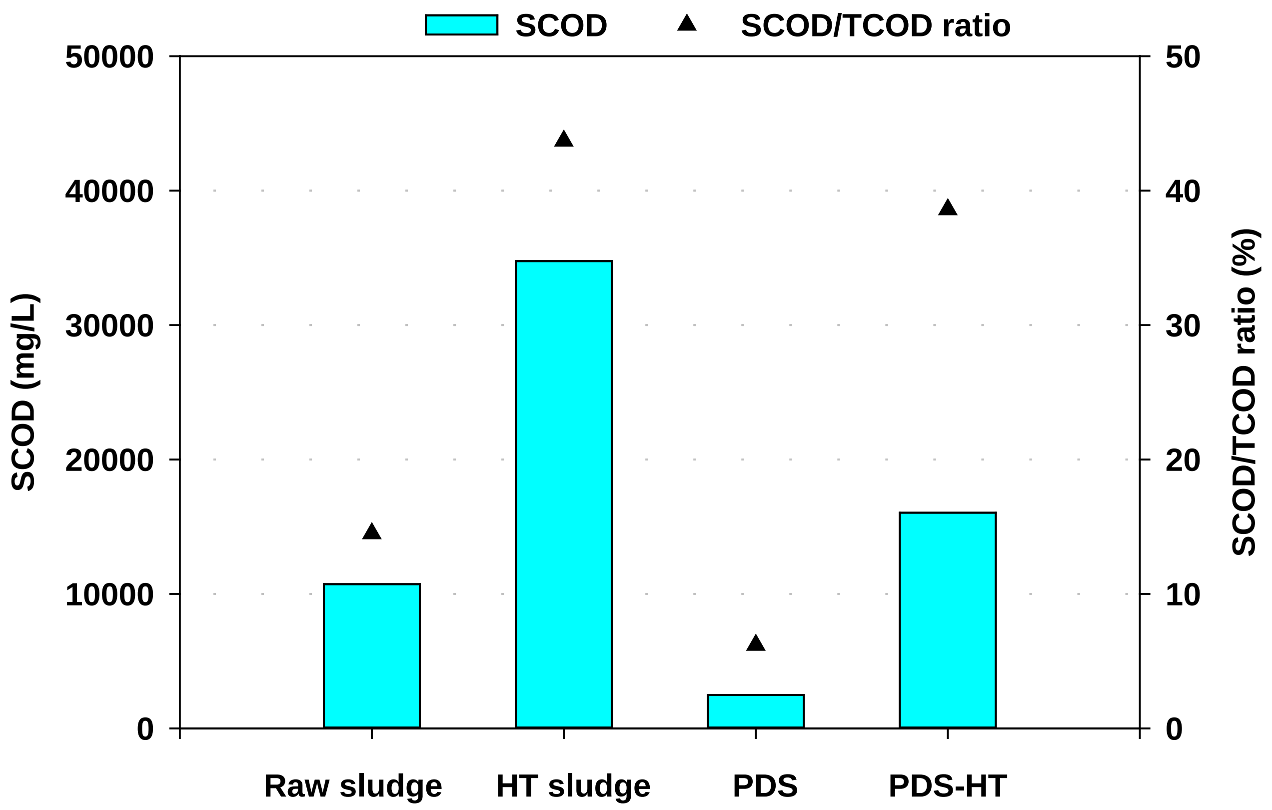

Fig.1. Effect of pre- and inter-stage HT on SCOD concentration

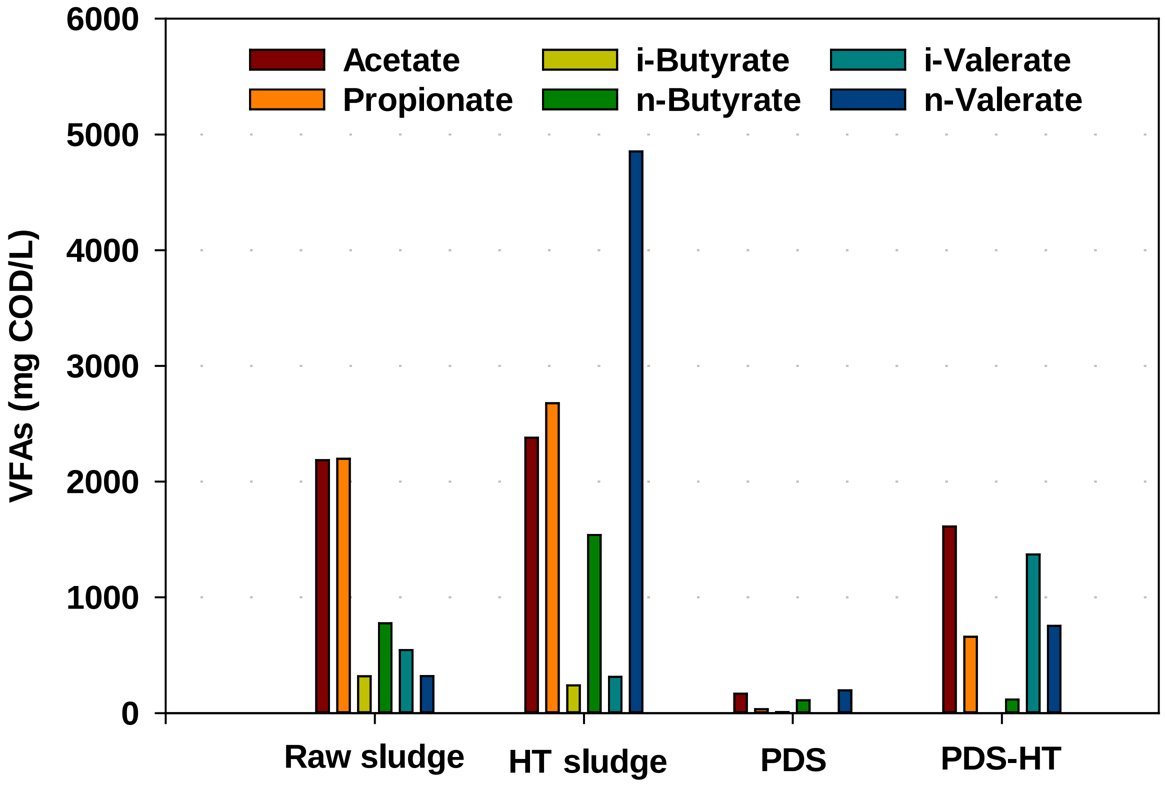

Fig.2. Effect of pre- and inter-stage HT on VFAs concentration

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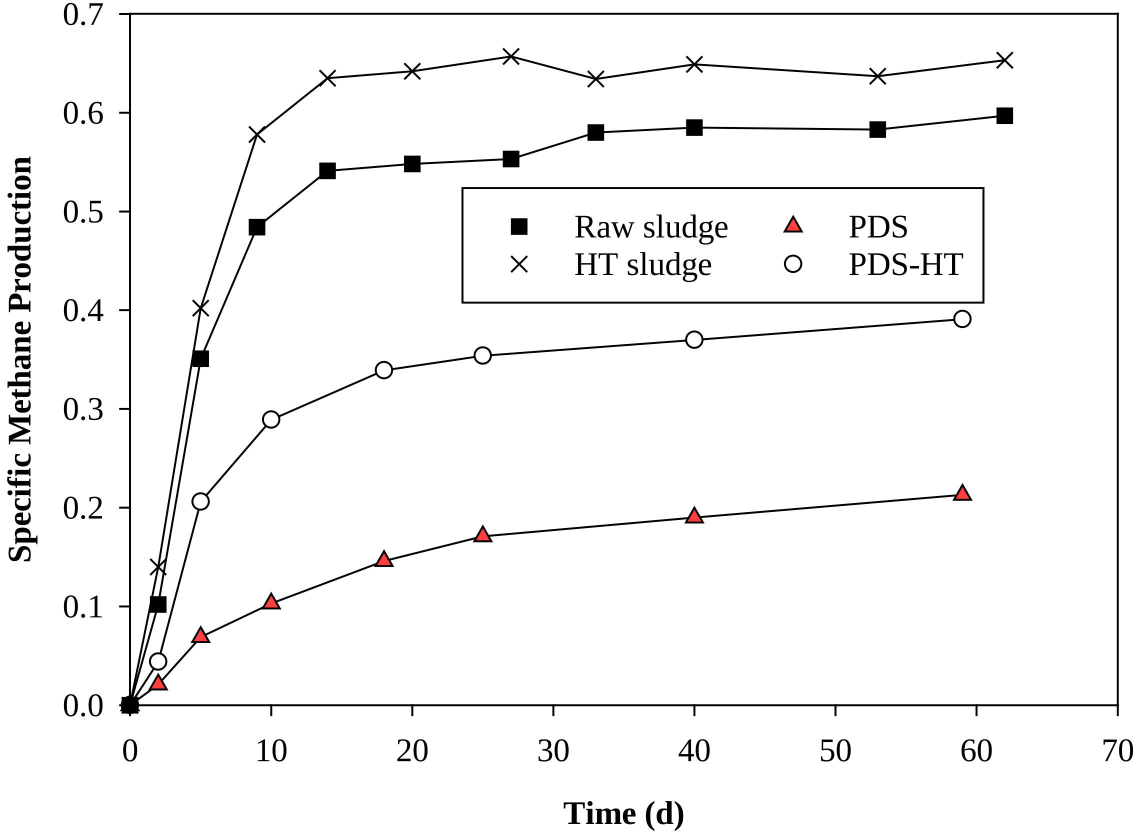
Sludge Mixture Ultimate Biodegradability

- Pre vs. inter-stage hydrothermal treatment (155°C)
- Four configurations: AD, HT-AD, AD-AD, AD-HT-AD (35°C)

- Biochemical Methane Potential (BMP) test



- Methane production estimates

Sludge	k_f (d^{-1})[a]	P_u (g COD_M/g total COD)[b]	R^2
Raw sludge	0.169±0.016[c]	0.583±0.012	0.985
HT sludge	0.191±0.017	0.655±0.012	0.986
PDS	0.067±0.005	0.211±0.005	0.996
PDS-HT	0.133±0.017	0.378±0.014	0.982

[a] Pseudo-first-order rate constant; $P_t = P_u[1 - \exp(-k_f t)]$

[b] Ultimate specific methane production;

[c] Mean ± standard error.

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AD Performance

Table 2. Performance of the four configurations (semi-continuously fed digesters)

Parameter	AD	HT-AD	1st AD	2nd AD (AD-AD)	2nd AD (AD-HT-AD)
SRT (d)	20	20	10	10	10
pH	7.67±0.02[a]	7.65±0.05	7.65±0.05	7.67±0.02	7.57±0.01
TS destruction (%)	28.1±0.9[b]	34.3±1.1	26.3±1.3	6.2±0.9	23.5±2.7
VS destruction (%)	39.2±0.8[b]	48.4±1.3	36.6±1.9	9.5±1.2	33.3±1.9
Total COD destruction (%)	44.3±2.0[b]	53.5±1.9	43.3±3.0	10.6±2.7	28.8±2.7
COD to CH_4 conversion (%)	46.7±0.8[a]	55.4±1.2	40.5±1.8	8.5±0.7	26.7±0.9
Total COD balance (%)	-2.4	-1.9	2.8	2.1	2.1

[a] Mean ± standard deviation (n = 4); [b] Mean ± standard deviation (calculated).

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AD Performance

- Pre vs. inter-stage hydrothermal treatment (155ºC). AD reactors operated with 10 d solids retention time (35ºC).
- Four configurations: AD, HT-AD, AD-AD, AD-HT-AD

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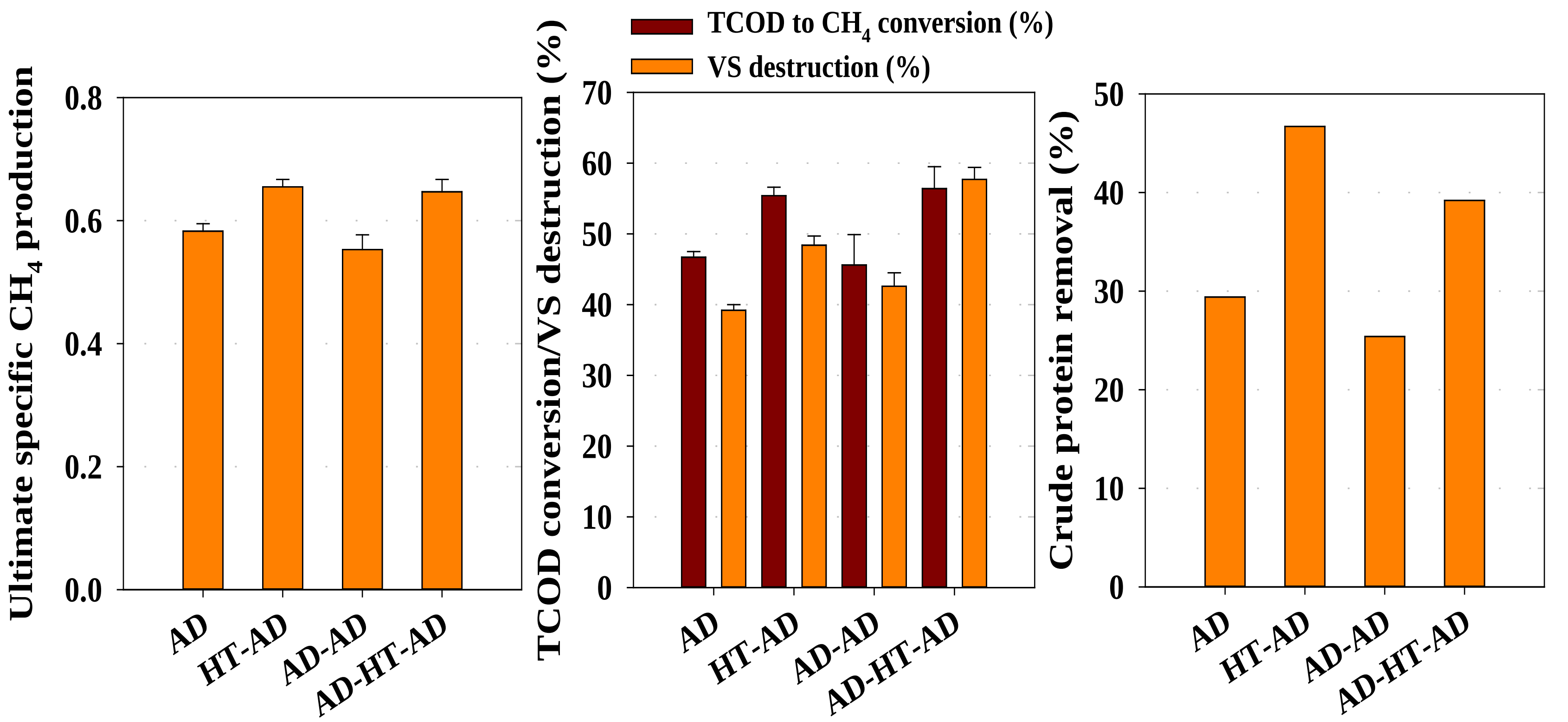

Ultimate biodegradability

AD performance

Crude protein removal

AD Performance: VS Destruction vs. COD-to-CH_4 Conversion

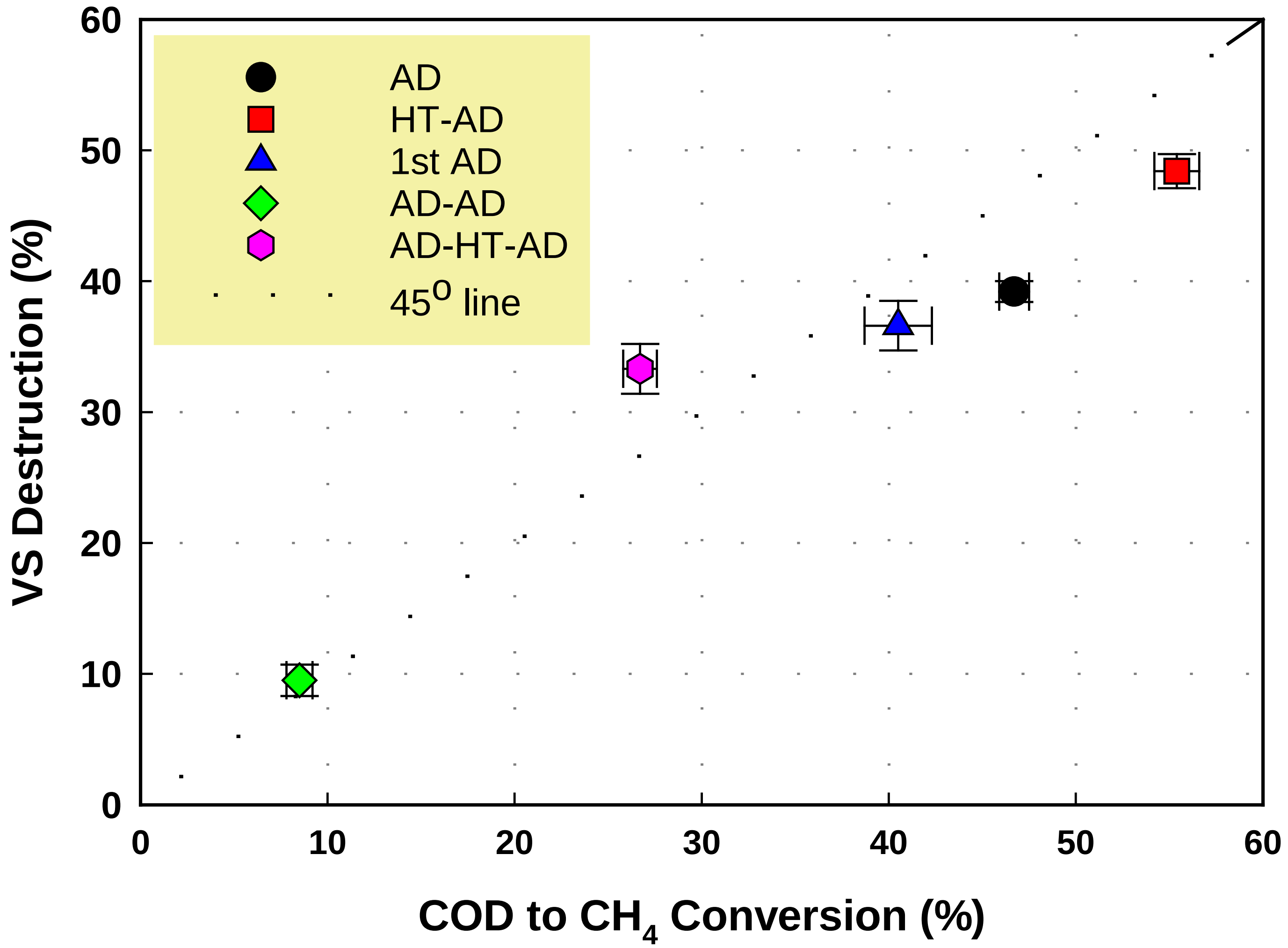

Fig.4. VS destruction vs. COD-to-CH_4 conversion by the five processes involved in the four AD configurations

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Pre- vs. Inter-stage HT: Ultimate Biodegradability and AD Performance

Table 3. Overall methane production and solids destruction by the four configurations.

Parameter	AD	HT-AD	AD-AD	AD-HT-AD
Ultimate methane production (P_u) (g COD_M/g total COD)	0.583±0.012	0.655±0.012	0.553±0.024	0.647±0.020
TCOD to CH_4 conversion (%)	46.7±0.8	55.4±1.2	45.6±4.3	56.4±3.1
TS destruction (%)	28.1±0.9	34.3±1.1	30.9±1.3	43.6±2.2
VS destruction (%)	39.2±0.8	48.4±1.3	42.6±1.9	57.7±1.7

- There was not a statistically significant difference between the P_u of AD and AD-AD (p = 0.125), HT-AD and AD-HT-AD (p = 0.584);
- There was a statistically significant difference between the overall TCOD-to-CH_4 conversion in AD and HT-AD ($p \leq$ 0.001), AD-AD and AD-HT-AD (p = 0.024);
  there was not a statistically significant difference between the TCOD-to-CH_4 conversion in AD and AD-AD, HT-AD and AD-HT-AD.
- There was a statistically significant difference between the overall VS destruction in AD and HT-AD ($p \leq$ 0.001), AD and AD-AD (p = 0.046), HT-AD and AD-HT-AD (p = 0.002), AD-AD and AD-HT-AD ($p \leq$ 0.001).

Pre- vs. Inter-stage HT: VS Destruction vs. COD-to-CH_4 Conversion

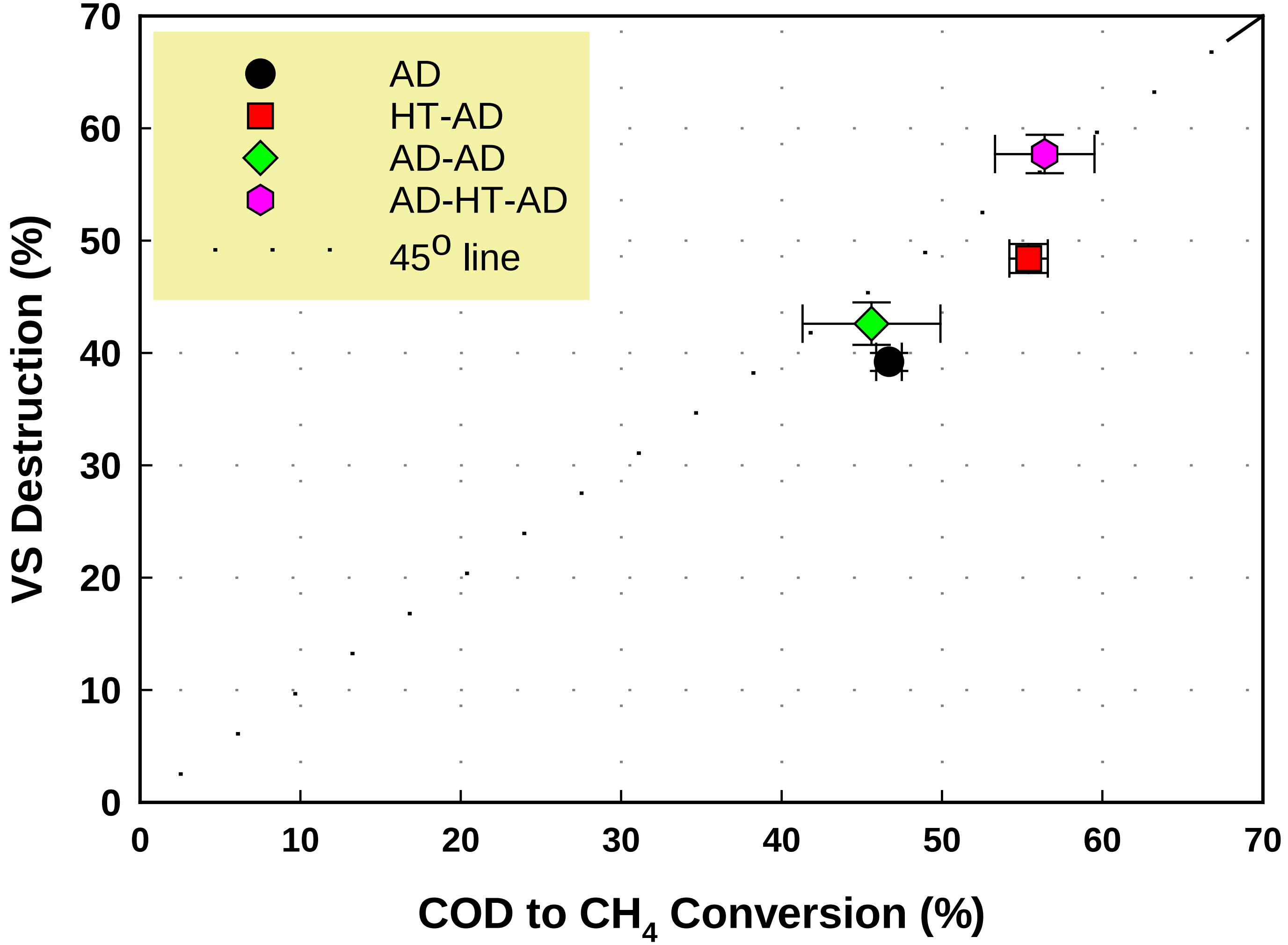


Fig.5. VS destruction vs. COD-to-CH_4 conversion by the four configurations

Energy Balance (GJ/d)

Table 4. Energy balance (GJ/d) for the four configurations.

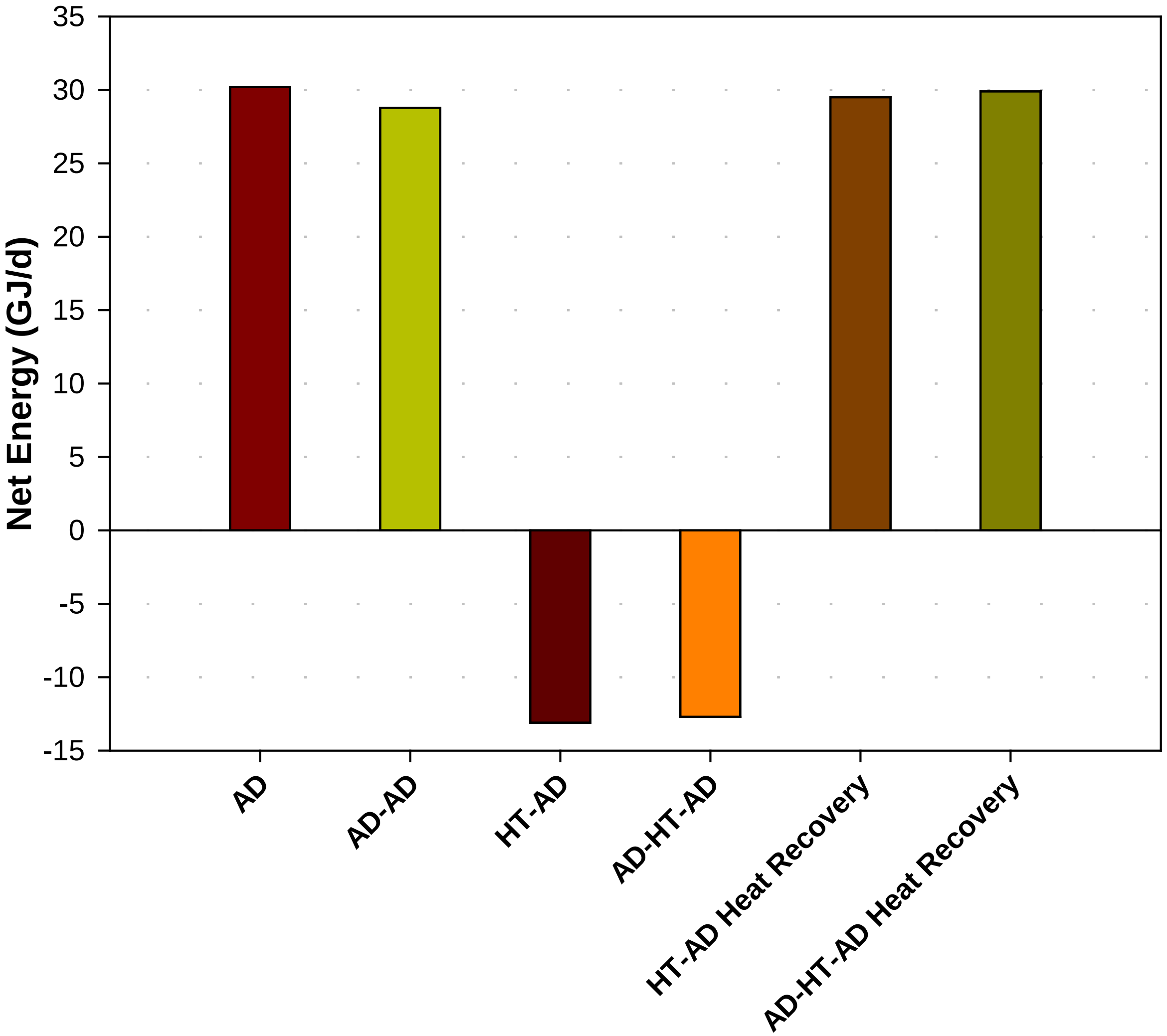
Energy component	AD	AD-AD	Without HT heat recovery		With 85% HT heat recovery	
			HT-AD	AD-HT-AD	HT-AD	AD-HT-AD
Input heat ($E_{i,\ heat}$)	5.5	5.4	55.6	55.6	55.6	55.6
Heat recovered ($E_{i,heat\ recovered}$)	NA[a]	NA	0.0	0.0	42.6	42.6
Heat losses ($E_{i,\ heatloss}$)	0.5	0.7	0.5	0.7	0.5	0.7
Input electricity ($E_{i,\ electricity}$)	0.8	1.0	0.8	1.0	0.8	1.0
Energy input (E_{input})	6.8	7.0	56.9	57.2	14.3	14.6
Energy output (E_{output})	37.0	35.8	43.8	44.5	43.8	44.5
Net energy gain (ΔE)	**30.2**	**28.8**	**-13.1**	**-12.7**	**29.5**	**29.9**

[a] NA, not applicable; control digester without HT

- Both pre- and inter-stage HT had a negative effect on energy balance. High HT heat recovery (83-86%) would be required for the HT-AD and AD-HT-AD configuration to achieve a net energy yield comparable to that of AD and AD-AD.
- The energy balance of AD and AD-AD without HT, as well as HT-AD and AD-HT-AD with pre- or inter-stage HT, was comparable.

Energy Balance (GJ/d)

- Net energy (GJ/d) of four HT/AD configurations. AD reactors operated with 10 d solids retention time, maintained at 35^{o}C. Heat recovery, 85%



Liu, Wang, Tang, Pavlostathis;
Applied Energy (2021)

Conclusions

- ❑ Pre- and inter-stage HT resulted in comparable ultimate methane yield from the sludge mixture.
- ❑ Single-step AD and two-step AD, as well as pre- and inter-stage HT resulted in comparable methane production.
- ❑ Compared to single-step AD, two-step AD led to higher VS destruction.
- ❑ Minimal difference in net energy production by AD and AD-AD (singe digester vs. two digesters), as well as by HT-AD and AD-HT-AD (pre-stage HT vs. inter-stage HT).
- ❑ Significant recovery of HT heat is necessary to attain a net energy gain comparable to the control (AD and AD-AD).
- ❑ Compared to single-step AD, the two-step AD process is more complex and thus less attractive. However, as two-step AD and inter-HT resulted in higher VS destruction, two-step AD and inter-HT may be more beneficial considering post-AD sludge handling processes, such as dewatering, incineration, etc.

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