Tecnologie per il recupero e la valorizzazione del carbonio dagli impianti di depurazione

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October 18th, 2024

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OUTLINE

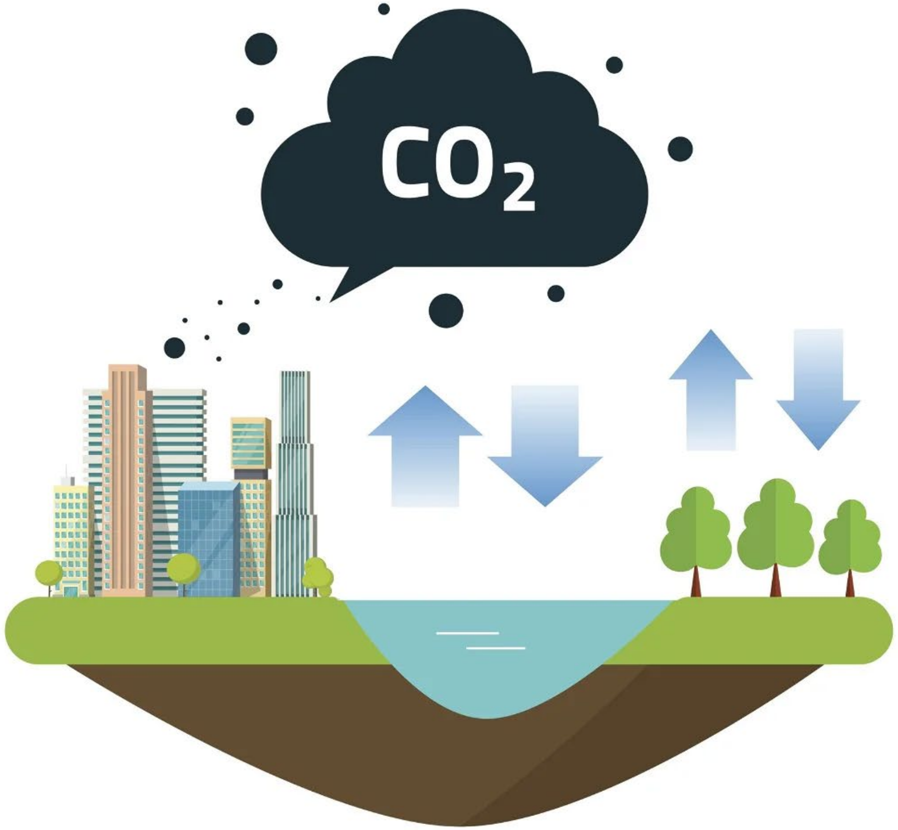
(1) The problem of carbon redirection

(2) Existing solutions for carbon redirection

(3) A closer look to the HRAS process

(4) HRAS application

(5) Open research questions



THE PROBLEM OF CARBON DIVERSION

- Currently, urban water cycle accounts for 1–3% of the total electric energy consumption and 3–10% of the global warming potential (GWP) by contributing towards **GHG emissions into the atmosphere**, both as **direct and indirect** footprints

- The **new Urban Wastewater Treatment Directive** (UWWTD) is setting the scene

  > Energy neutrality for WWTP by 2045 (with max 35% of external renewable sources)

- Need for rethinking the wastewater treatment (shift towards biorefineries) by:

  - **Reducing** the demand of **impacting resources** (energy and other components)
  - **Improve the resource recovery**, primarily from energy (AD, incineration)
  - Defining **integrated assessment platforms** for plant-wide optimized operation

THE PROBLEM OF CARBON REDIRECTION

- Some figures about mid-strength wastewater:

  - Chemical energy > about 500 mgCOD L^{-1} / 1.9 kWh m^{-3}

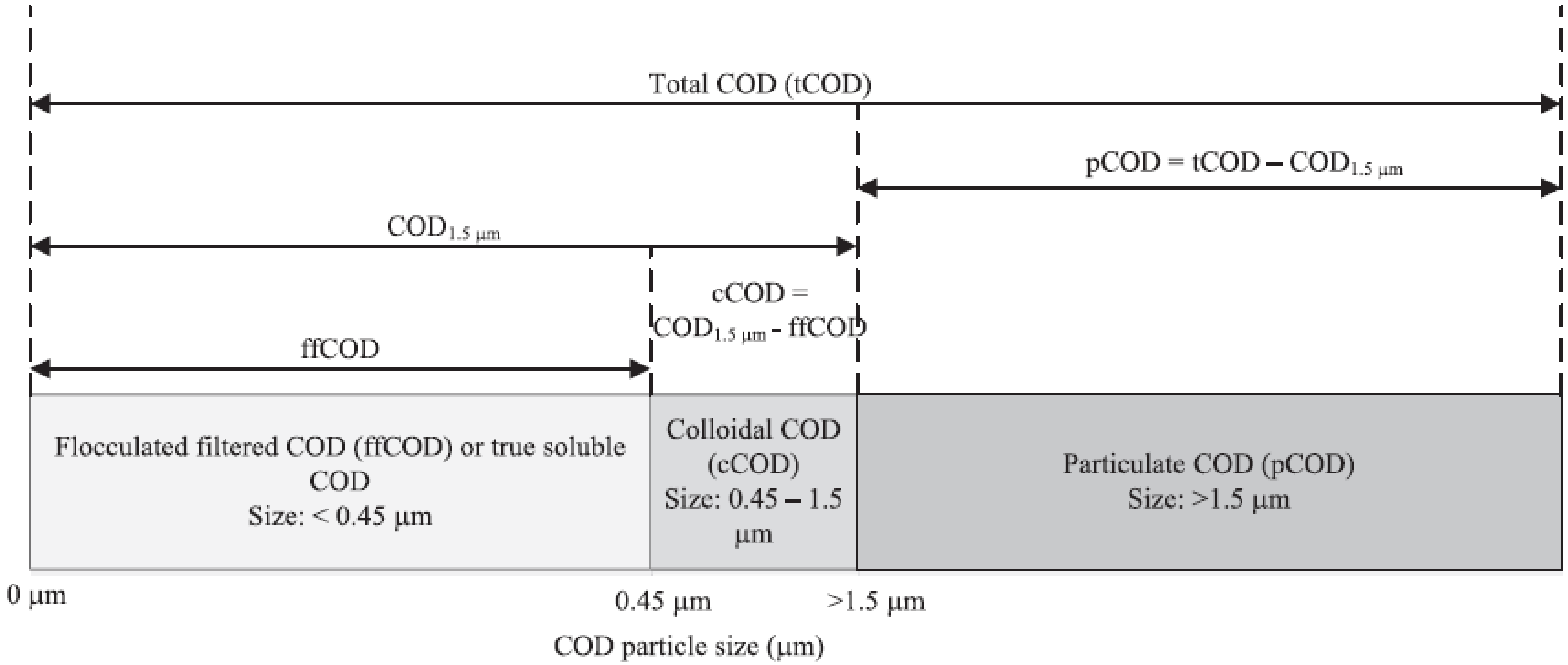
  - TOC > about 175 mg L^{-1}

  - Volatile dissolved solids > about 225 mg L^{-1}

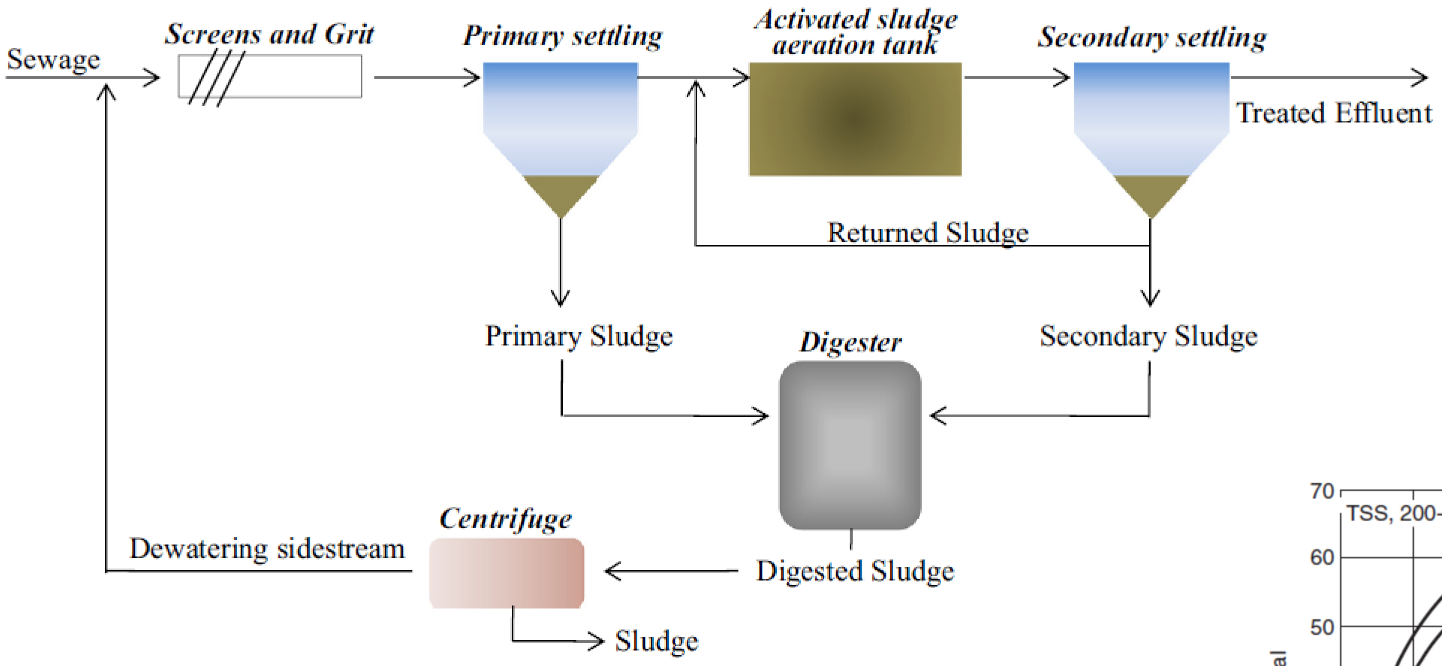
  - Volatile suspended solids > about 150 mg L^{-1}

Parameters	Units	High strength wastewater	Medium strength wastewater	Low strength wastewater
Total Suspended Solids (TSS)	mg/L	227 ± 39	185 ± 24	33 ± 11
Volatile Suspended Solids (VSS)	mg/L	203 ± 36	164 ± 22	29 ± 9
Total COD (tCOD)	mgCOD/L	749 ± 213	519 ± 55	161 ± 20
Particulate COD (pCOD)	mgCOD/L	512 ± 212	333 ± 43	85 ± 24
Colloidal COD (cCOD)	mgCOD/L	81 ± 22	48 ± 24	18 ± 9
Flocculated Filtered COD (ffCOD)	mgCOD/L	155 ± 24	149 ± 24	59 ± 10
Total Kjeldahl Nitrogen (TKN)	mgN/L	50.9 ± 3.0	–	–
Ammonia Nitrogen (NH_3-N)	mgN/L	34.3 ± 7.7	31.2 ± 2.7	23.1 ± 3.3
Soluble Total Kjeldahl Nitrogen (sTKN)	mgN/L	37.2 ± 2.2	–	–
Total Phosphorous (TP)	mgP/L	7.4 ± 0.7	5.2 ± 0.9	1.6 ± 0.2
Ortho-Phosphorous (OP)	mgP/L	4.1 ± 1.3	3.4 ± 0.4	0.85 ± 0.31

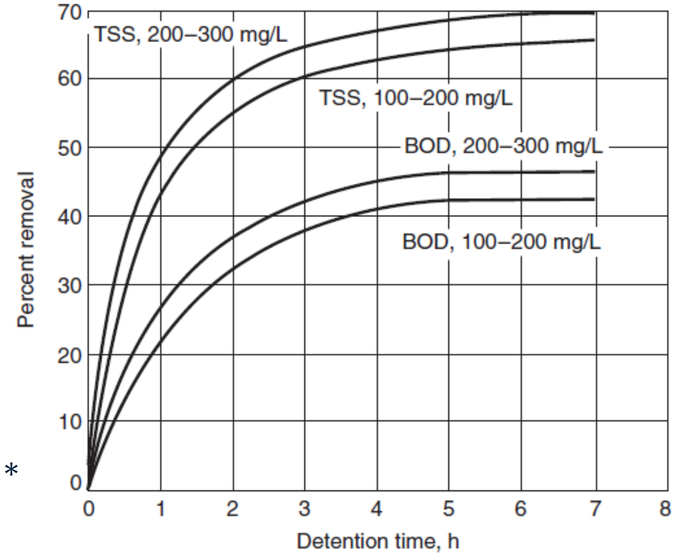
THE PROBLEM OF CARBON REDIRECTION



THE PROBLEM OF CARBON REDIRECTION



PRIMARY SETTLING



Metcalf and Eddy (2014)

- Some figures about wastewater treatment:

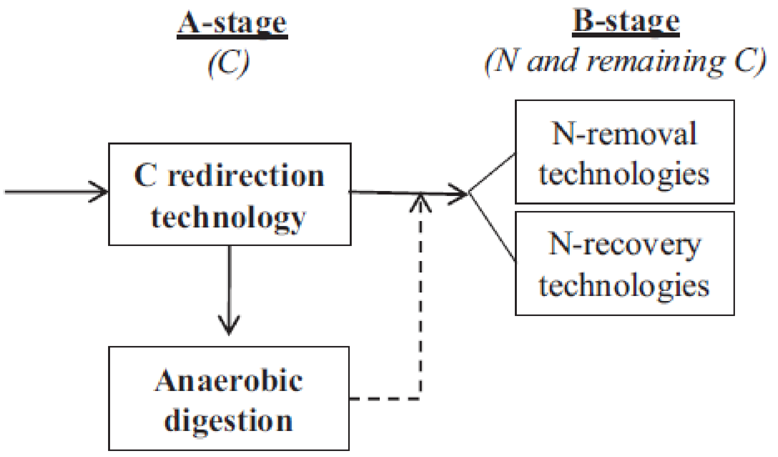
  - Primary treatment removes 35 – 40% of COD in form of primary sludge

  - Secondary treatment mineralizes 30 – 40% of organic load with 0.3 – 0.7 kWh m^{-3} (30 – 60%) *

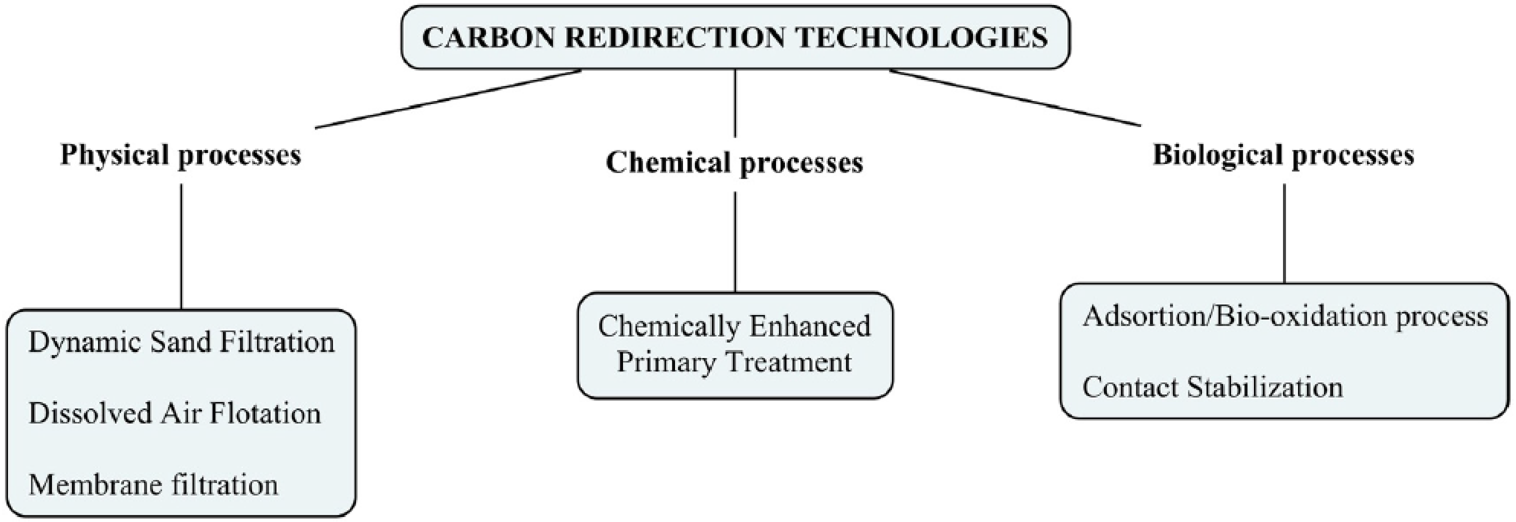
  - The residual organic load (60 – 70%) is converted into secondary sludge (30 – 60% of OPEX)

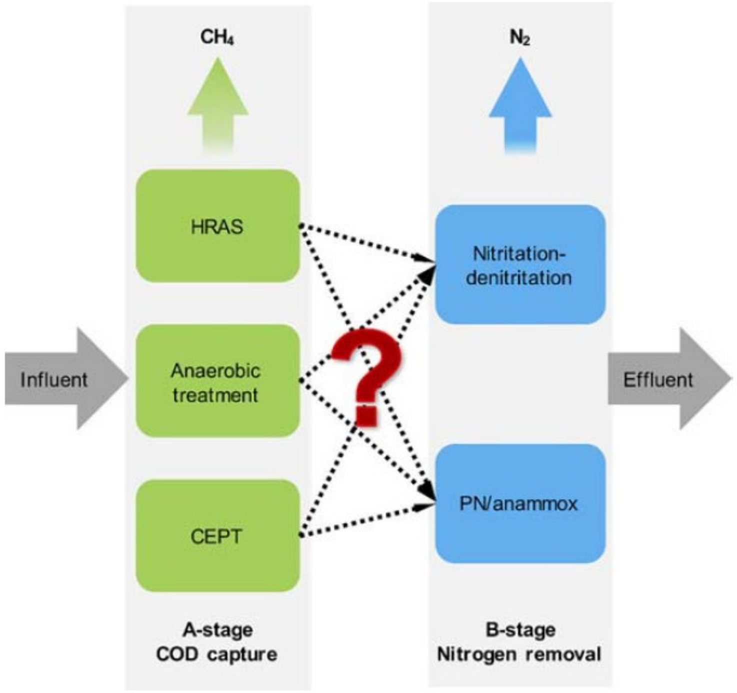
* 20–35 $kWh_e \cdot PE^{-1} \cdot y^{-1}$ in Wes. Europe

EXISTING SOLUTIONS FOR CARBON REDIRECTION

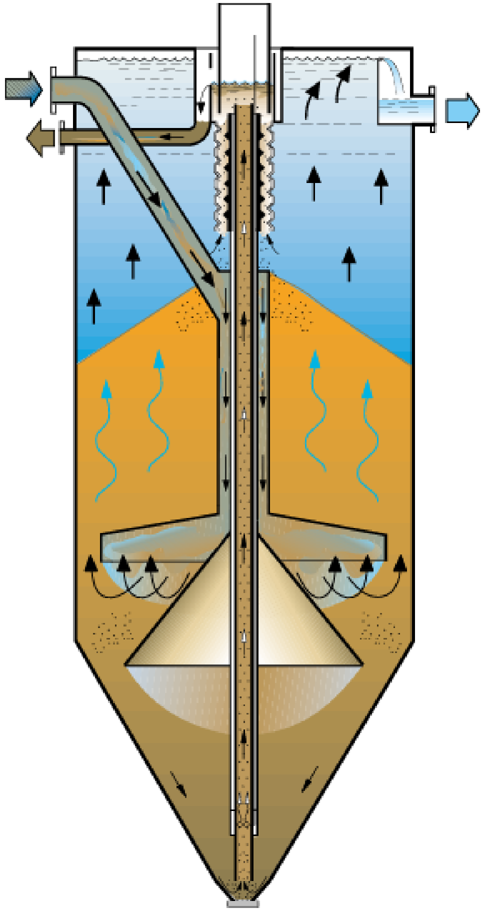


- **Increment** the fraction of organic **load to AD** to recover energy and stabilize biosolids
- The big issue is related to wastewater **dilution** (need to reach the g L^{-1} dimension)
- Growing hype towards the **AB concept** (an old one!)
- Fluctuating interest towards **anaerobic treatments in the mainstream**

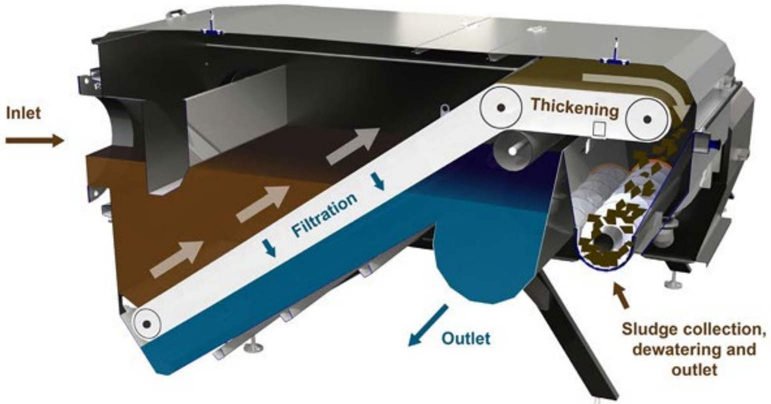




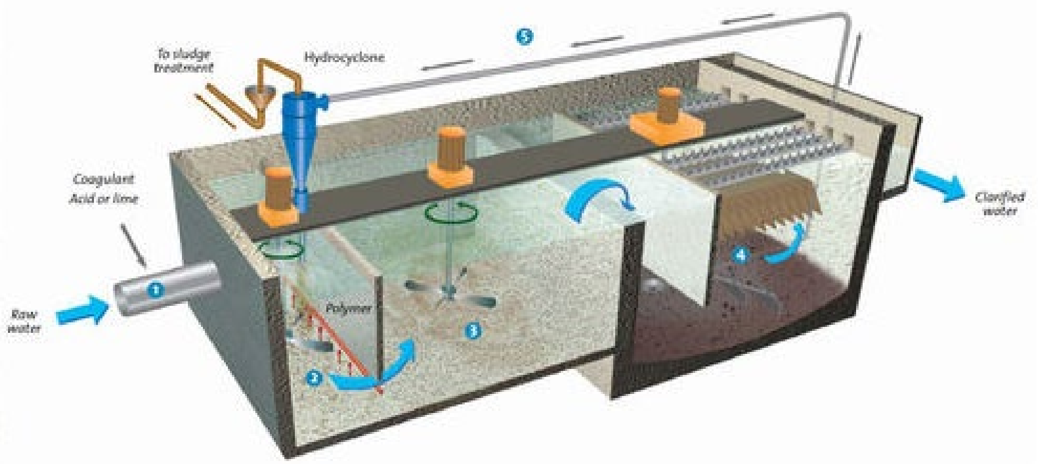
EXISTING SOLUTIONS FOR CARBON REDIRECTION



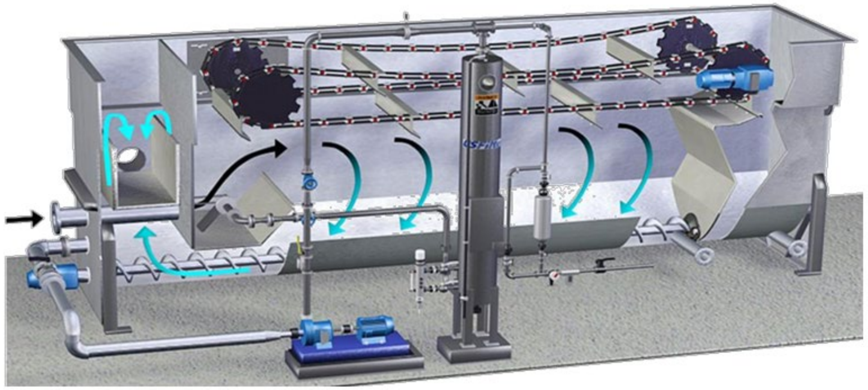
NORDIC WATER
DYNASAND



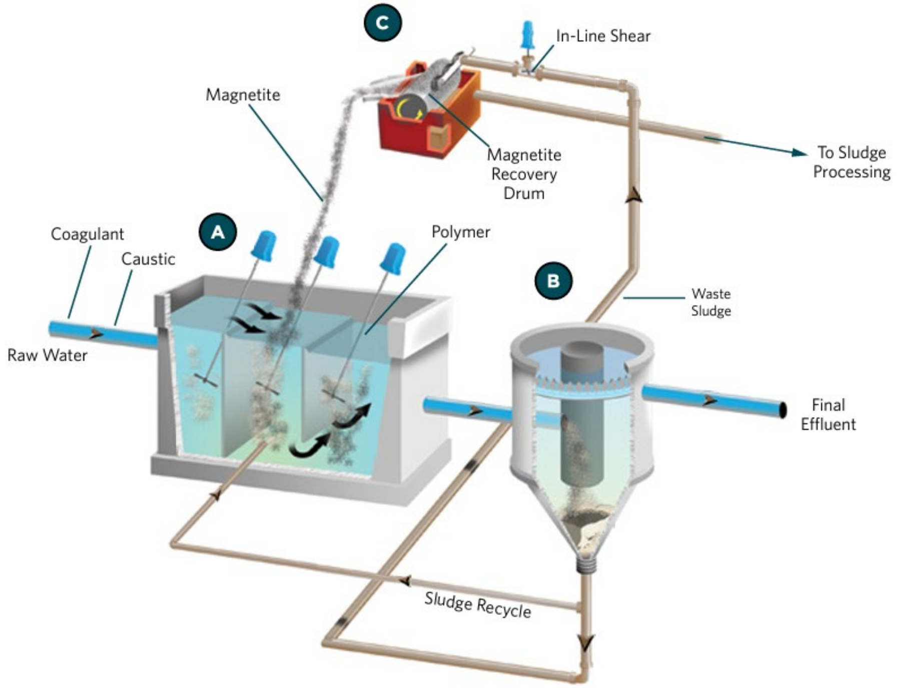
ROTARY BELT FILTERS



VEOLIA ACTIFLO



EVOQUA CAPTIVATOR

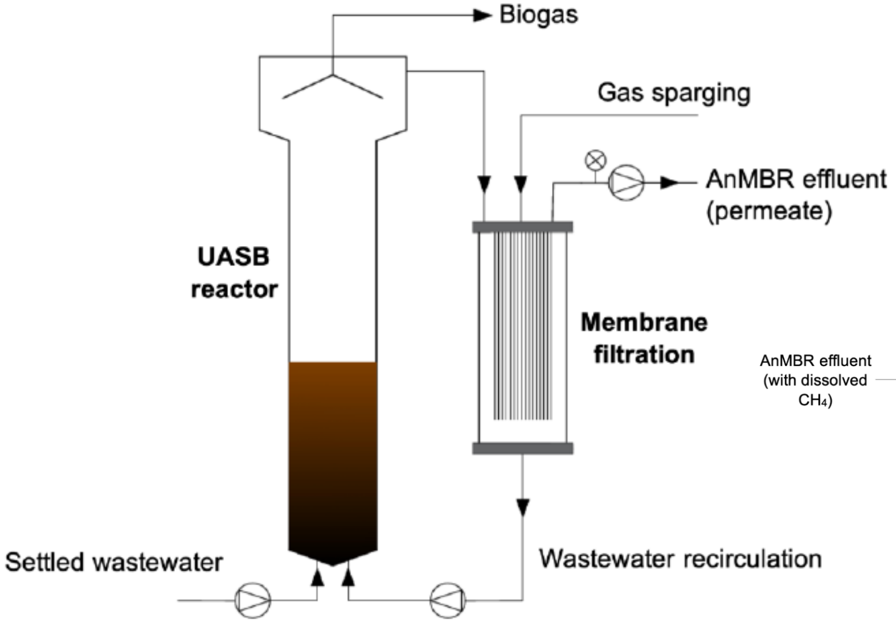


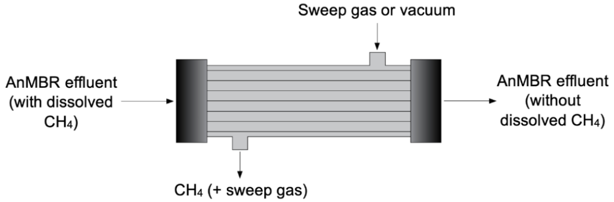
EVOQUA COMAG

EXISTING SOLUTIONS FOR CARBON REDIRECTION | MAINSTREAM AnMBR

- Combination of an upflow anaerobic sludge blanket reactor (UASB) with physical separation membranes (ultrafiltration for solid-liquid separation and membrane contactor for gas-liquid separation)

- Low sludge production and associated treatment efforts
- Chemical-free process to remove methane (99%) from liquids
- Membrane fouling and investment cost

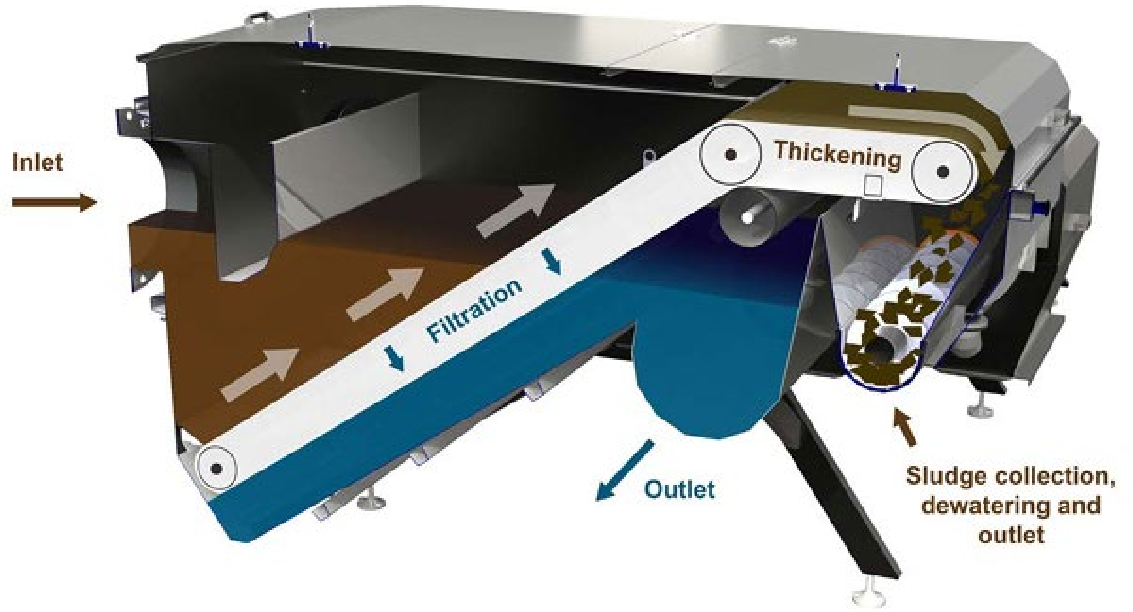


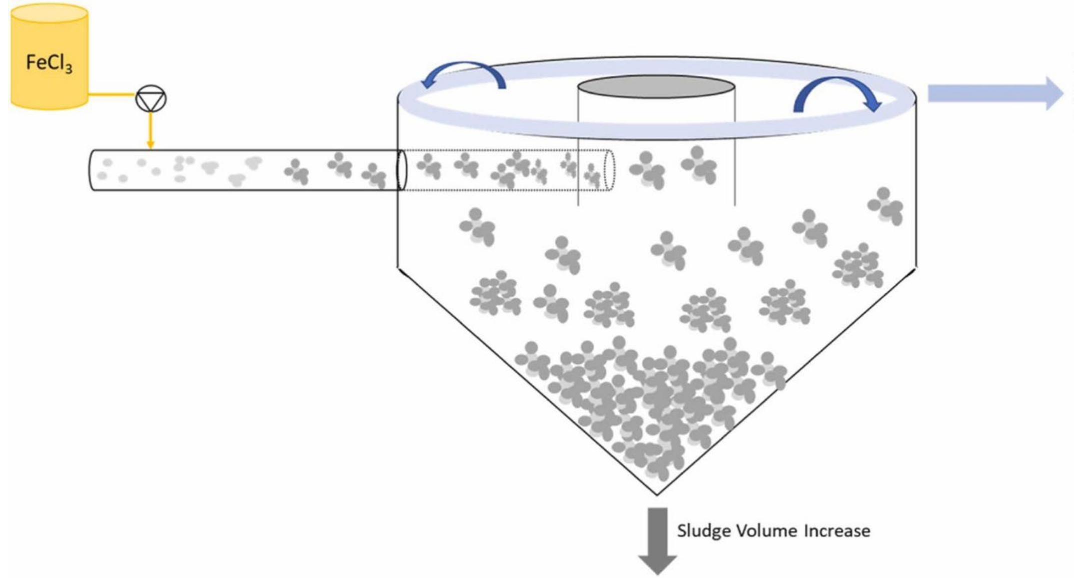


NextGen EU H2020 project, Spernal (UK) demonstration

EXISTING SOLUTIONS FOR CARBON REDIRECTION | ROTATING BELT FILTERS AND CEPT

- Enhanced primary treatments via physical separation or coagulation
- Lower land footprint (30-60%), additional removal of TSS and COD/BOD

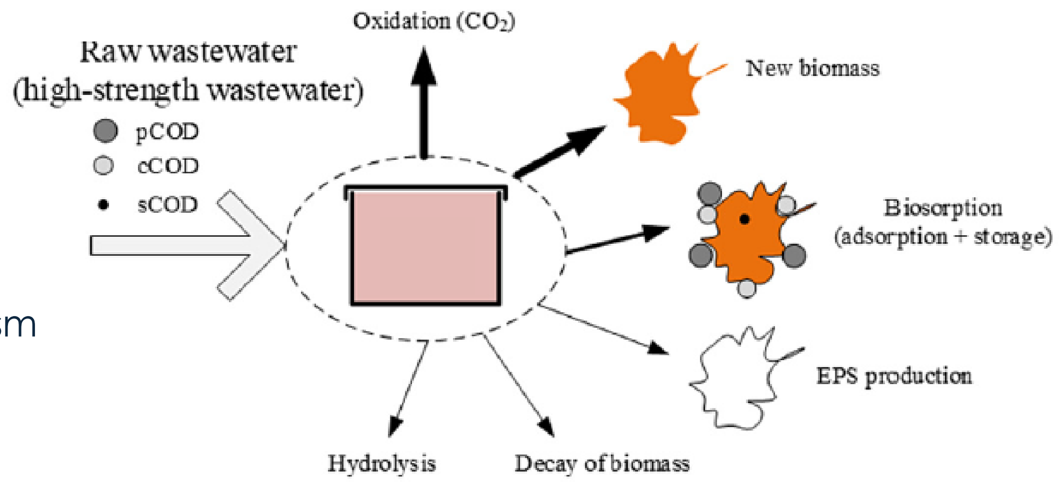




- + 50% removal of TSS
- + 15 - 20% removal of COD
- 20-30% SS in sludge
- CAPEX and OPEX

- 80 - 90% TSS removal
- 40 - 70% COD removal
- Issues with downstream AD
- Higher OPEX for reagents

EXISTING SOLUTIONS FOR CARBON REDIRECTION



- Biological solutions are based on the promotion of **biosorption**:

  (1) Soluble, colloidal and particulate components are adsorbed

  (2) Particulate and colloidal compounds are hydrolyzed to smaller ones

  (3) Soluble and smaller compounds are used for catabolism and anabolism

- Need for **maximizing the harvesting of particulate and colloidal COD, while minimizing hydrolysis and mineralization of biodegradable COD**

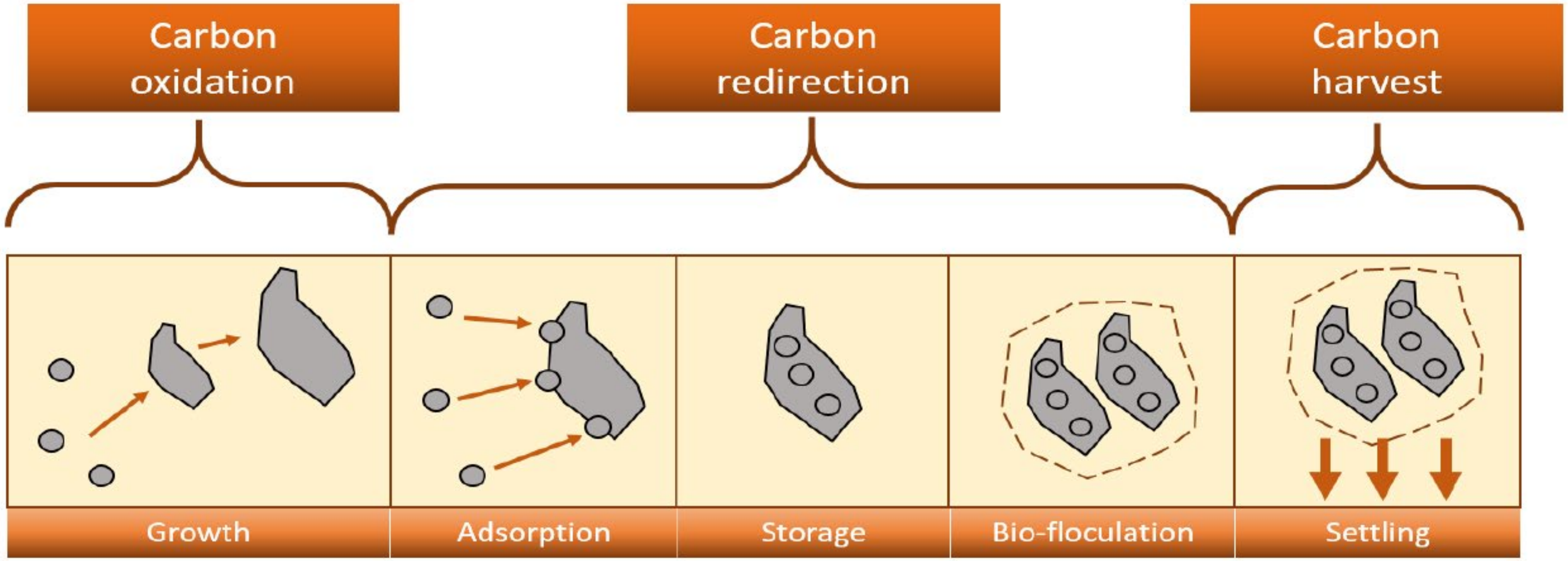
- Importance of promoting (A) EPS formation, (B) intracellular accumulation and (C) good sludge settleability

- Recovery of **highly biodegradable sludge** with a reagent-free process capable of redirecting carbon

- Need for appropriate **operating conditions** for promoting the process, primarily F/M, HRT, SRT and DO

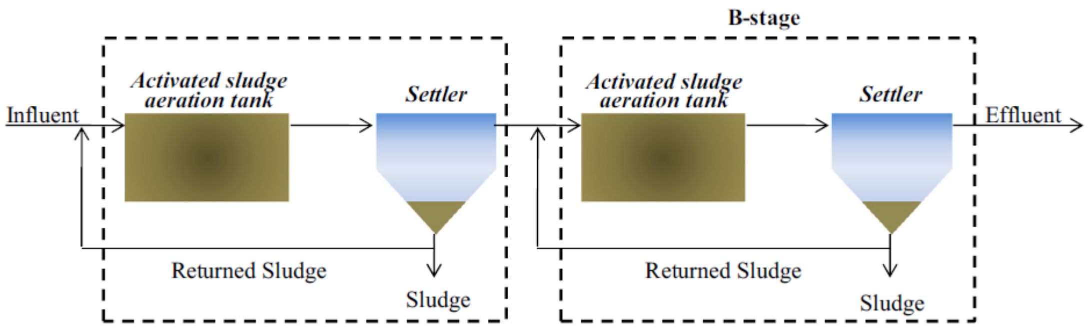
- These treatments are generally referred to as **HIGH RATE ACTIVATED SLUDGE** processes

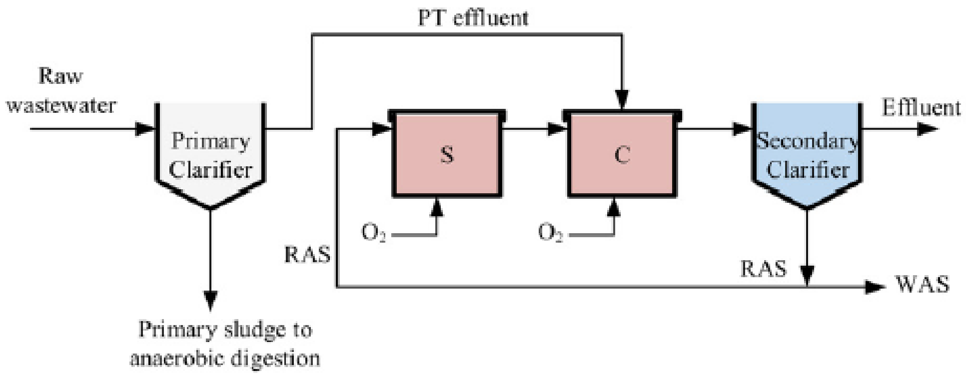
EXISTING SOLUTIONS FOR CARBON REDIRECTION



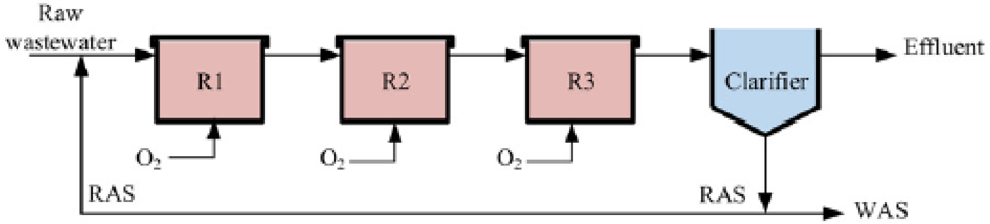
EXISTING SOLUTIONS FOR CARBON REDIRECTION

- HRAS processes exists from a long time and are applied as **A-stage at full-scale** (COD removal 53 to 74%)
- The development of **B-stage** for nutrient removal is needed (e.g., PN/A process, short-cut N removal, ion exchange, …)
- A-stage is misleading as it is also a major HRAS configuration, another relevant type is called **Contact-Stabilization**





(c) Contact-Stabilization (CS) with primary treatment



(d) A-stage (3 series of reactor) without primary treatment

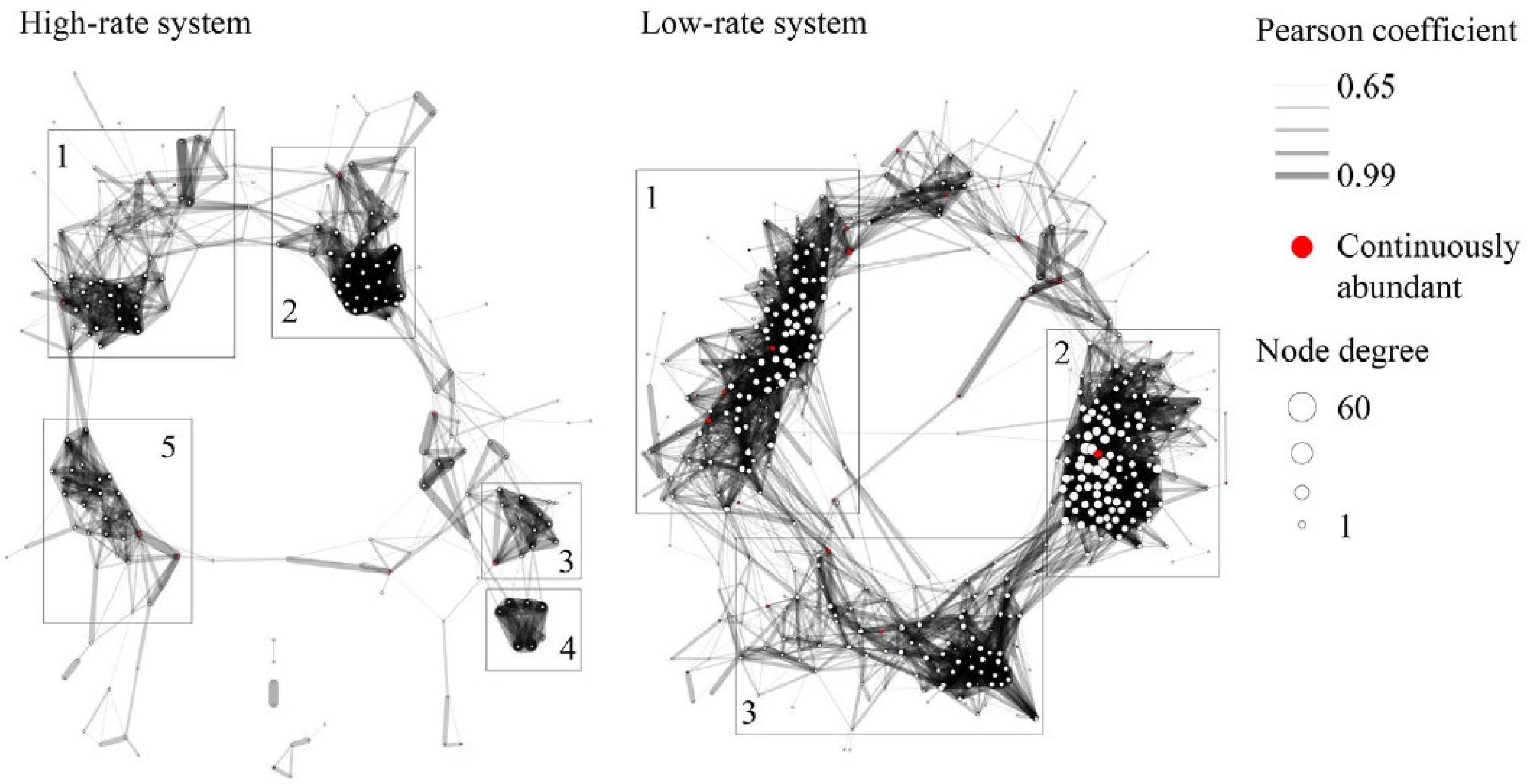
A CLOSER LOOK TO THE HRAS PROCESS

- Looking for operating conditions promoting (A) EPS formation, (B) intracellular accumulation and (C) good sludge settleability:
  - **High Food-to-Microorganisms (F/M) ratio** > 2 – 10 gbCOD $gVSS^{-1}$ d^{-1} (vs. 0.2 – 0.6 gbCOD $gVSS^{-1}$ d^{-1} for CAS)
  - **Low Hydraulic Residence Time (HRT)** > 30 – 60 min (vs. 3 – 18 h for CAS)
  - **Low Sludge Residence Time (SRT)** > 0.5 – 2 d (vs. 3 – 25 d for CAS)
  - **Low Dissolved Oxygen (DO) concentration** > 0.5 – 2 mg L^{-1} (in general, slightly lower than CAS)

- Effects on operating conditions on the process
  - Provide enough process time for **biosorption but not for COD mineralization and sludge losses** (cell decay, …)
  - Promote the enrichment of **fast-growing microorganisms** with sufficient concentration and good settleability
  - **Avoid** the presence of **other microorganisms** in the community (e.g., nitrifiers, grazers)
  - **Lower influent dilution** and promote the biosorption while avoiding a decrease in oxygen transfer rate
  - Production of **larger amount of sludge**, 0.7 – 1.0 kgTSS per kg of removed COD (vs. 0.4 – 0.6 in CAS)

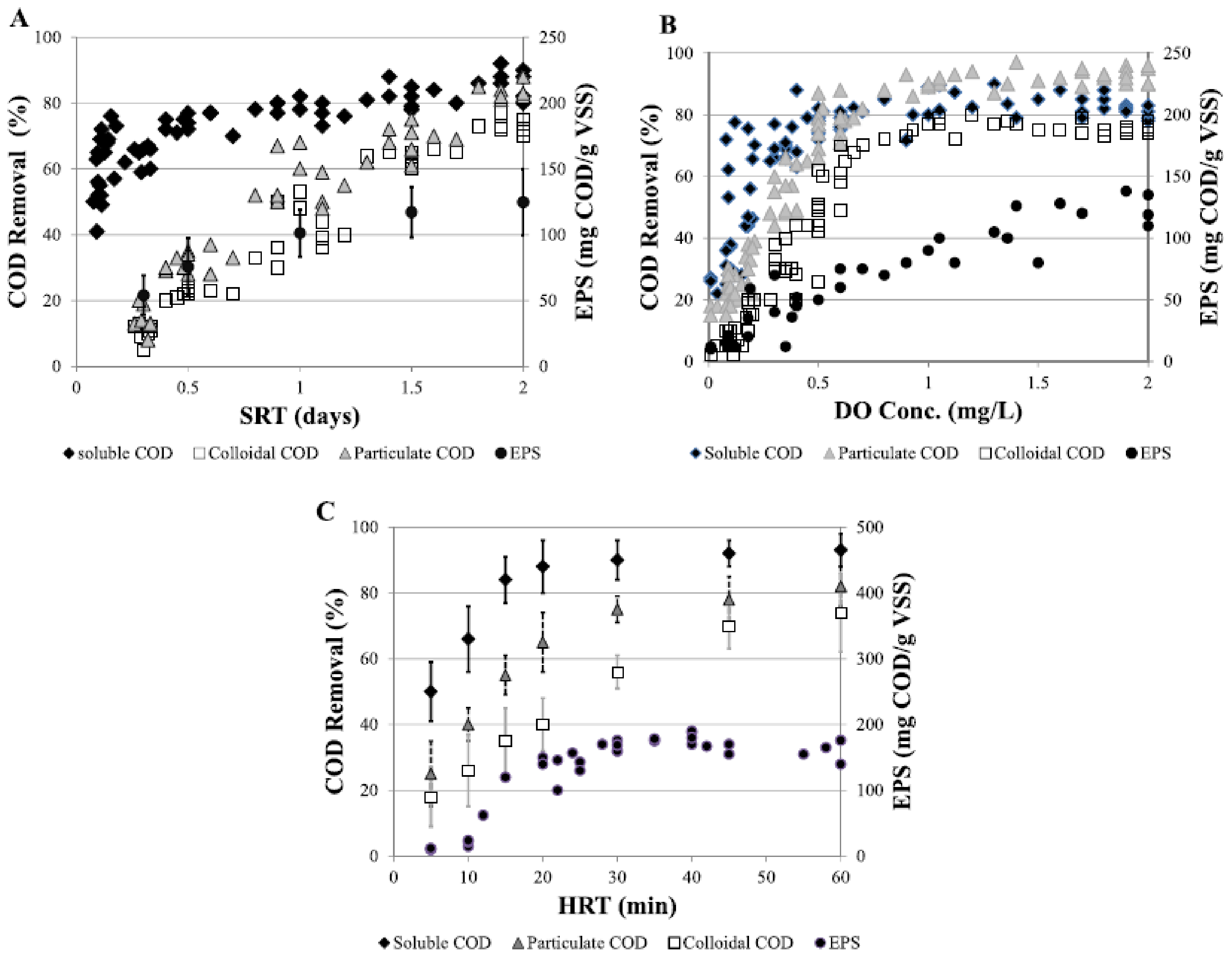
A CLOSER LOOK TO THE HRAS PROCESS

- Communities are distinctly different in terms of richness, evenness and composition
- High-rate communities are less shaped by deterministic factors, as environmental and operational variables



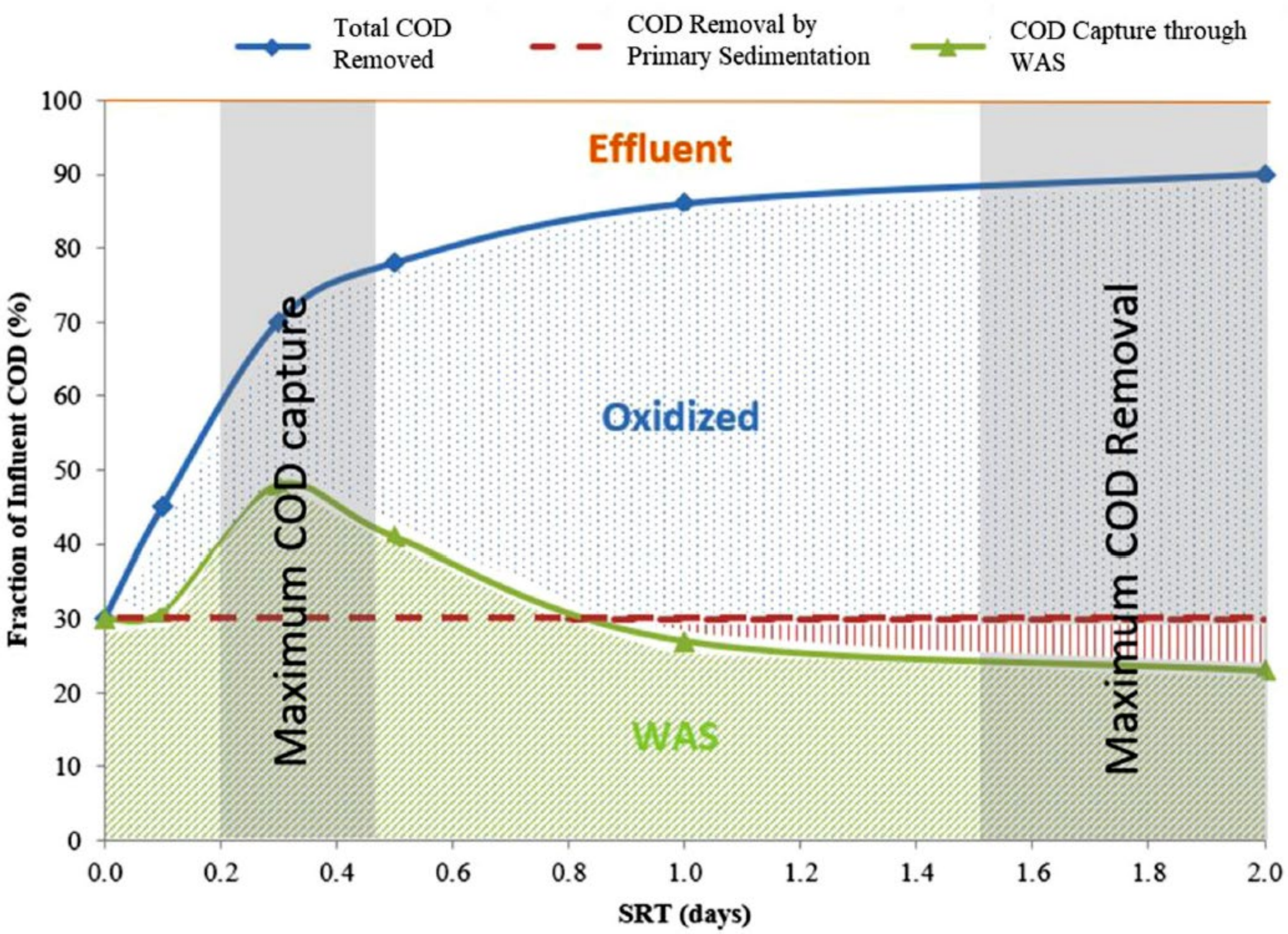
Meerburg et al. (2016)

A CLOSER LOOK TO THE HRAS PROCESS



Jimenez et al. (2015)

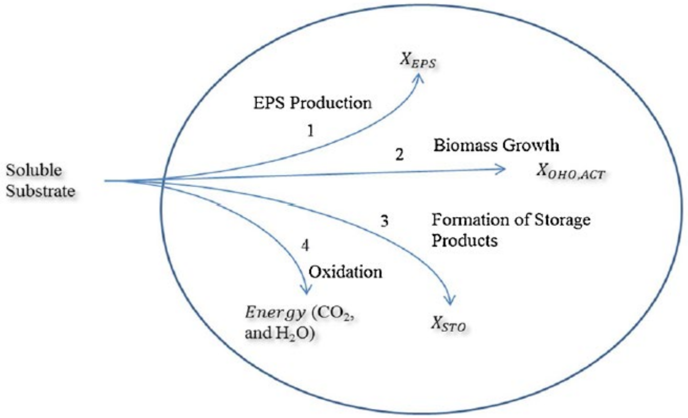
A CLOSER LOOK TO THE HRAS PROCESS



A-STAGE

Rahman et al. (2020)

A CLOSER LOOK TO THE HRAS PROCESS



SBf - rapidly biodegradable soluble organics

SBs - slowly biodegradable soluble organics

CB - colloidal biodegradable organics

CU - colloidal non-biodegradable organics

kEPS,PC - coefficients for EPS production

kSTO,PC - coefficients for formation of storage products

XB - particulate biodegradable organics

XU - particulate non-biodegradable organics

XEPS - extracellular polymeric substances

XSTO - intracellular storage polymeric substances

XOHO,ACT – active heterotrophic biomass

YOHO,AER - maximum yield for biomass

fU - cell debris non-biodegradable fraction

		S_{Bf}	S_{Bs}	C_B	C_U	X_B	X_U	$X_{OHO,\ ACT}$	X_{EPS}	X_{STO}
r1	Aerobic growth of X_{OHO}s – Fast	$-1/(Y_{OHO,AER}*(1-k_{EPS,PC}-k_{STO.PC}))$						1	$k_{EPS,PC}/(Y_{OHO,AER}*(1-k_{EPS,PC}-k_{STO,PC}))$	$k_{STO}/(Y_{OHO,AER}*(1-k_{EPS,PC}-k_{STO,PC}))$
r2	Aerobic growth of X_{OHOs} – Slow		$-1/(Y_{OHO,AER}*(1-k_{EPS,PC}-k_{STO.PC}))$					1	$k_{EPS,PC}/(Y_{OHO,AER}*(1-k_{EPS,PC}))$	$k_{STO}/(Y_{OHO,AER}*(1-k_{EPS,PC}-k_{STO,PC}))$
r3	Decay of heterotrophs					$1-f_U$		-1		
r4	Hydrolysis of entrapped organics		1			-1				
r5	Flocculation of colloidal substrate			-1		1				
r6	Flocculation of colloidal inerts				-1		1			
r7	Hydrolysis of storage products		1							-1
r8	EPS hydrolysis		1						-1	

Nogaj et al. (2019)

A CLOSER LOOK TO THE HRAS PROCESS

- Shunting more carbon to CO_2 leaves **less carbon available for synthesis and other removal mechanisms**

- **Longer SRT** provides greater opportunity for **biomass decay** and requires more energy for maintenance

- Less maintenance energy leaves **more electrons available for by-product formation**

- Bioflocculation is strongly related to extracellular polymeric substances - **EPS** (more to loosely bound than tightly bound)

- EPS production depends on **SRT, F/M ratio, HRT and DO** (as proxies of so many other things that we still do not know!)

> EPS production is the complex result of a combination of **stressful conditions and electron donor availability**

HRAS APPLICATION | GENERAL FEATURES

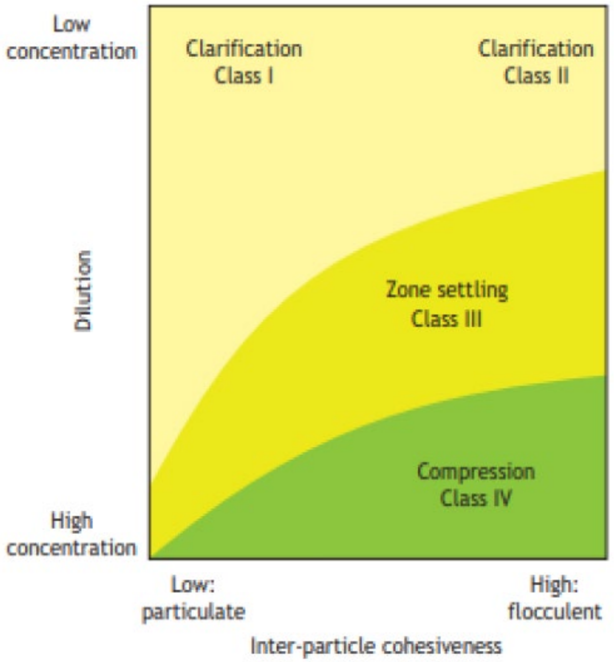
- **Check on B-stage feasibility** based on influent characteristics (C/N ratio: 5-10 for high-strength, 3-5 for low-strength)

- **Reduction in CAPEX and OPEX** for the water line due to reduced tank volumes (proportionally)
  reduced aeration requirements (up to 40%)

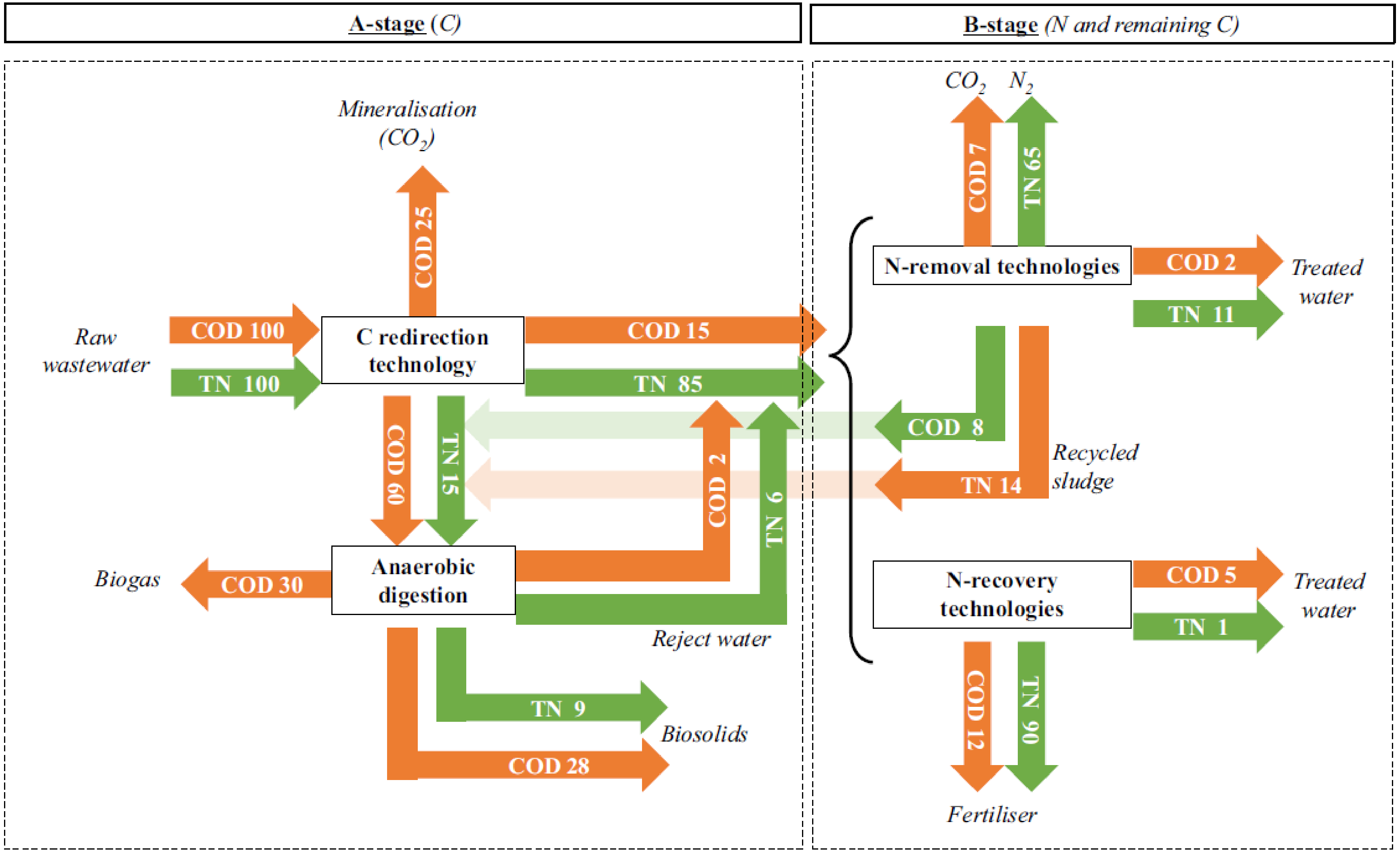
- Increase in the sludge and biogas flowrates, modification in **sludge characteristics**

- Need for **accurate oxygen control** to cope with influent wastewater fluctuations

- Modification in the **settling behavior of sludge**, possible process bottleneck



HRAS APPLICATION | PRELIMINARY MASS BALANCE



Sancho et al. (2019)

HRAS APPLICATION | A COMPARISON BASED ON MODELS

Influent

Q	20648	$m^3.d^{-1}$
COD	12235	$kg.d^{-1}$
N	1149	$kg.d^{-1}$

Clarifier_out

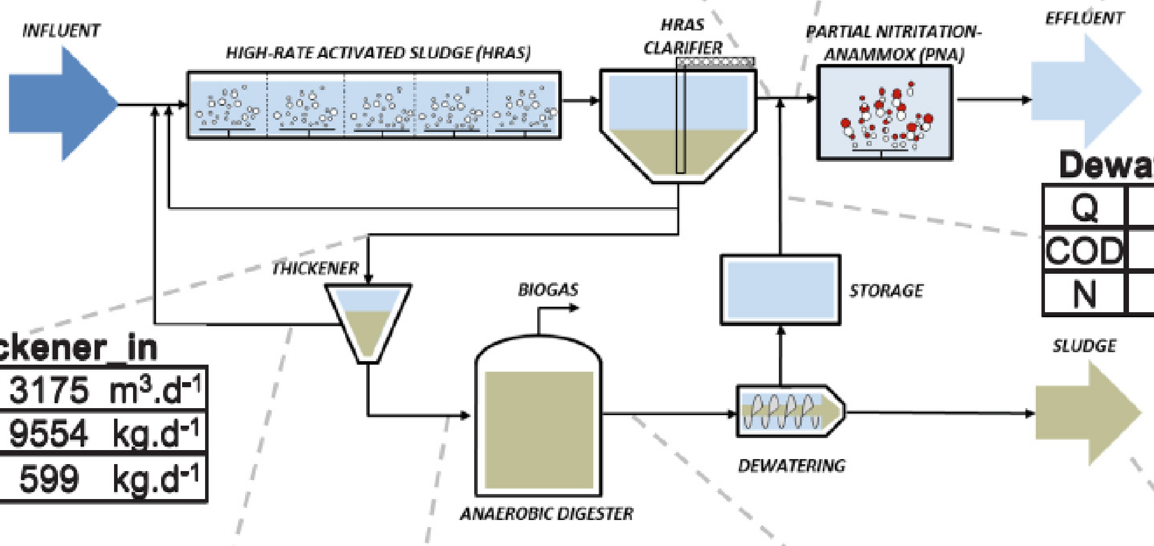
Q	20549	$m^3.d^{-1}$
COD	1954	$kg.d^{-1}$
N	647	$kg.d^{-1}$

PNA_in

Q	20641	$m^3.d^{-1}$
COD	2113	$kg.d^{-1}$
N	961	$kg.d^{-1}$

Effluent

Q	20641	$m^3.d^{-1}$
COD	1312	$kg.d^{-1}$
N	95	$kg.d^{-1}$



Dewatering_reject

Q	92	$m^3.d^{-1}$
COD	160	$kg.d^{-1}$
N	313	$kg.d^{-1}$

Thickener_in

Q	3175	$m^3.d^{-1}$
COD	9554	$kg.d^{-1}$
N	599	$kg.d^{-1}$

Thickener_out

Q	3076	$m^3.d^{-1}$
COD	285	$kg.d^{-1}$
N	97	$kg.d^{-1}$

Digester_in

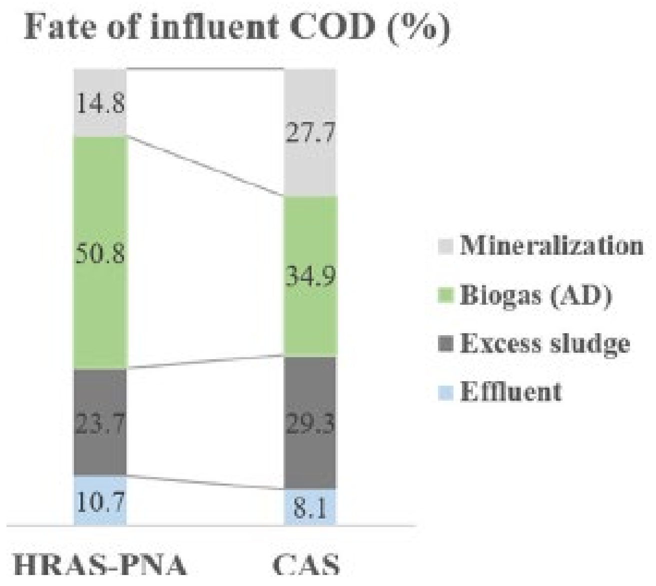
Q	99	$m^3.d^{-1}$
COD	9269	$kg.d^{-1}$
N	502	$kg.d^{-1}$

Digester_out

Q	99	$m^3.d^{-1}$
COD	3059	$kg.d^{-1}$
N	502	$kg.d^{-1}$

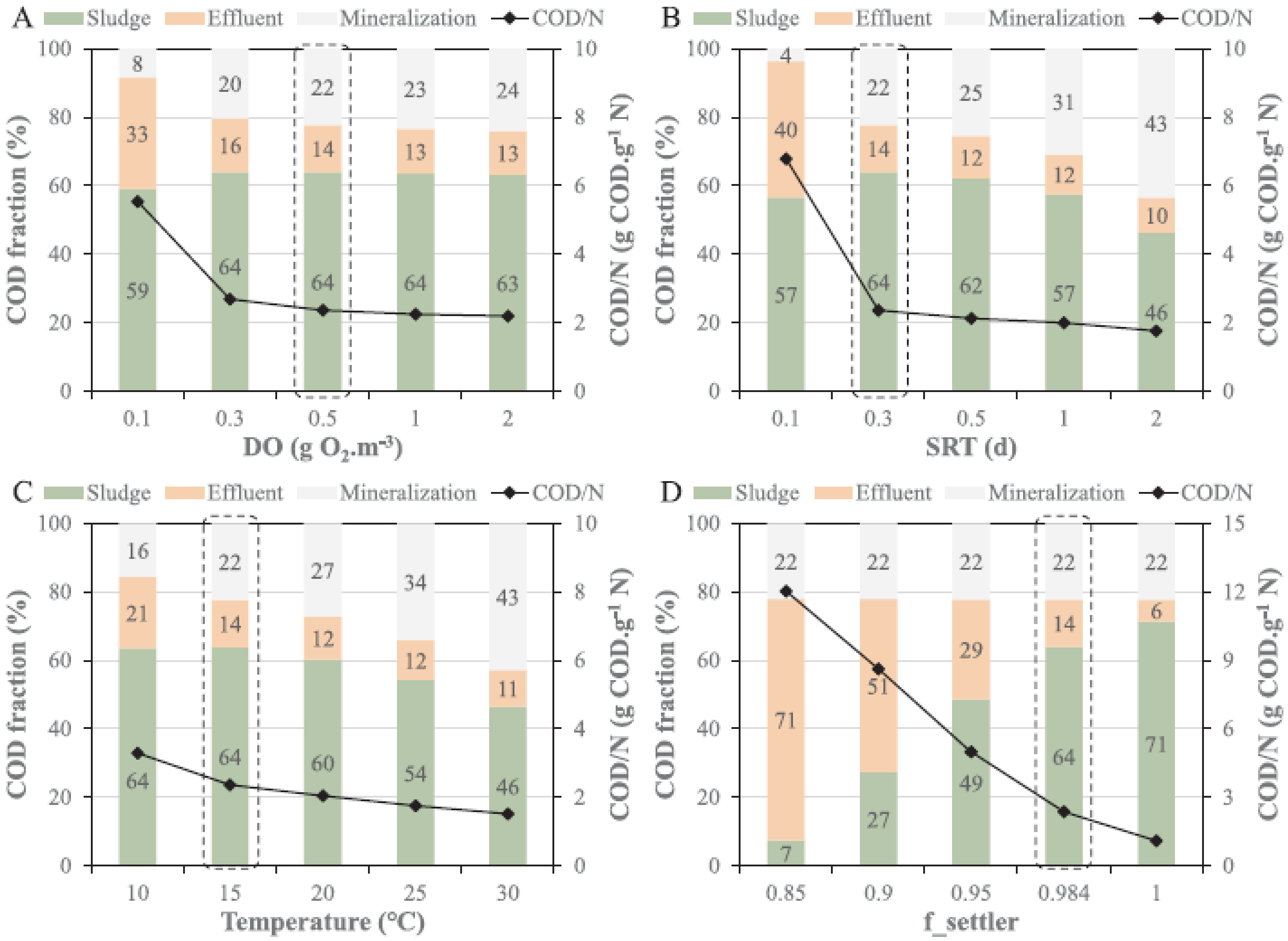
Sludge

Q	8	$m^3.d^{-1}$
COD	2899	$kg.d^{-1}$
N	189	$kg.d^{-1}$



Jia et al. (2020)

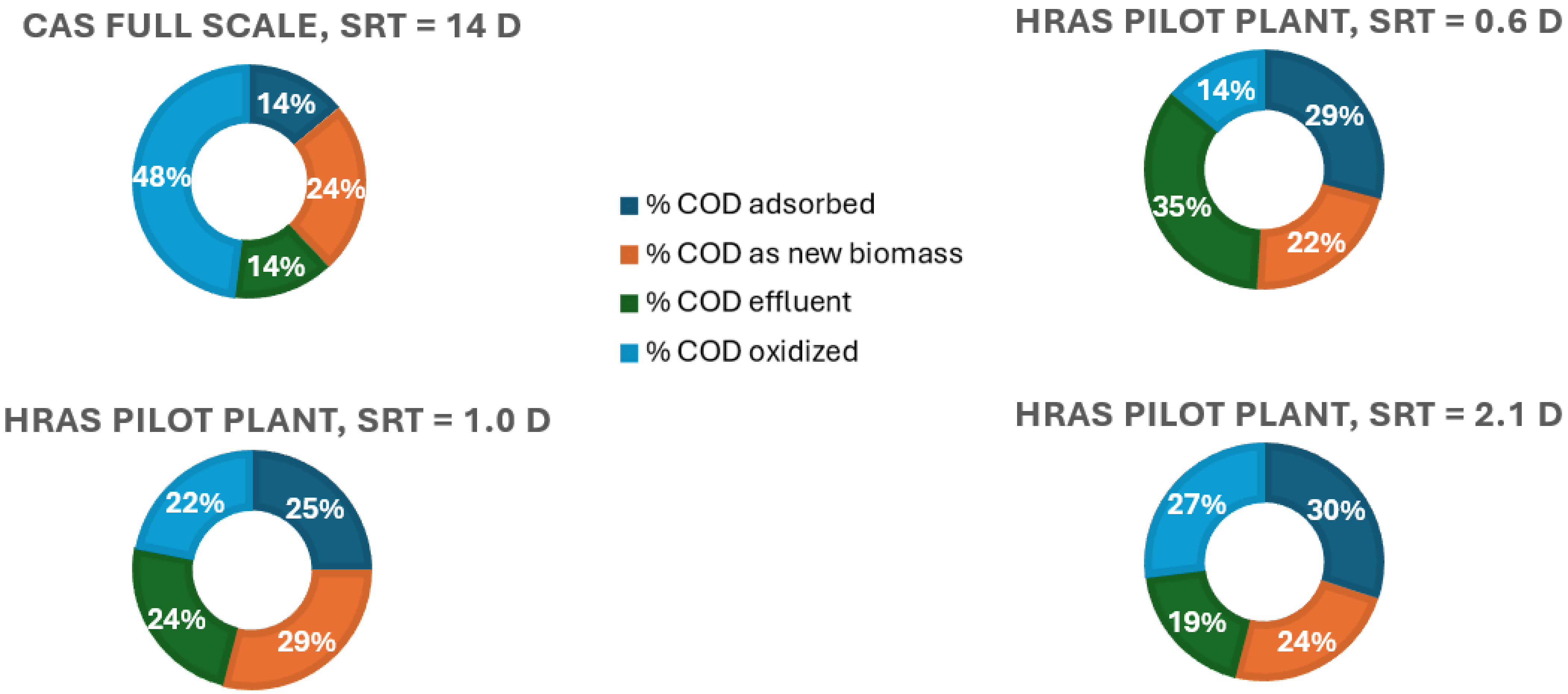
HRAS APPLICATION | A COMPARISON BASED ON MODELS



Jia et al. (2020)

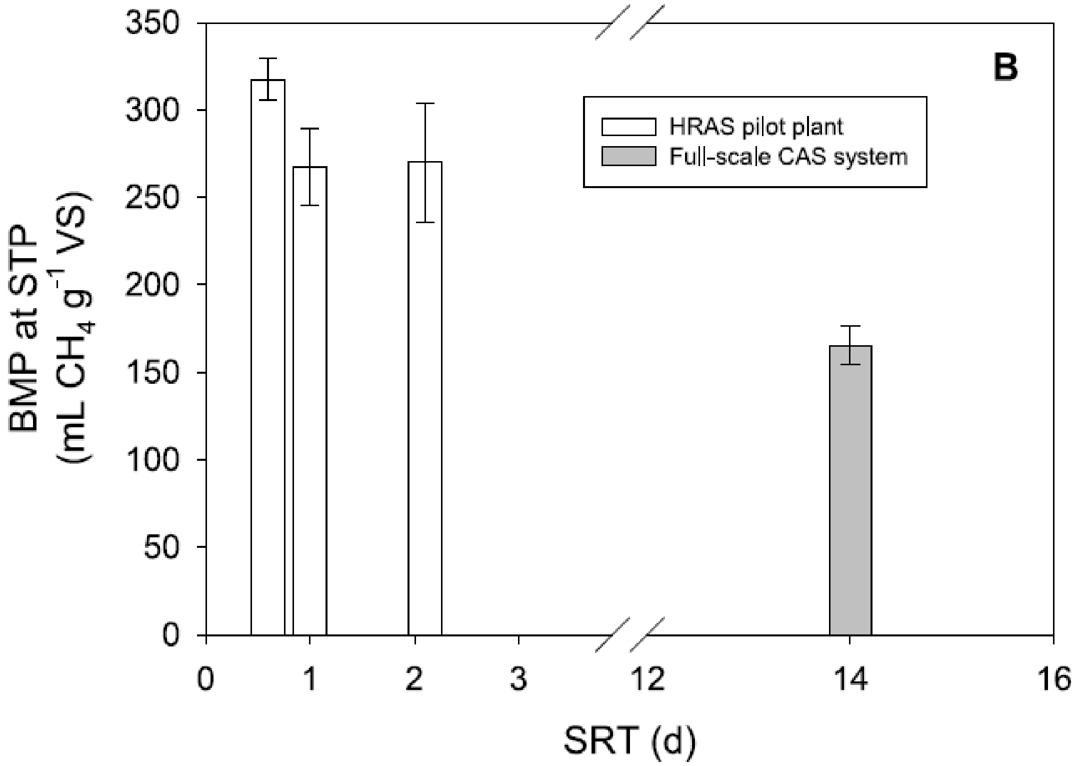
HRAS APPLICATION | A REAL-LIFE COMPARISON

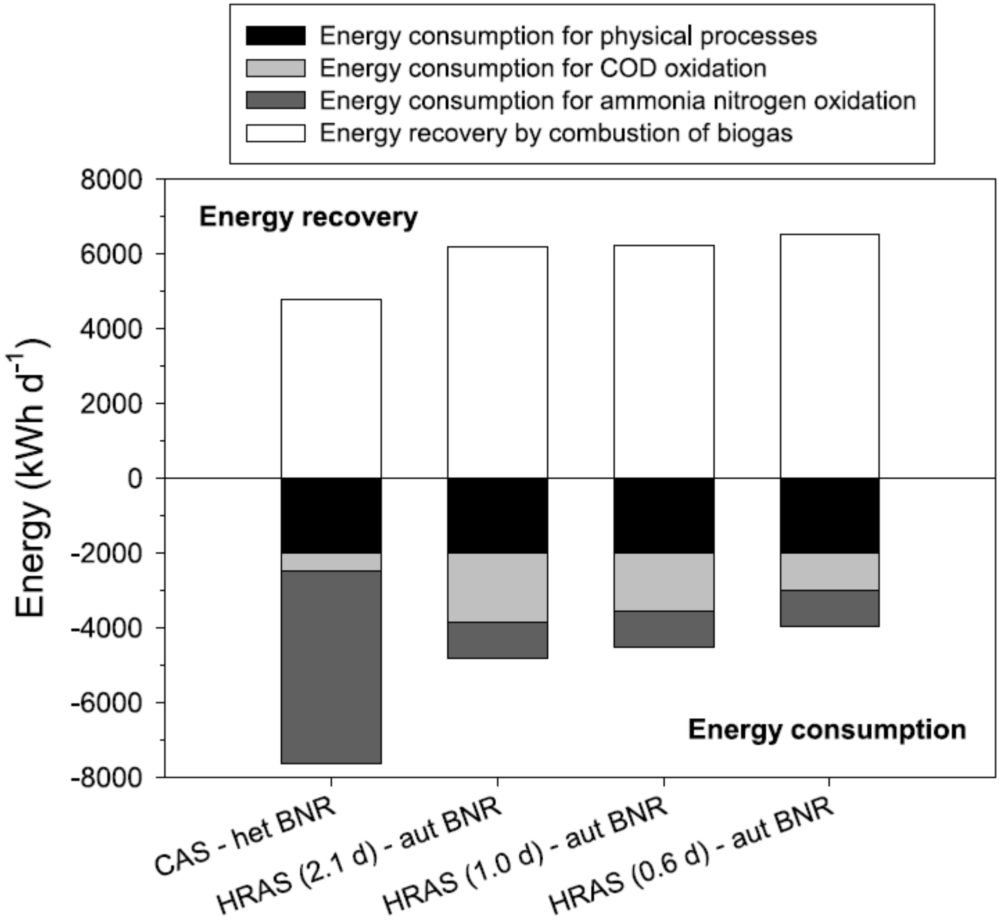
- Performance comparison between full scale CAS and HRAS pilot plant (250 L) inside the same WWTP



Carrera et al. (2022)

HRAS APPLICATION | A REAL-LIFE COMPARISON





- The sludge from the HRAS configuration has **significantly higher BMP**
- The **energy recovered from biogas production** is 29-36% higher than in the CAS
- **Two-thirds of energy reduction of aeration requirements** and one-third increase of biogas production
  > average net energy production of ca. 0.1 kWh per cubic meter of wastewater treated in a HRAS-autBNR

Carrera et al. (2022)

OPEN RESEARCH QUESTIONS

(1) Improve the knowledge about **the influence of operating conditions on EPS formation, internal storage and settleability**

(2) Based on improved knowledge, identify **guidelines for system design and operation** for enhancing performance and stability

(3) Develop **process modelling and control** tools for supporting phenomena understanding and optimized management

(4) Effectively **integrate HRAS in AB stage systems** looking at process scale-up

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