Wastewater and Biosolids Treatment and Reuse: Bridging Modeling and Experimental Studies

Proceedings

Spring 6-10-2014

Valorization of sewage sludge via nitrite nutrients removal from anaerobic effluents

F. Fatone
University of Verona

S. Longo
University of Verona

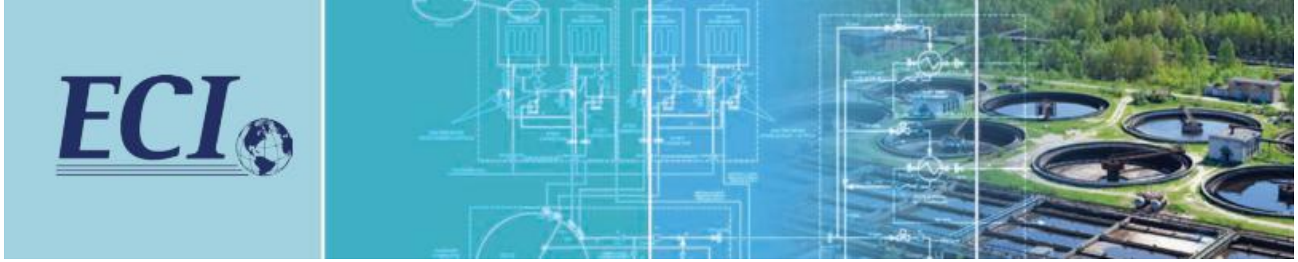
N. Frison
University of Verona

E. Karsou
University of Verona

S. Malamis
University of Verona

See next page for additional authors

Authors
F. Fatone, S. Longo, N. Frison, E. Karsou, S. Malamis, D. Renzi, and L. Lijo



Valorization of sewage sludge for via nitrite nutrients removal from anaerobic effluents

S. Longo, N. Frison, E. Katsou, S. Malamis, D. Renzi, L.Lijò, **F. Fatone**

Department of Environmental Sciences, Informatics and Statistics, University Ca’Foscari of Venice,

Department of Biotechnology, University of Verona,

Alto Trevigiano Servizi, Montebelluna, Italy

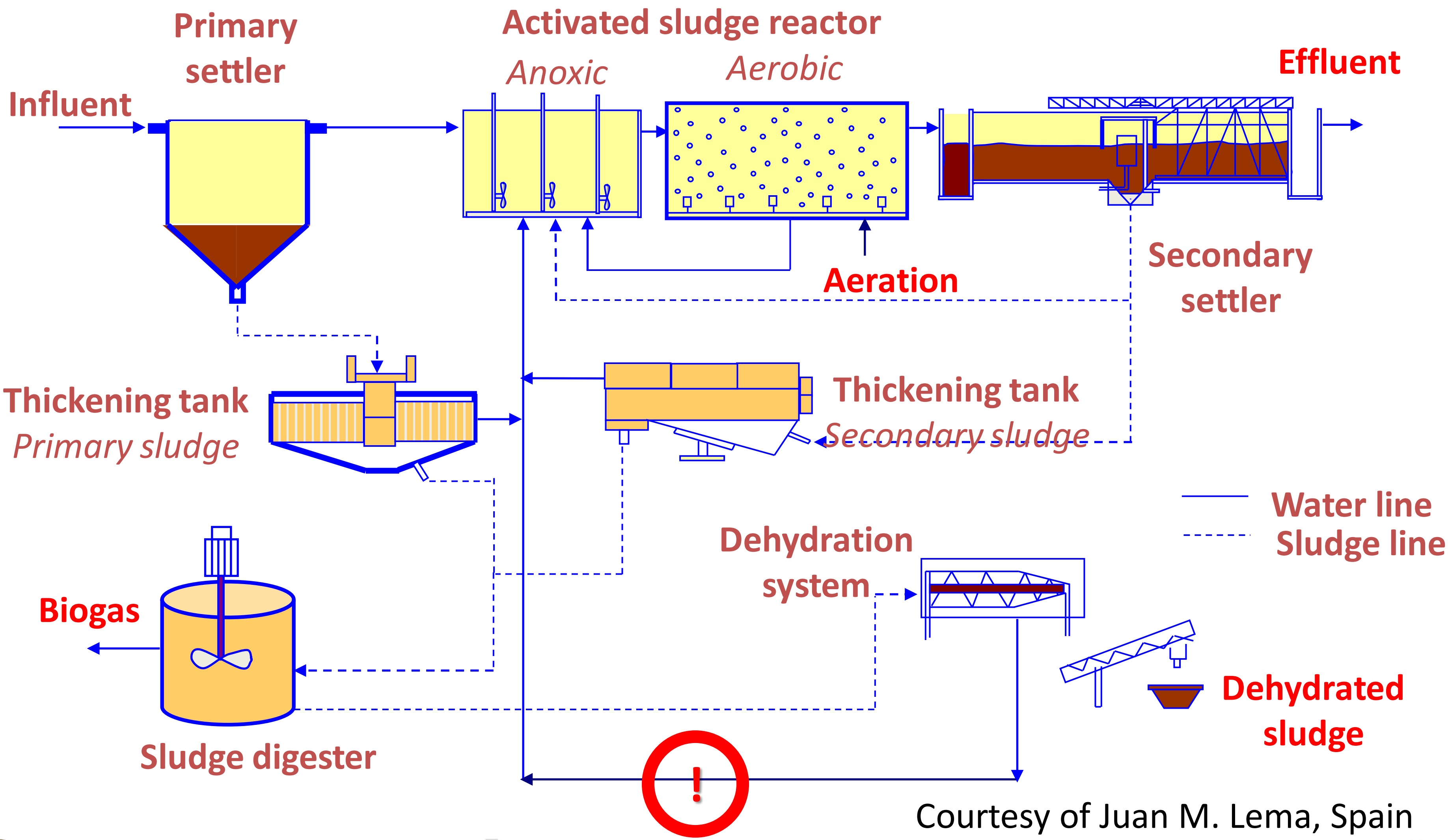
Biogroup, University of Santiago de Compostela, Spain

June 8-14, 2014
Otranto (Lecce), ITALY

Outline

- Anaerobic side-stream: a key-stream to optimize nutrients management in WWTPs
- Short-cut nitrogen removal and via nitrite phosphorus bioaccumulation
  - Bioprocesses
  - Pilot-scale application
  - Full scale development
- Conclusions and future perspectives

Conventional MLE and AD in WWTPs



Courtesy of Juan M. Lema, Spain

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Ammonification within anaerobic digestion of sewage sludge

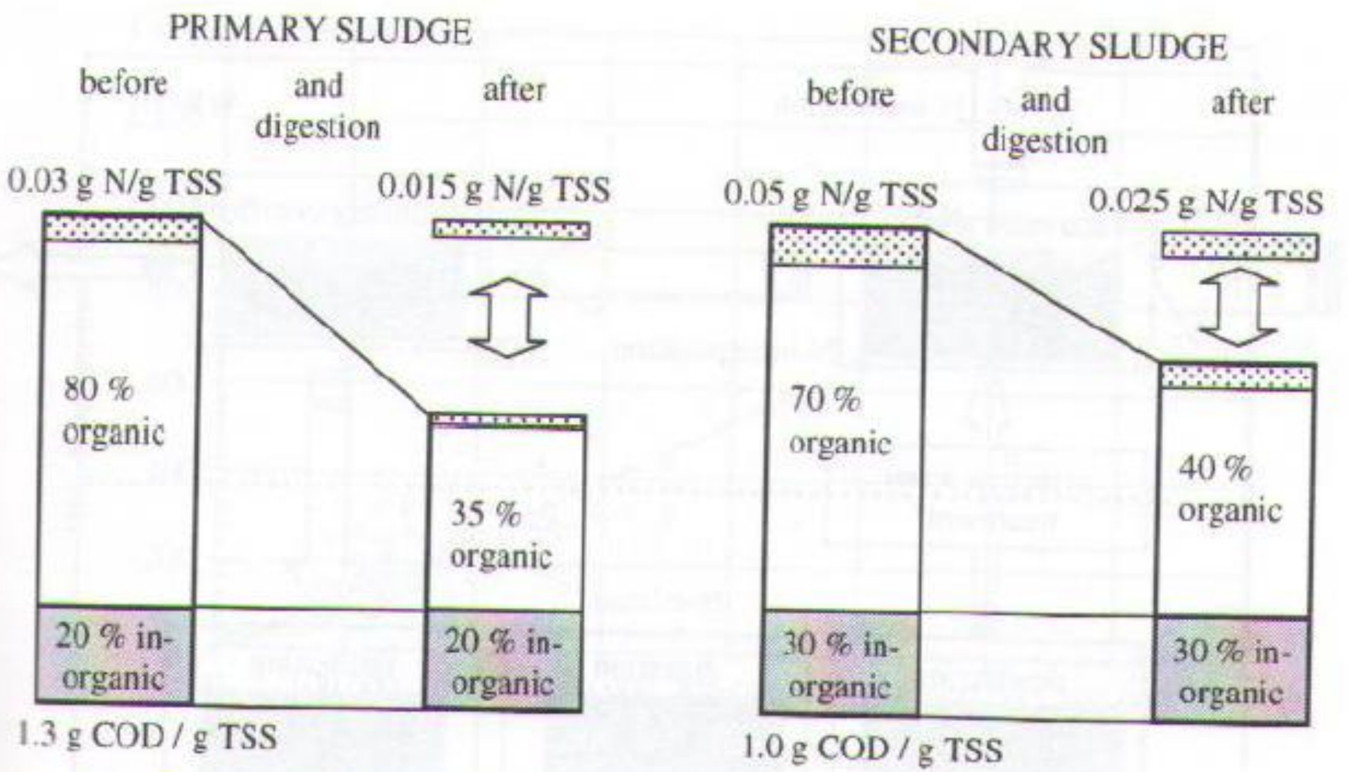
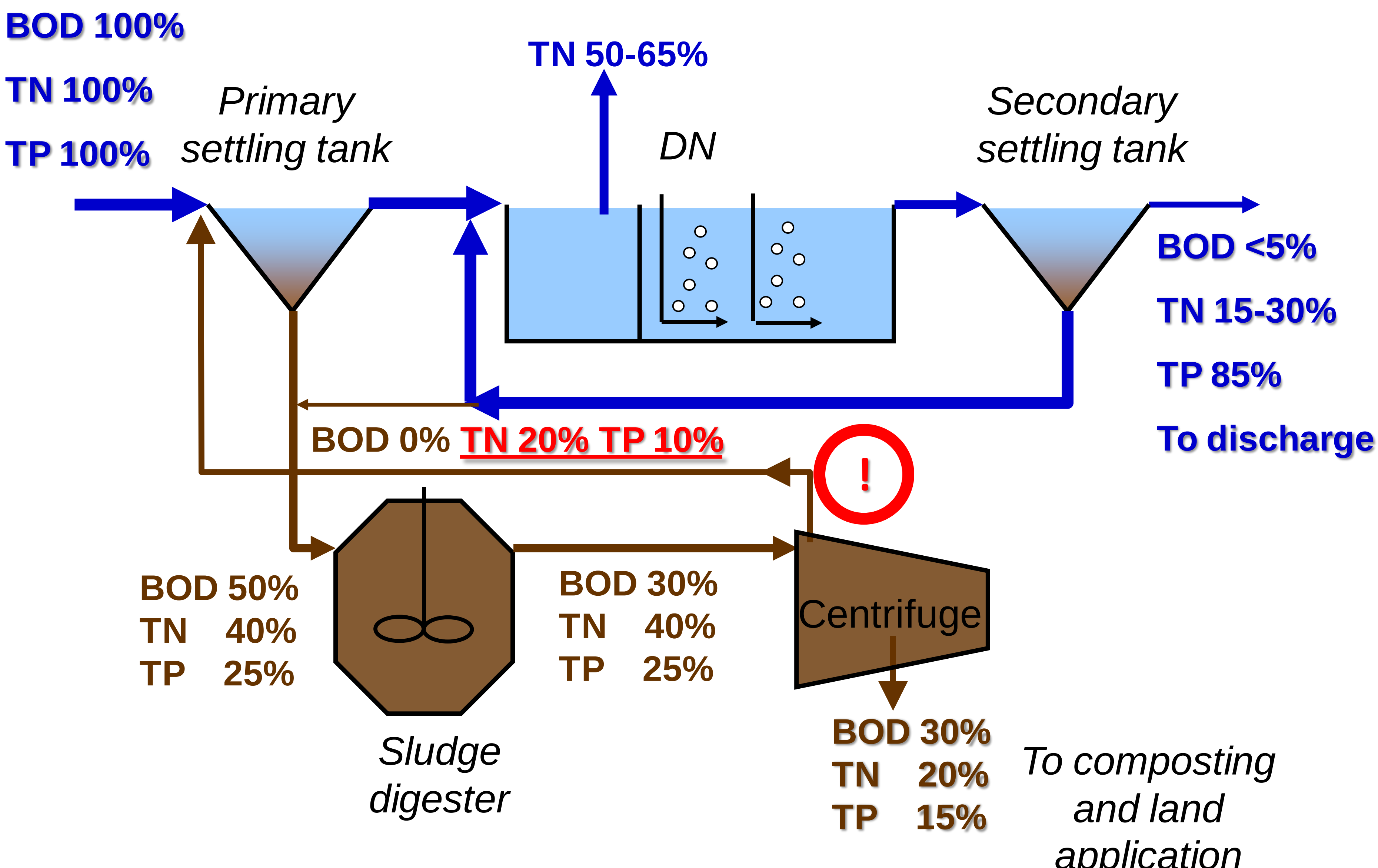
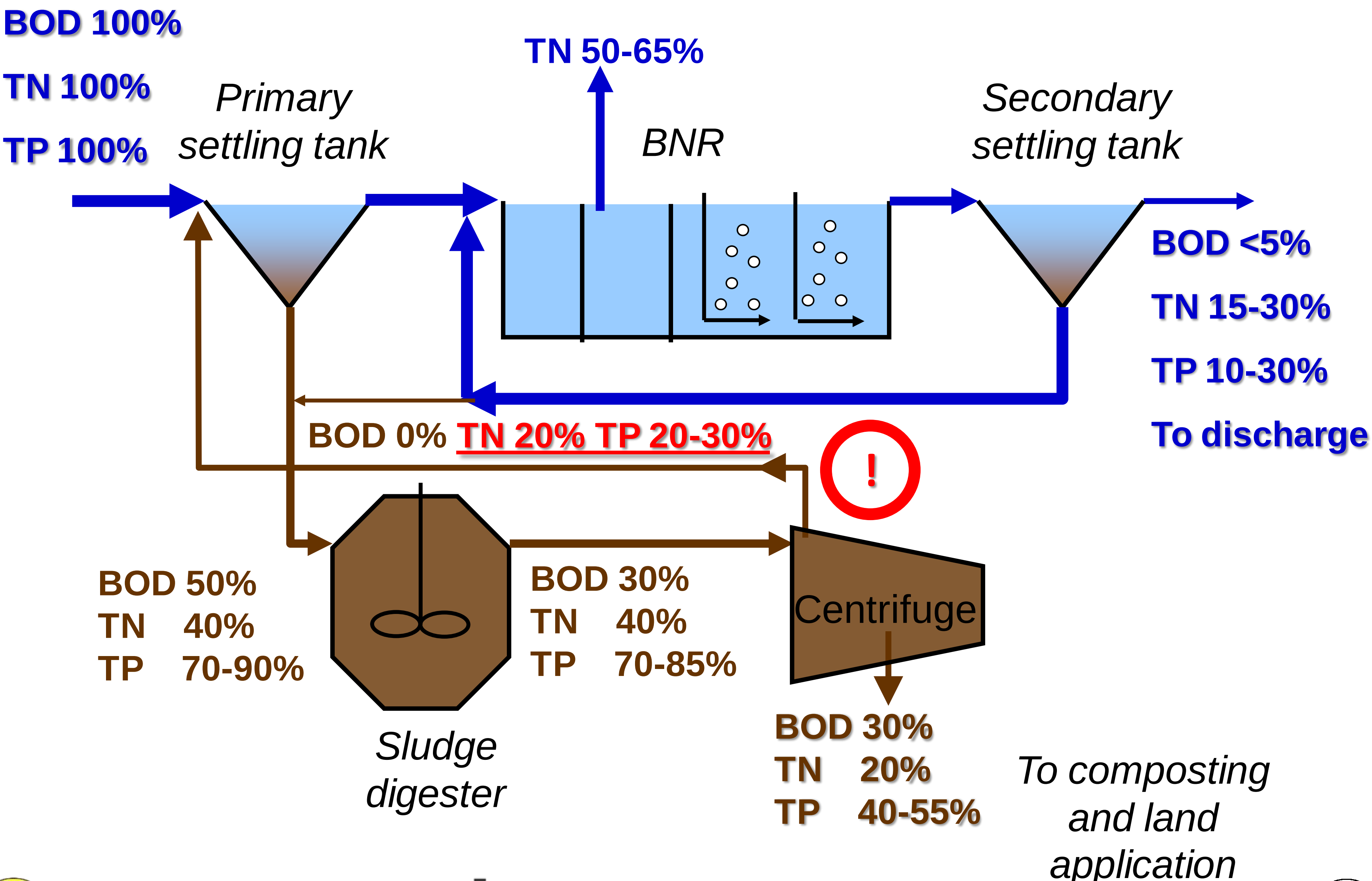


Figure 6.2. Release of nitrogen bounded in primary and secondary sludge (values related to initial total suspended solids TSS in digester feed)

Conventional MLE and AD in WWTPs



Conventional BNR-AD in WWTPs



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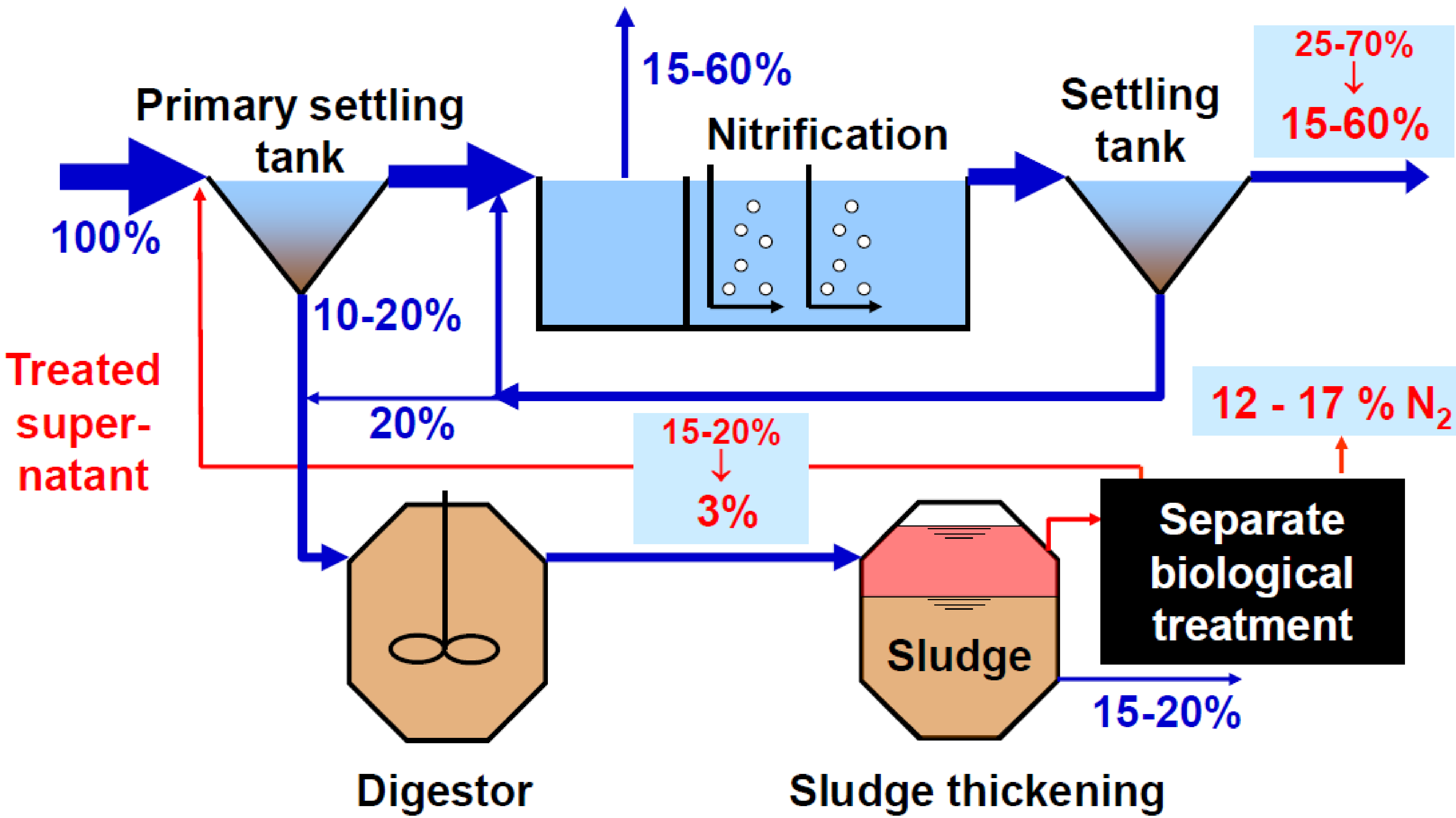
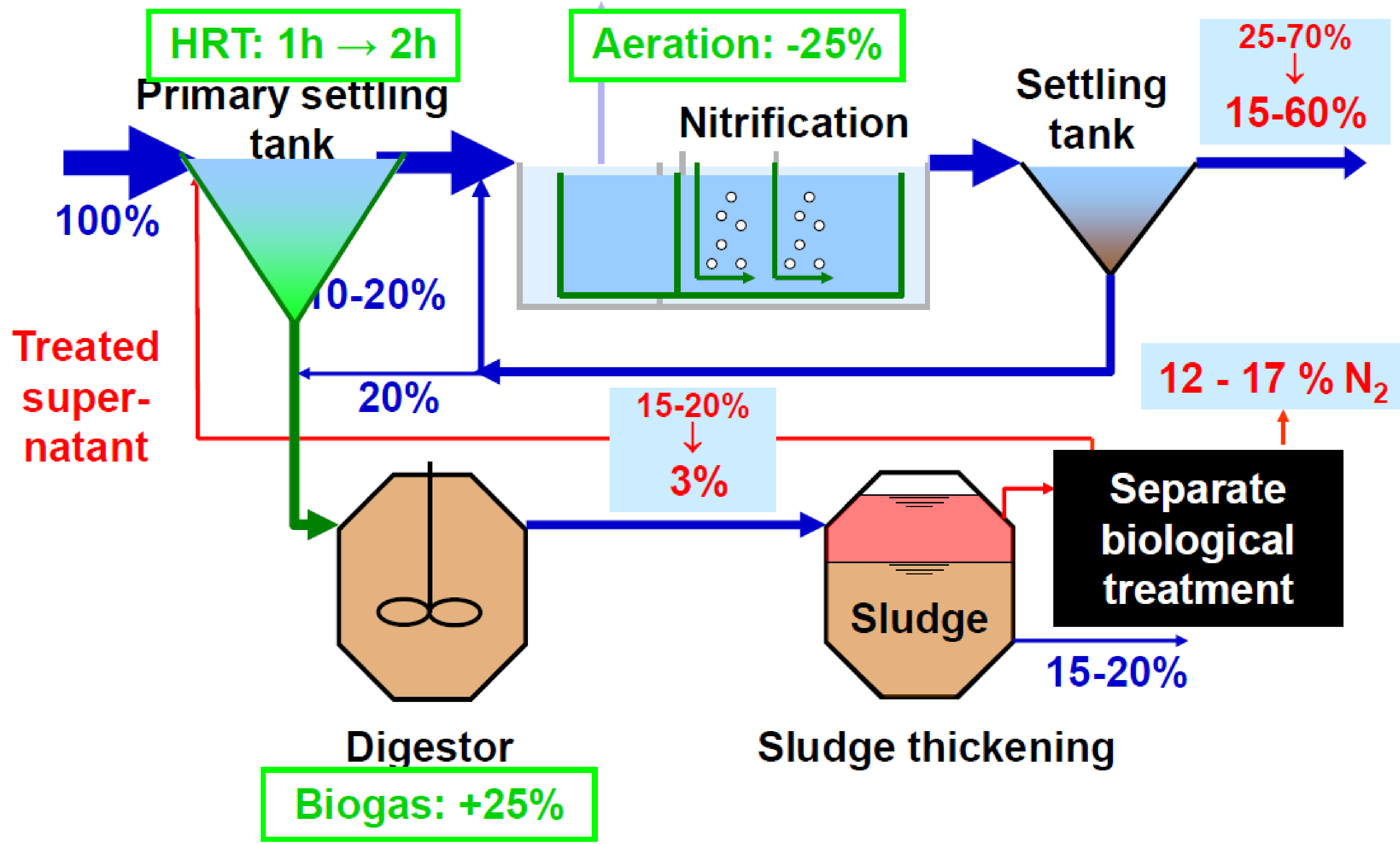
Revamping and optimization - scheme 1



Revamping and optimization - scheme 2



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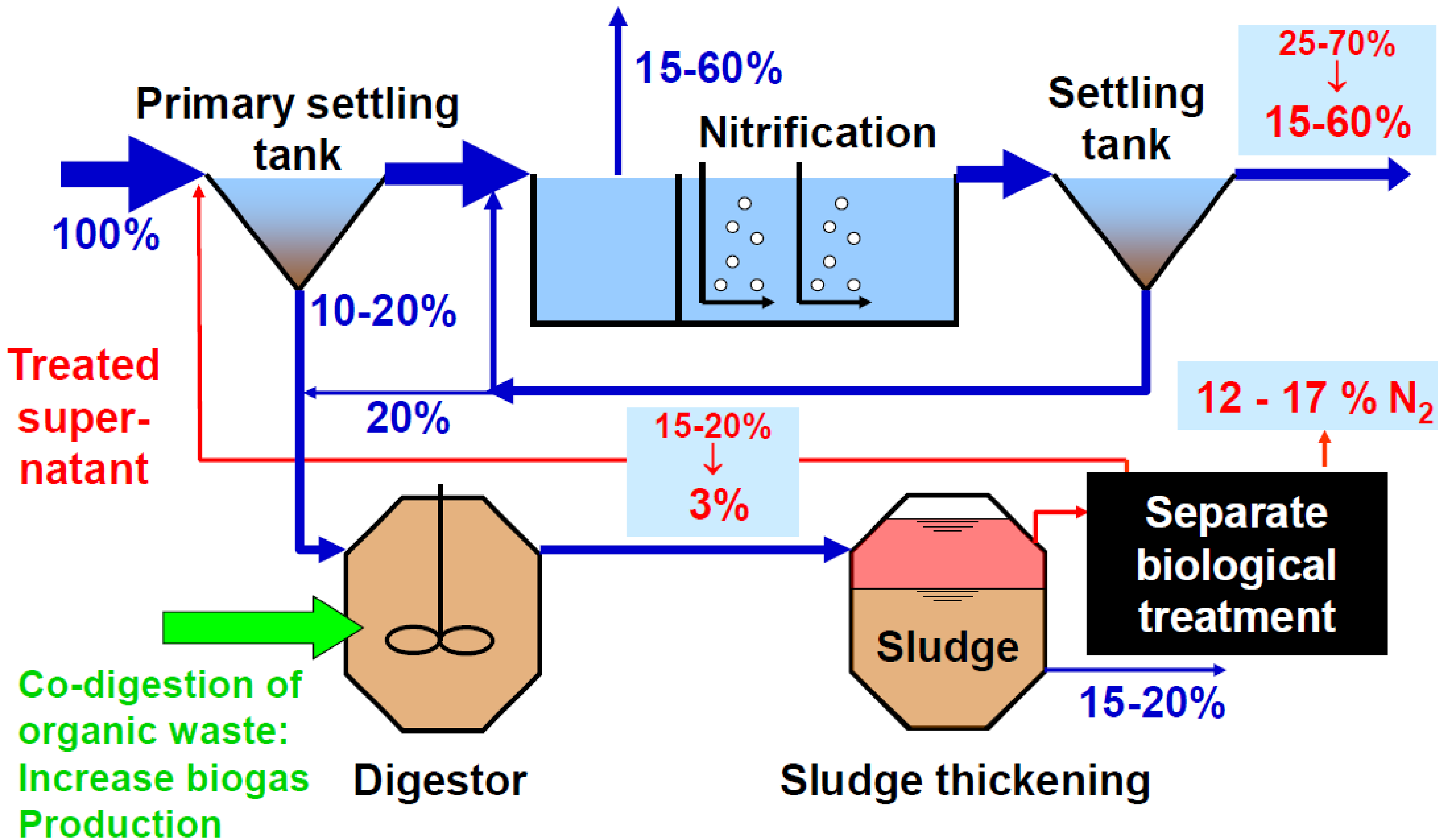
Revamping and optimization - scheme 3



⟶ Energy neutral wastewater treatment (WWTP Zurich, WWTP Strass)

Anaerobic supernatant from WAS and/or OFMSW

	TSS	COD	N-NH4	TN	Ptot	pH	Alcalinità totale	Conducibilità
	g/L	gCOD/L	gN/kg	gN/kg	mgP/L	-	gCaCO3/kg	mS/cm
Only OFMSW	1.6-2.57	2.7-8.2	500-3000	3000-8000	50-300	7.3-8.5	Fino a 8000	1.47-23.8
WAS + OFMSW	<0.1	50-170	355-535					

AFTER DIGESTION OF (ONLY) OFMSW:

Very variable depending on the quality and characteristics of the OFMSW

Critical Reviews in Biotechnology

http://informahealthcare.com/bty
ISSN: 0738-8551 (print), 1549-7801 (electronic)

Crit Rev Biotechnol, Early Online: 1–14
 DOI: 10.3109/07388551.2013.791246

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REVIEW ARTICLE

Biological nutrient removal from the supernatant originating from the anaerobic digestion of the organic fraction of municipal solid waste

S. Malamis, E. Katsou, S. Di Fabio, D. Bolzonella, and F. Fatone

Department of Biotechnology, University of Verona, Verona, Italy

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Anaerobic supernatant from WAS and/or OFMSW

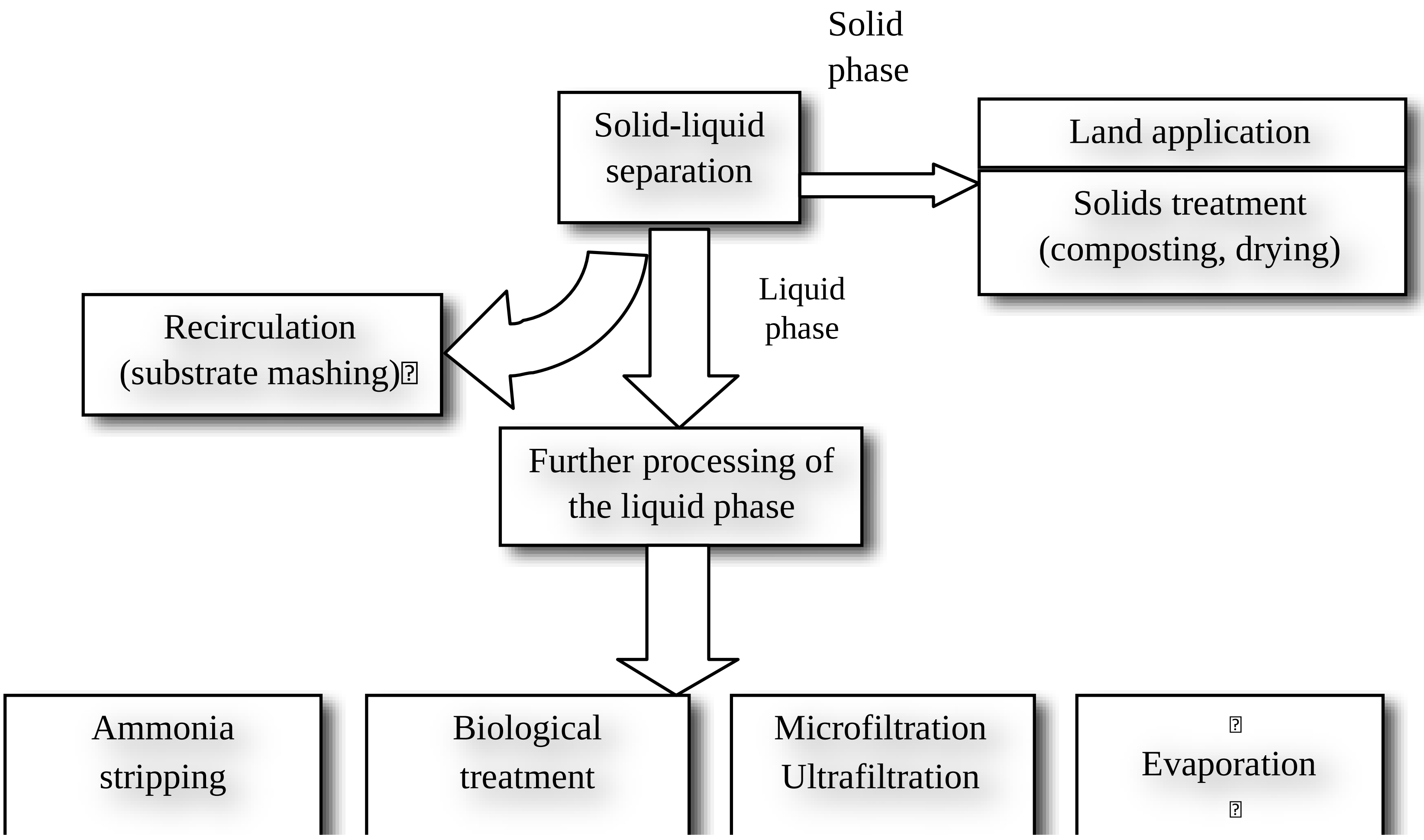
	TSS	COD	N-NH4	TN	Ptot	pH	Alcalinità totale	Conducibilità
	g/L	gCOD/L	gN/kg	gN/kg	mgP/L	-	gCaCO3/kg	mS/cm
Only OFMSW	1.6-2.57	2.7-8.2	500-3000	3000-8000	50-300	7.3-8.5	Fino a 8000	1.47-23.8
WAS + OFMSW	<0.1	50-170	355-535 (446)	355-535 (491)	33-117	7.5-7.9	1380-2270	3-6

AFTER CODIGESTION OF WAS AND OFMSW

Generally, linear relation between ammonium and OFMSW fed

$$NH4\text{-}N\ (g/L) = 0.132\ OLR_{OFMSW} + 0.485$$ (Pavan et al. 2008)

Treatment alternatives for anaerobic side-stream



Treatment alternatives for anaerobic side-stream

Nutrients recovery by chemical-physical treatments	
Membrane processes (UF-RO)	Pretreatment for solids separation. Expensive treatment of the retentate (**>5 €/m3**)
Struvite precipitation and/or crystallization	Recovery of N and P as MAP. Unknown investment costs and market for MAP (**>6 €/m3**)
Ammonia stripping and recovery by acid scrubbing	High performances (>90%). VOC production and high O&M costs (**>6-8 €/m3**)
Ion exchange	High O&M costs for strong nitrogenous wastewater
Nutrients removal (nitrogen elimination N → N_{2gas})	
Biological processes	**Conventional** (**3-5 €/m3**) Costly for aeration requirement and external carbon source **Innovative (1-2 €/m3)** Short-cut nitrification denitrification, complete autotrophic nitrogen removal
Constructed wetland (Submerged Flow Systems –SFS-, Free Flow Systems –FFS-)	Efficient as tertiary (finishing) treatment . Scarce denitrification, frequent clogging

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(Van Kempen et al., 2001)

Via-nitrate and via-nitrite processes: the framework

Processes	O_2 consumption (kg O_2 (kg N)$^{-1}$)	COD consumption (kg COD (kg N)$^{-1}$)	CO_2 emission (kg CO_2 (kg N)$^{-1}$)	Yield (kg VSS (kg N)$^{-1}$)
Nitrification-Denitrification	4.57	2.86	5.76	1.0 - 1.2
Partial Nitrification-Denitrification	3.43	1.71	4.72	0.8 - 0.9
Partial Nitrification-Anammox	1.71	0	3.14	< 0.1

$$NH_4^+ + 0.625\ CH_3COOH + 2\ O_2 + HCO_3^- \rightarrow 0.5\ N_2 + 3.75\ H_2O + 2.25\ CO_2$$

$$NH_4^+ + 0.375\ CH_3COOH + 1.5\ O_2 + HCO_3^- \rightarrow 0.5\ N_2 + 3.25\ H_2O + 1.75\ CO_2$$

$$NH_4^+ + 0.85\ O_2 + 1.11\ HCO_3^- \rightarrow 0.44\ N_2 + 0.11\ NO_3^- + 2.56\ H_2O + 1.11\ CO_2$$

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AnAmmOx: current development

two-stage

spatial separation

Nitritation
- **PANDA**
- **SAT**
- **SHARON®**

Anammox
- **PANDA+** (susp. BM)
- **ANAMMOX®** (gran. BM)
- **Moving Bed** (Biofilm)

Diffusion limited
- **DeAmmon** (Moving Bed)
- **CANON/OLAND** (RD)
- **SNAP** (Submerged Fixed Bed)
- **ANAMMOX®** (gran. BM)
- **PNAA** (susp./gran. BM)

Intermittent aeration
- **DEMON®** (SBR)
- **DIB** (Moving Bed)

single-stage

Temporal separation / diffusion

More than 50 full scale plants for side-stream treatment

Courtesy Yvonne Schneider

AnAmmOx or non AnAmmOx: selection criteria

- Investment costs (volume, materials)
- Energy demand (aeration, mixing, pumping)
- Chemicals (NaOH, C-source)
- Sludge disposal (treatment, transport)
- **Start-up (duration, effort)**
- Control system (complexity, degree of automation)
- **Experience (full-scale plants in operation)**
- **Stability (endurance, resistance against peak loads, inhibition)**

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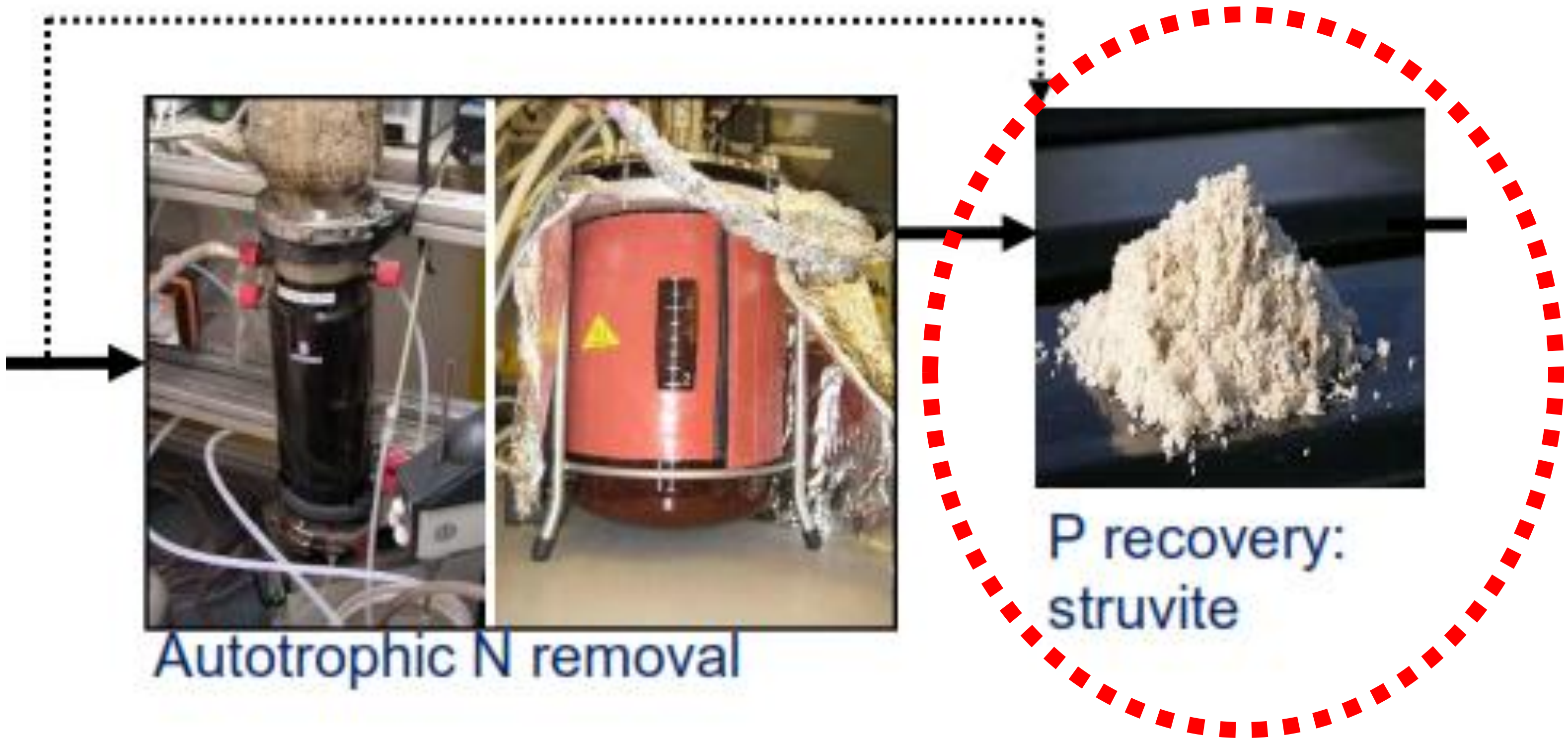
What about phosphorus?



Post-treatment is necessary for phosphorus recovery

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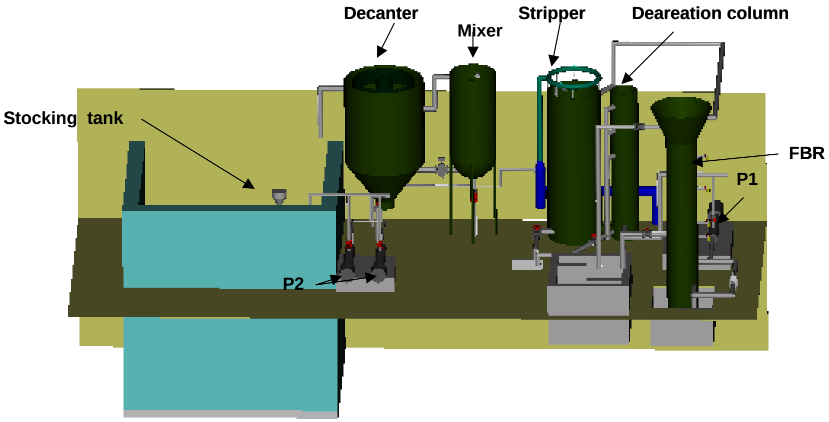
Struvite Crystallization Process at the Treviso municipal WWTP



The recovered struvite must be disposed as waste >> the SCP plant was dismissed after the plant and process validation

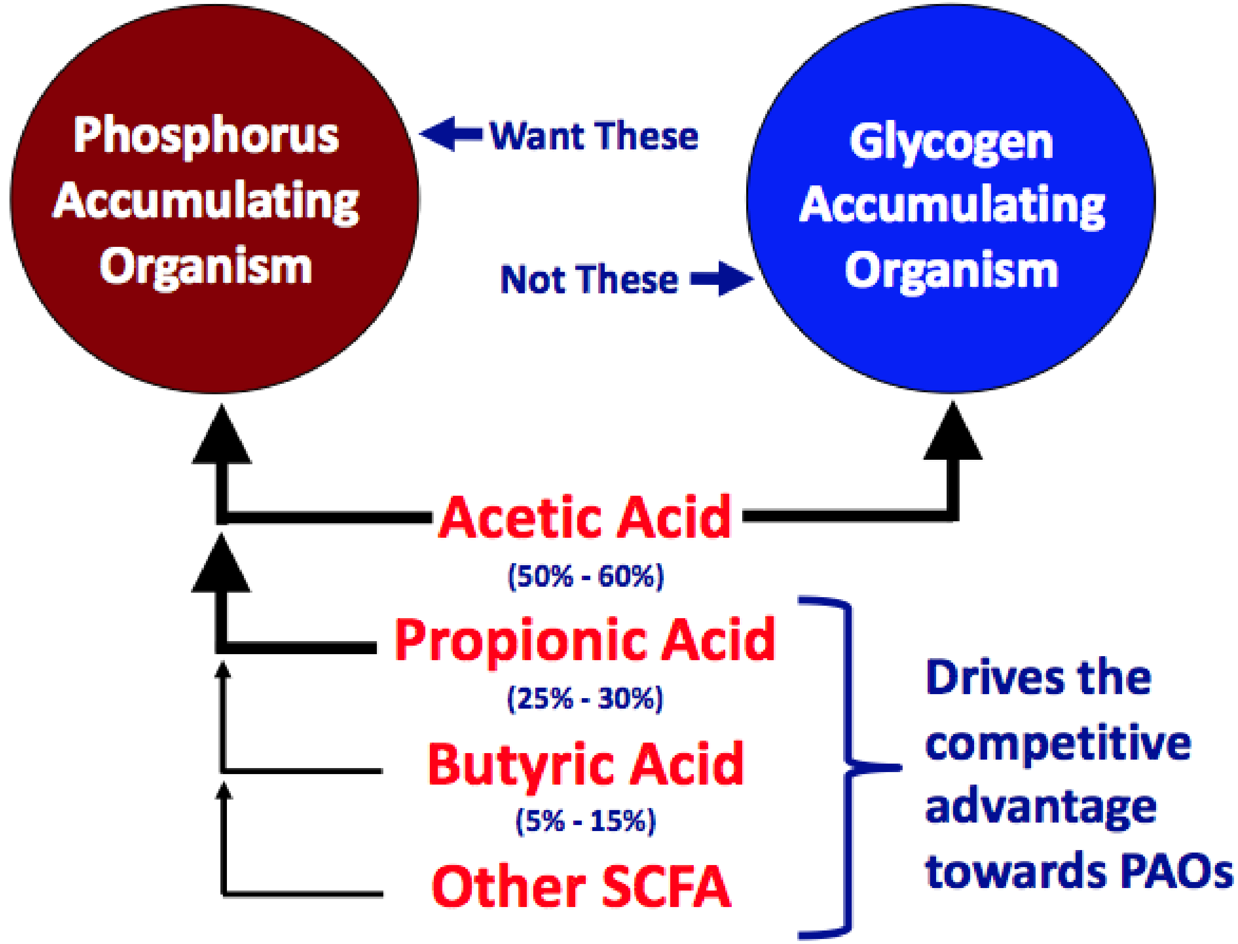
Struvite vs BioP: an open debate

Struvite (MgNH4 PO 4 ·6HO) is generally considered as the optimal phosphate mineral for recovery as it **contains 51.8% of P_2O_5** (based on MgNH 4 PO2) and could potentially be used as a slow-release fertilizer. If the **economic and life cycle costs are taken into account**, however, **phosphate recovery as struvite was not considered the best approach**, for the following reasons: (1) production of P-mineral with a high content of struvite from real wastewater is a difficult and costly process; and (2) struvite is not superior to other phosphate based compounds in fertilization efficiency, nor is it an exclusive form of raw materials favored by the fertilizer industry. Hence, phosphate recovery could be aimed at any acceptable forms of phosphate-based compounds by the fertilizer industry, depending on onsite circumstances. **Accordingly, efforts should also go to the use of (composted) sludge for effective fertilization**

Xiaodi Hao, Chongchen Wang,Mark C. M. van Loosdrecht, Yuansheng Hu. Looking Beyond Struvite for P-Recovery ***Environ. Sci. Technol. 2013, 47, 4965-4966***

Best Available Carbon Source for EBPR: a mix of SCFAs mixture enhances the biological processes for nutrients removal

PHOSPHOROUS REMOVAL



CH_3COOH

CH_3CH_2COOH

$CH_3CH_2CH_2COOH$

$CH_3CH_2CH_2...COOH$

Fermentation promotes production of acetate <u>and</u> propionate as primary by-products

Zeng, et al (2006)
Bouzas, et al (2000)

Comparison of the via nitrite with the via nitrate EBPR

- Guisasola et al. (2009) found a **higher anoxic NUR/PUR ratio for the via nitrite EBPR** compared to the respective ratio found in literature for the via nitrate EBPR. Since the energy obtained from the denitrification of one mole of nitrite is lower than the respective one for one mole of nitrate a higher amount of nitrite is required to uptake 1 mole of phosphate.
- Lee et al. (2001) found that **PUR was higher when nitrite was the electron acceptor rather than nitrate**.
- Martín et al. (2006) showed that **the dominant DPAOs of *Accumulibacter* used nitrite instead of nitrate as electron acceptor**.
- Peng et al. (2011) found that the **short-cut nutrients removal process could save more than 22.3% and 49.4% of poly-b-hydroxyalkanoate (PHA)** for phosphorus and nitrogen removal respectively compared to the conventional BNR process when a real-time step feed was employed.

The bioprocesses in the Short-Cut Enhanced Nutrients Abatement (S.C.E.N.A.)

- Alkaline production of Best Available Carbon Source (BACS) from sewage sludge (or OFMSW)
- **Nitritation in aerobic conditions** (so as to also minimize N_2O emissions)
- **Denitritation and EBPR** (thanks to the BACS)
- *Sequencing Batch Reactor*
- *Control Automation on the basis of pH, ORP and conductivity*

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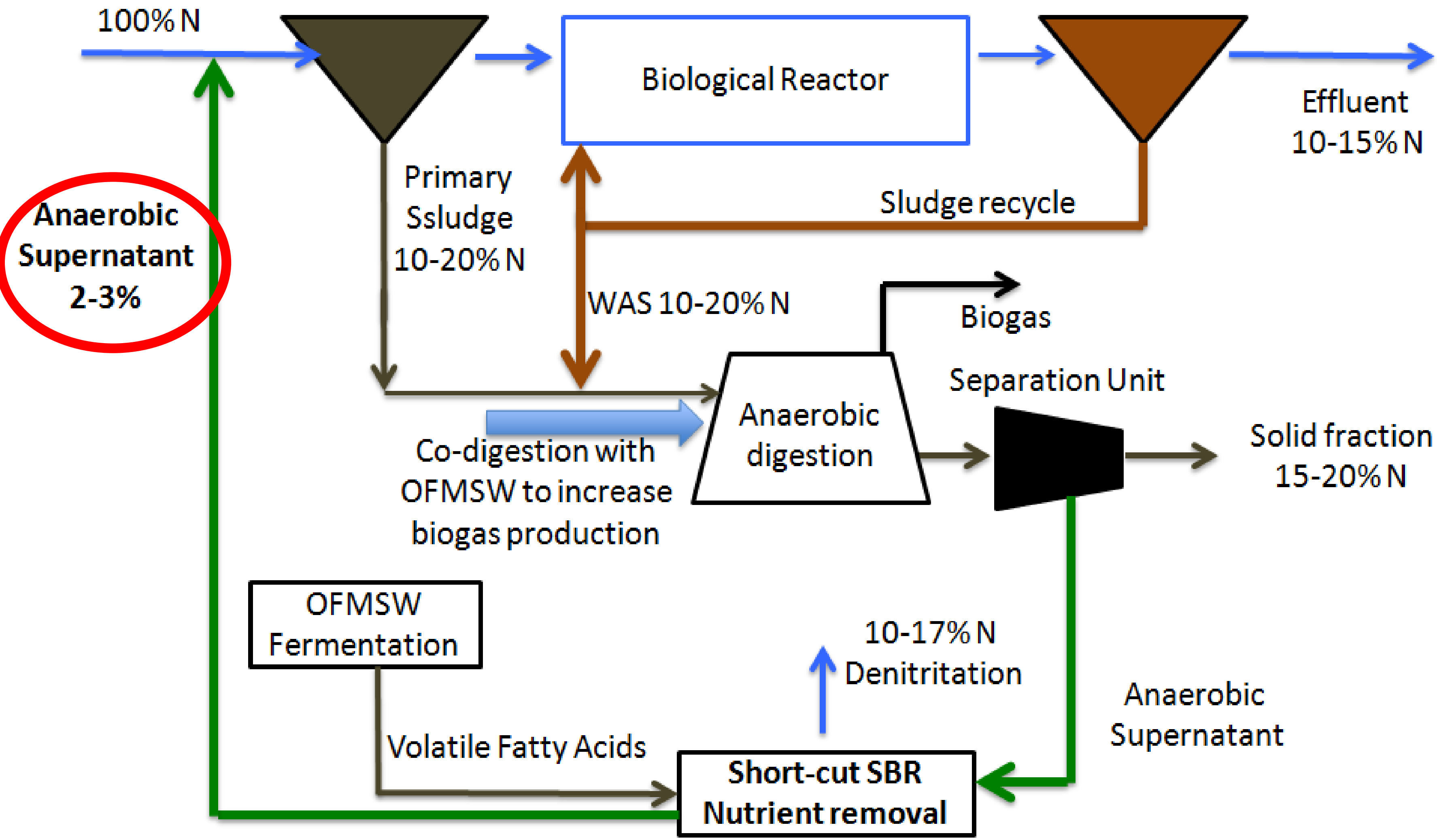
The first validated application:
BACS from OFMSW fermentation – Treviso –Italy-



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The first validated application: BACS from OFMSW fermentation

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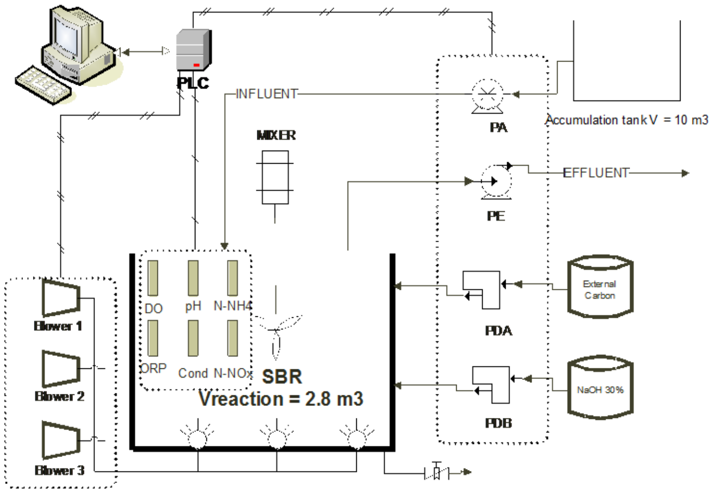
The short-cut Sequencing Batch Reactor

P&id of the scSBR



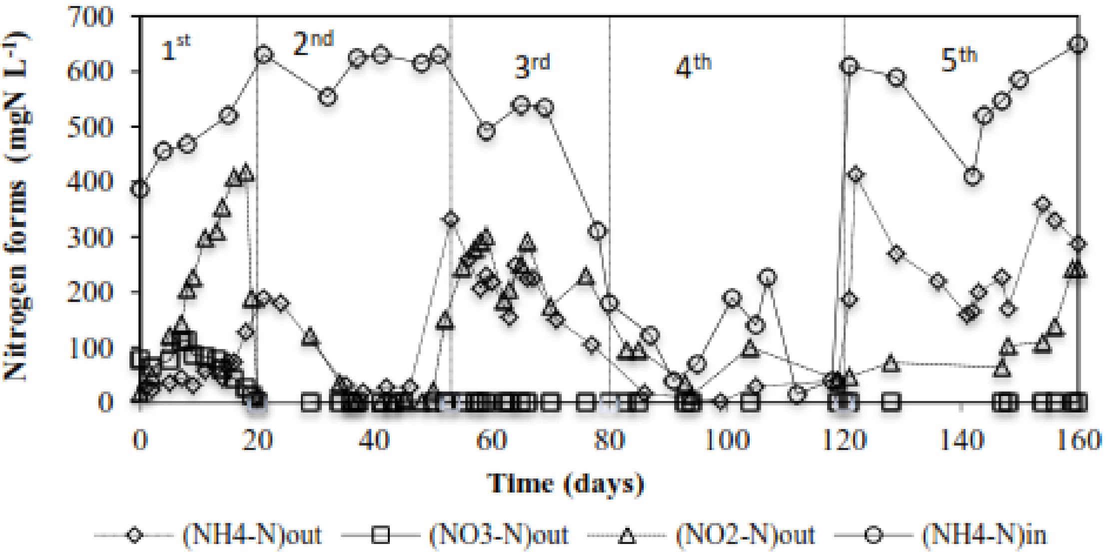
3 automatically controlled blowers: maximal flow of 25 m^3/h

Agitation up to 1500 rpm

Submerged probes to monitor the process
pH, DO, ORP, Conductivity, NH4-N, NOx-N

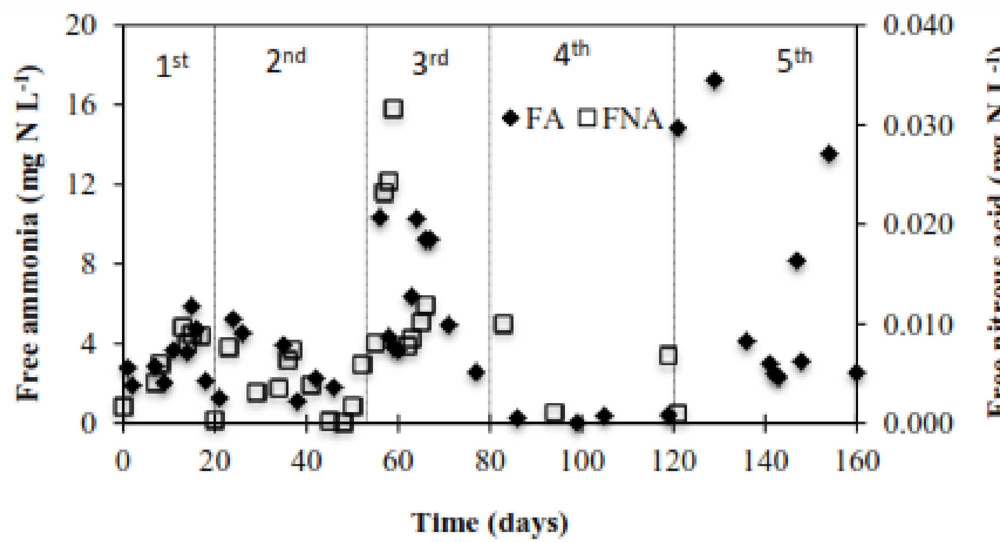
Pump for the external carbon sources:
in the figure <u>FERMENTATION LIQUID OFMSW</u>

Long term operation of the via-nitrite process



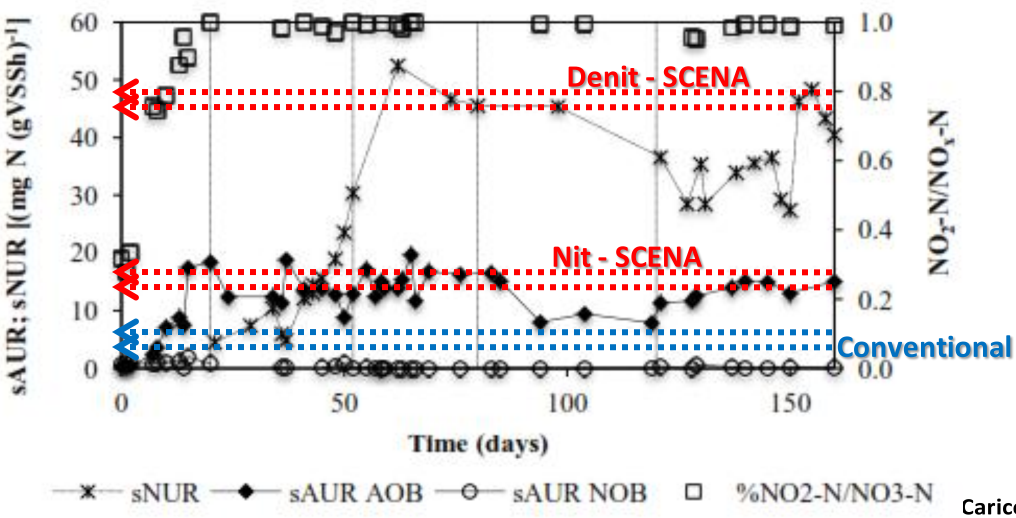
Strong variablity of the supernatant characteristics

FA and FNA very variable



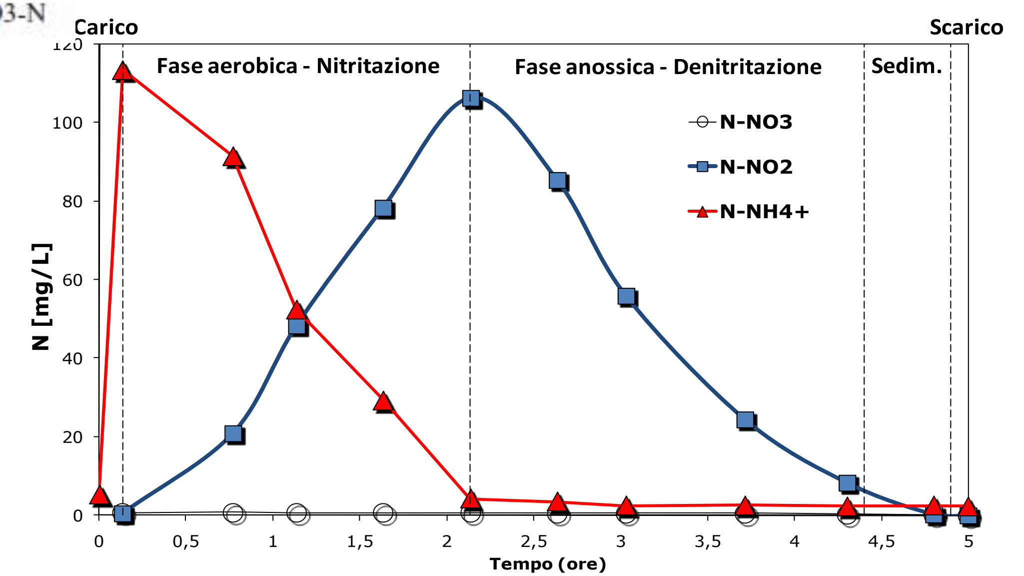
Frison et al. (2013) Chem Eng. J.

Short-cut nitrogen removal (nitritation-denitritation)



Start-up and long term operation

Nitrogen forms in a cycle



Frison et al. (2013) Chem Eng. J.

GHG Emissions in WWTPs

Mt CO_2 eq	1990	2000	2005	2010	2020
Landfill CH_4 (average a & b)	550	590	635	700	910
Wastewater CH_4 [a]	450	520	590	630	670
Wastewater N_2O [a]	80	90	100	100	100
Incinerator CO_2 [b]	40	50	50	60	60
Total	1120	1250	1345	1460	1660

[a] Based on reported emissions from national inventories and national communications, and (for non-reporting countries) on 1996 inventory guidelines and extrapolations (US EPA, 2006).

[b] Based on 2006 inventory guidelines and BAU projection (Monni et al., 2006).

Total includes landfill CH_4 (average), wastewater CH_4, wastewater N_2O and incineration CO_2.

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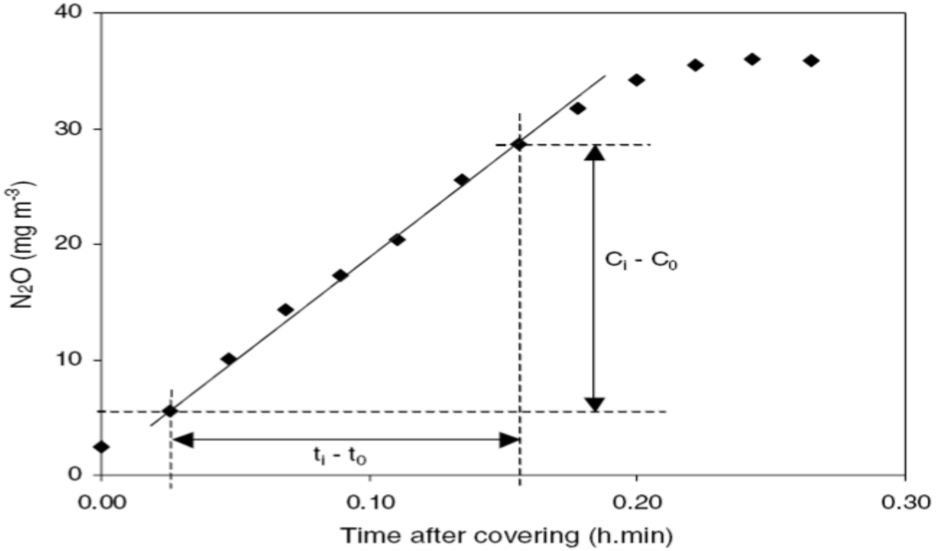
Determination of gaseous emissions

- ✓ The static chamber method and the Bruel and Kjaer photo-acoustic analyzer were used
- ✓ Measurement of N_2O, CO_2, CH_4 , NH_3 and CH_3SH at various times of the SBR, during aeration reaction, anoxic reaction and sedimentation.



$$E_R = \frac{C_i - C_0}{t_i - t_0} \frac{V_{ch}}{A_{ch}}$$

E_R (mg/m²h) is the emission rate of the gas
ti (h) and t_0 (h) : the time edges of the linear portion of the concentration plot
C_i (mg/m³) and C_0 (mg/m³): gas concentration at times t_i and t_0 respectively

Total amount of gas emitted in one SBR cycle

$$G_M = \sum(E_R A_{SBR} \Delta t)$$

G_M (mg/cycle) is the amount of the emitted gas per cycle
A_{SBR} (m^2) is the surface area of the pilot SBR, 1.5·1.5 = 2.25 m^2
Δt (h) is the time interval during which the gas emissions were recorded

Comparison with other studies treating anaerobic effluents in WWTPs

Wastewater	Process and conditions	N_2O emissions (% of N load)	Reference
Anaerobic supernatant from WAS & OFMSW co-digestion	Nitritation/ denitritation High DO Low nitrite accumulation	0.24	This work
Anaerobic supernatant from WAS & OFMSW co-digestion	Nitritation/ denitritation Low DO High nitrite accumulation	1.38	This work
Sludge reject water	2 stage partial nitritation – anammox	2.3	Kampschreur et al., 2008
Sludge reject water	1 stage partial nitritation – anammox	1.3	Weissenbacher et al., 2010
Sludge reject water	Nitritation	3.8	Gustavsson and Jansen, 2011

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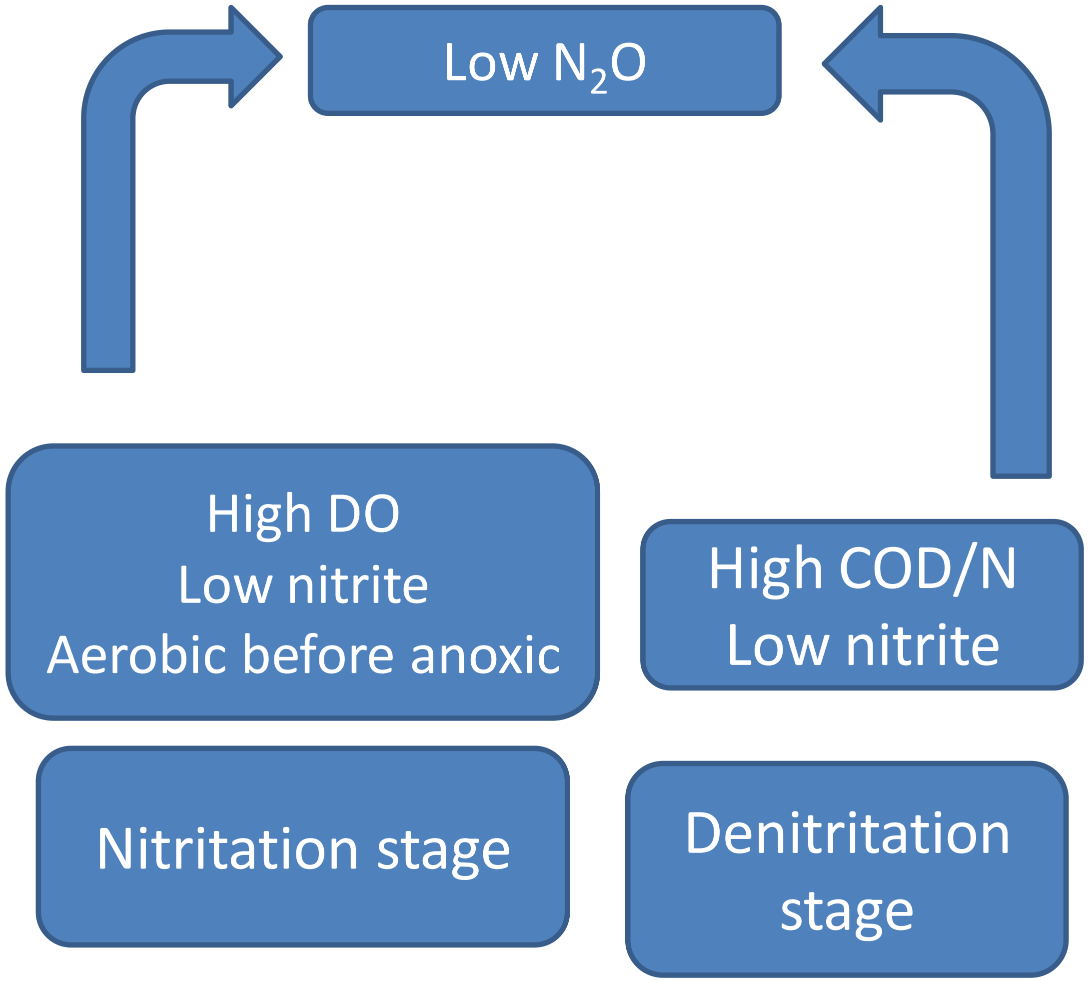
Strategies to mitigate N_2O as evidenced by our worked

- Providing sufficient aeration during the nitritation stage so that the DO is maintained at least at 1.5 mg/L
- Applying a vNLR that is not higher than the system's nitrifying and denitrifying capacity. This way the accumulation of ammonium and nitrite is limited
- Apply the aerobic/anoxic sequence



Conclusions on short-cut nitrogen removal

- **START-UP**: stable and robust wash-out of nitrite oxidizing bacteria can be achieved within 3 weeks treating anaerobic digestate of sewage sludge and OFMSW
- **LONG-TERM VALIDATION**: no disturbances of short-cut biological nitrogen removal were caused by extra-ordinary conditions
- **MAXIMAL TREATMENT POTENTIAL**: the short-cut process was stable up to 1,1 kgN/m^3*d, but total nitrogen removal was achieved at 0,8 kgN/m^3*d, which is the best option even for N_2O emissions
- **REAL-TIME PROCESS CONTROL**: may be reliable up to 0.8 kgN/m^3*d. It is feasible by indirect parameters, specifically pH, ORP and conductivity.
- **COST ESTIMATION:** nitritation-denitritation involved 1.2-1.5 €/kgN, this cost could be cut by 40-50% by complete autotrophic nitrogen removal

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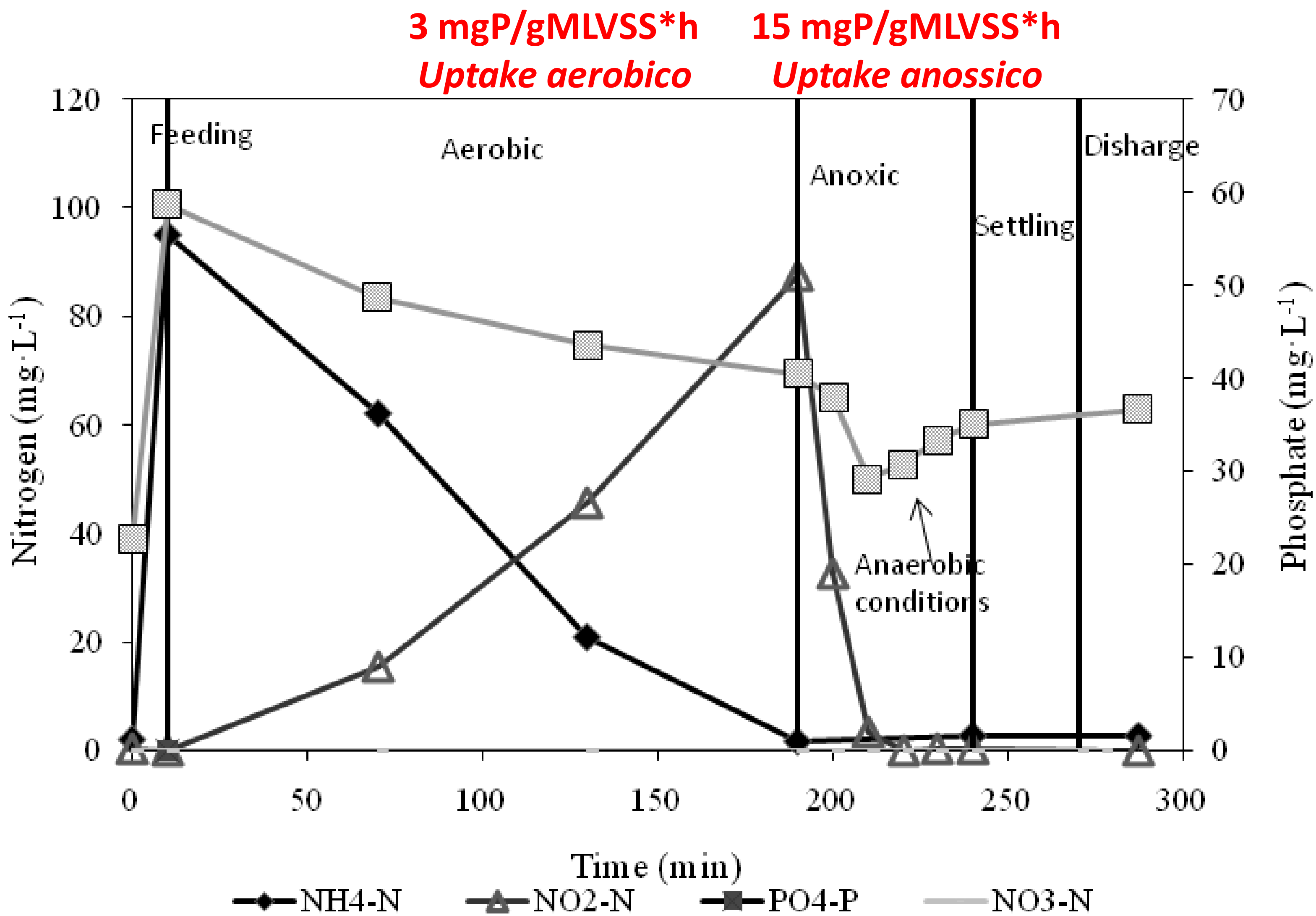
Short-cut nutrients removal in SBR



Mix of SCFA in the BACS

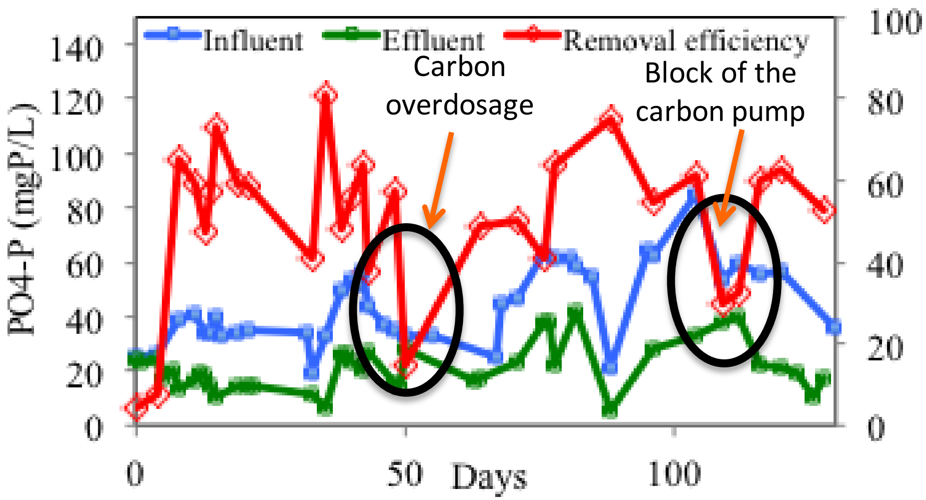
Type of Carbon source	HAc/TVFAs (%)	HPr/TVFAs (%)	HBt/TVFAs (%)	C5-C7/TVFAs (%)
LD OFMSW	**63.4 (55.71)**	**6.6 (6.3-7.0)**	**12.0 (4.8-19.2)**	18.0 (12 -24)
FL OFMSW	**73.2 (69-77)**	**9.6 (8.0-11.2)**	**16.0 (13.8-18.3)**	1.1 (0.6-1.7)

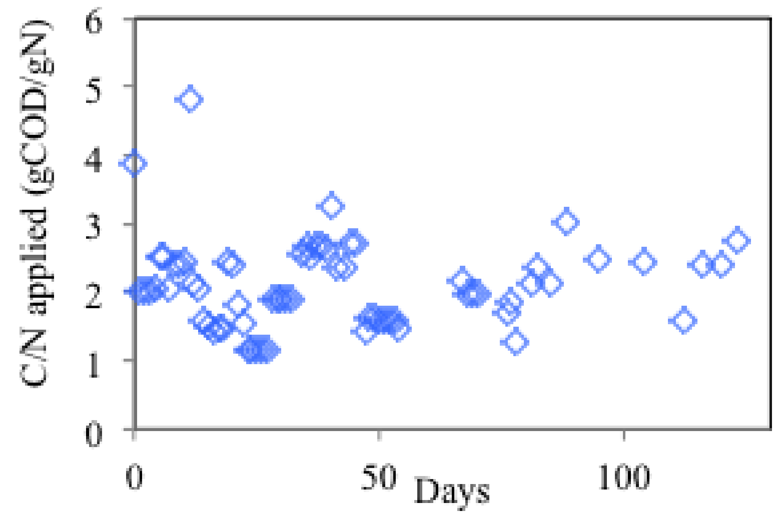
-Up to 80-90% are acetic, proprionic and butyric acids;

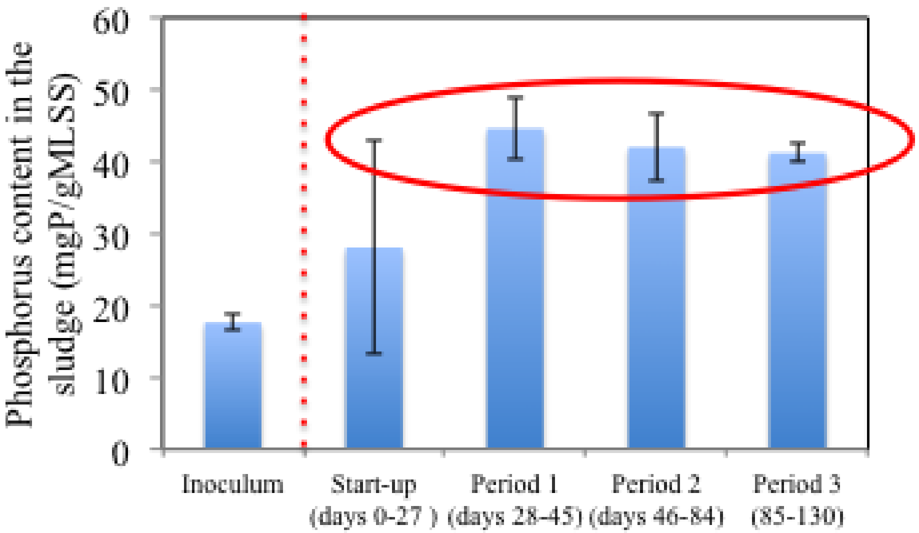
-SCFA enhanced the denitrifrying phosphorus removal via nitrite
(Tong et al., 2007; Ji and Chen, 2010; Li et al., 2011);

-Recent study states the possibility to enhance the production of SCFA (in particular propionic and butyric acids) by alkaline fermentation (Chen et al., 2013) through the addition of soda, but we need to perfom a sustainable and cost effective process

Pilot scale trials







- **Fermentation liquid BOD:N = 2;**

- **P removal up to 80%;**

- **P%TS up to 4.5**

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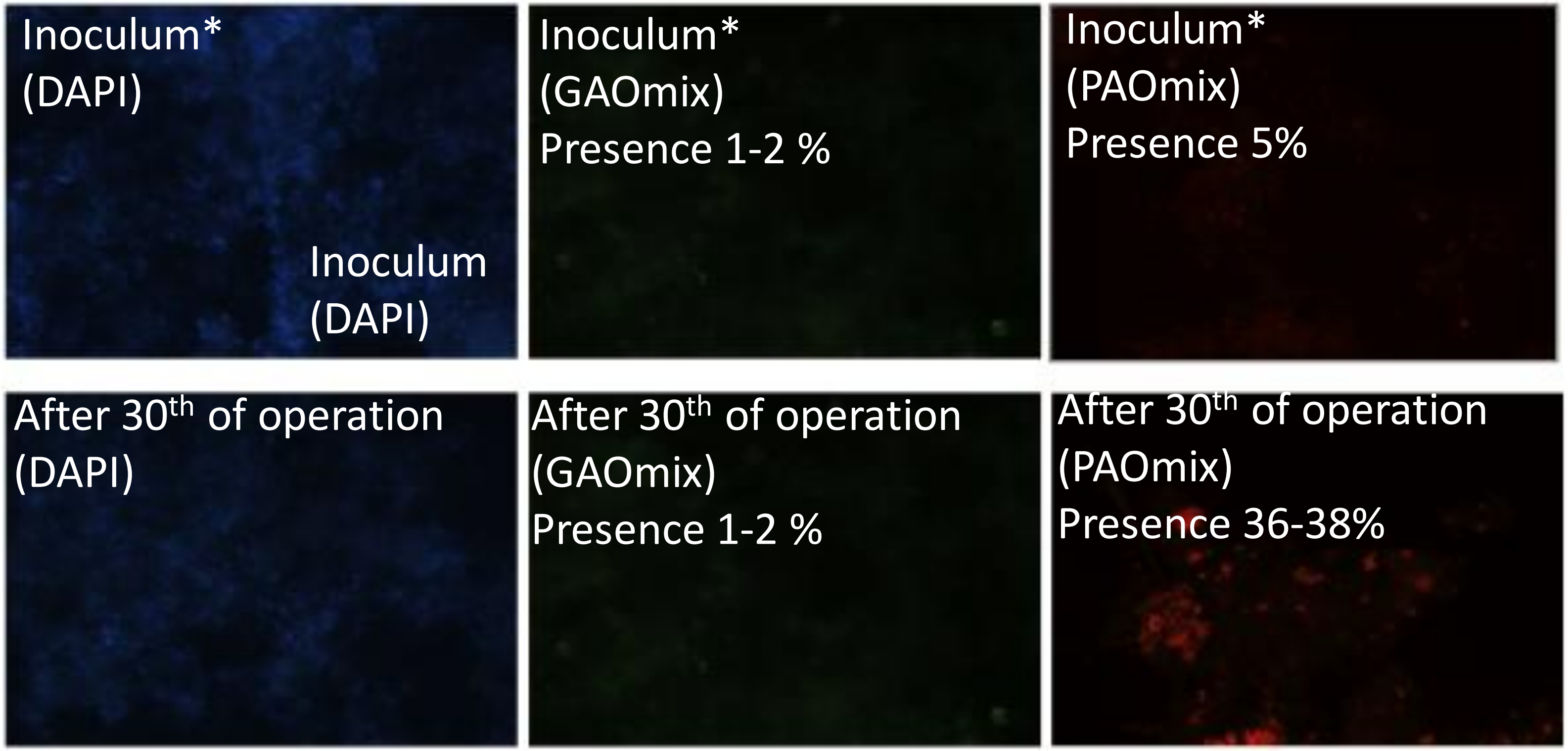
FISH Analysis



The quantification was perform using the software Jmage

* Activated sludge of Treviso WWTP.

<u>Predominance of coccus morphology (non rod morphology) which demonstrates the presence of nitrite-DPAO versus nitrate-DPAO</u>

(Guisasola et al., 2009; Carvalho et al.2007)

Frison et al., JCTB, Accepted

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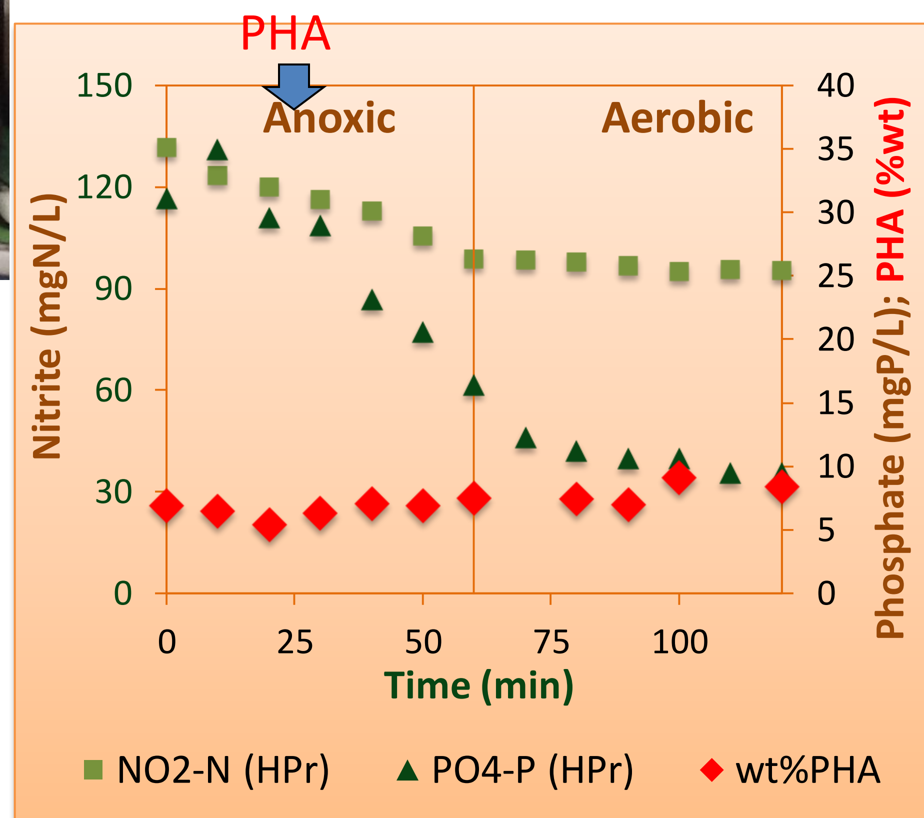
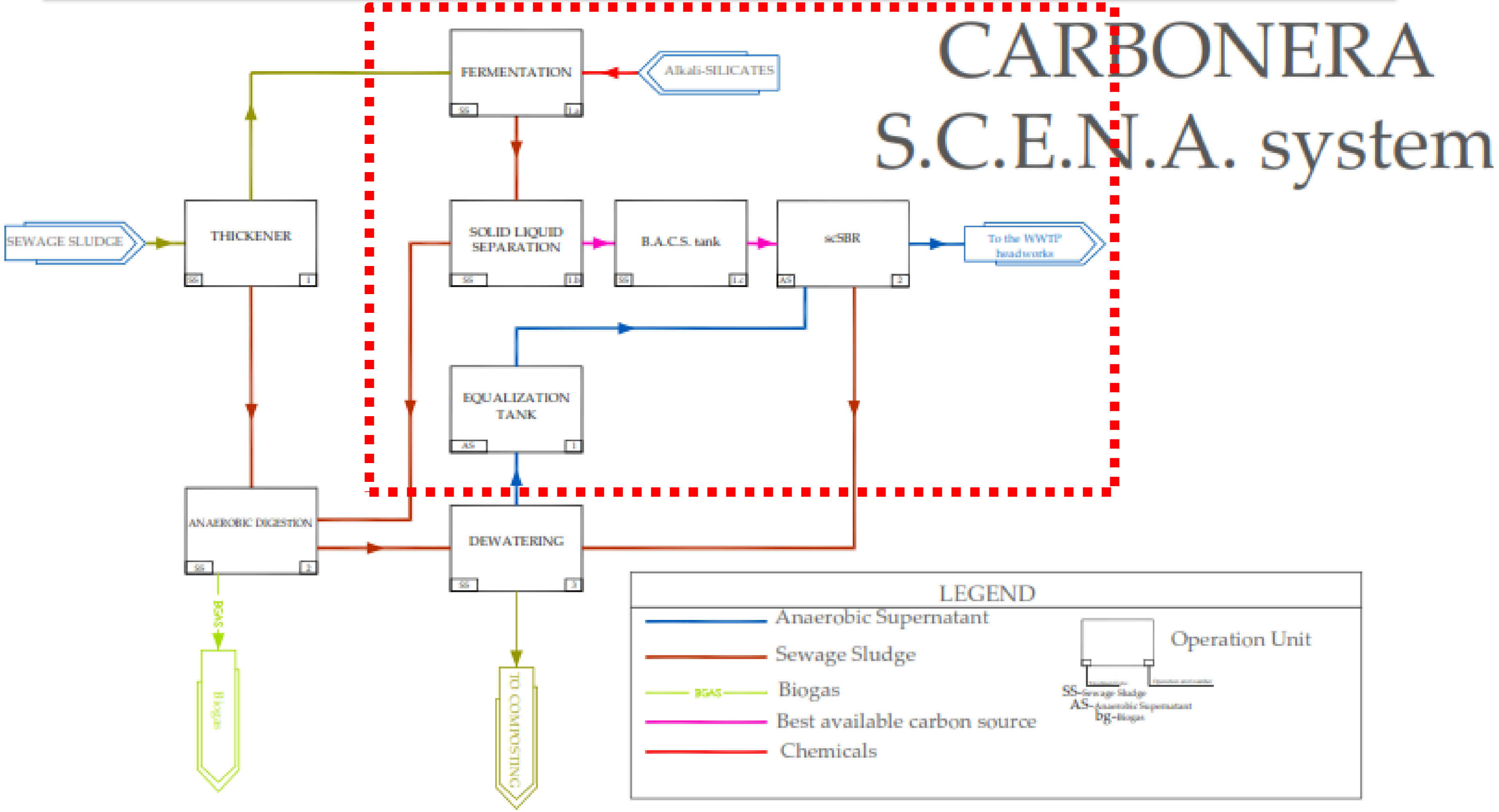
Accumulation of PHA…some tips of the afternoon presentation

In collaboration with Dr. A. Oehmen
University of Lisboa (Portugal)



The second validated application:
BACS from sewage sludge fermentation – Carbonera



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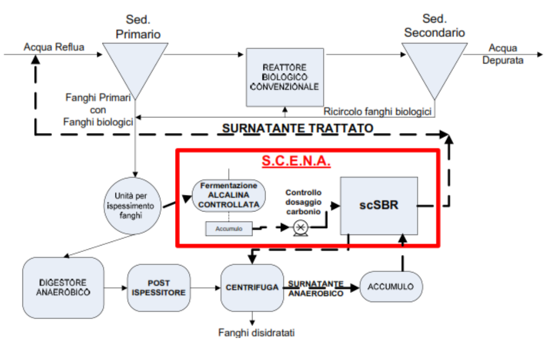

Short-Cut Enhanced Nutrients Removal (SCENA) from Anaerobic Supernatant
-Full Scale in 2014-

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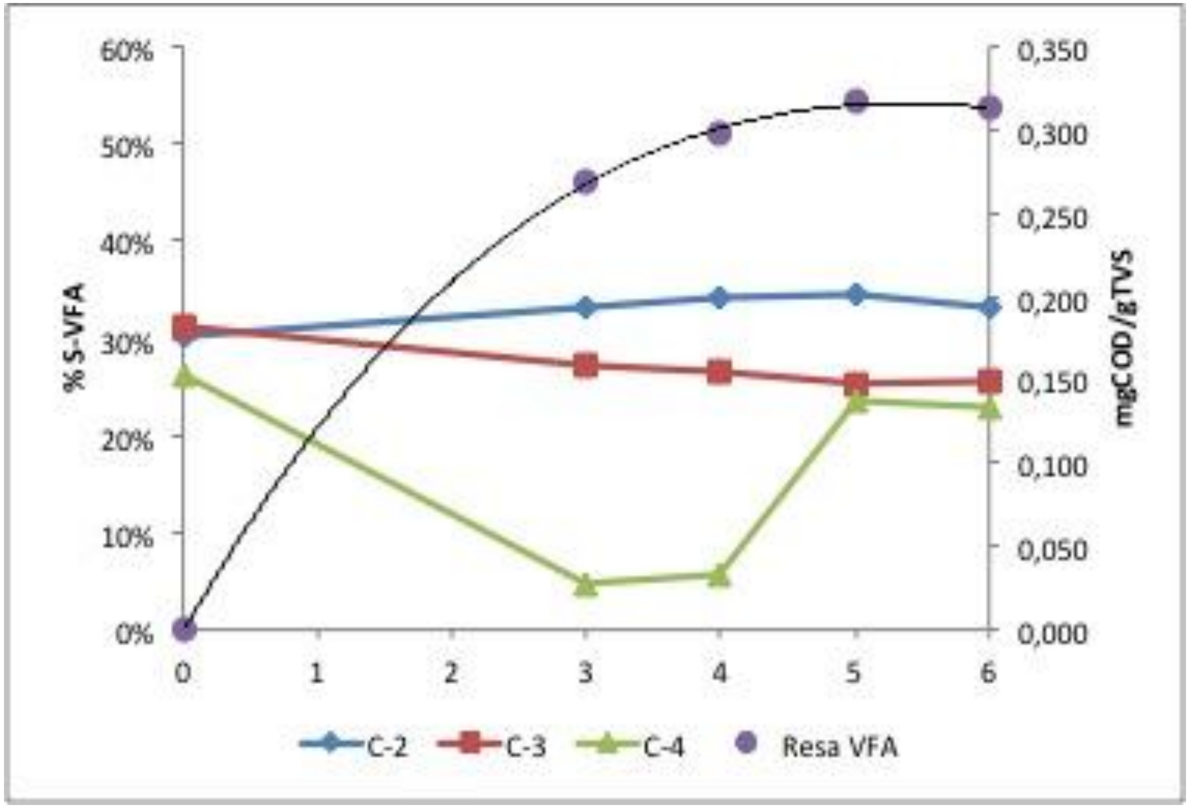
Alkaline fermentation using alkali-silicates



0.30-0.32 gSCFA/gTVS

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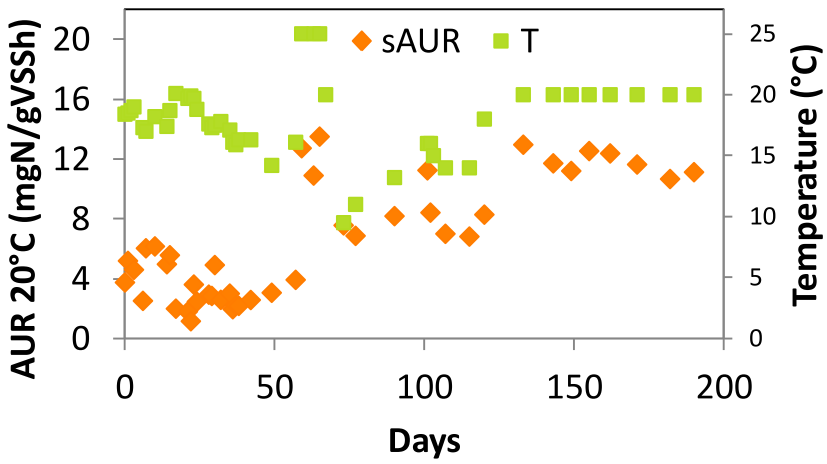
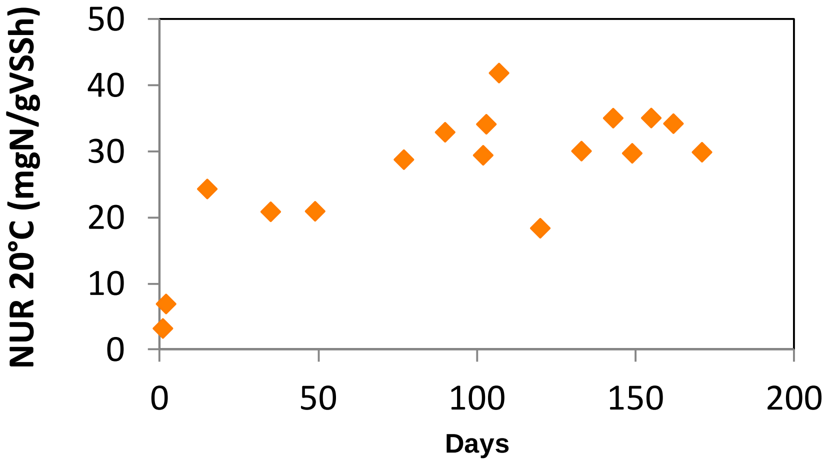
Pilot scale kinetics

Carbon source is dosed automatically during the anoxic or anaerobic phase of the scSBR operation



IN SITU KINETICS



Preliminary cost comparison for management of nutrients associated with digester supernatant

Costs		MLE	SCENA
CAPEX: for MLE [a]	€/year	1277	0
CAPEX: for SBR [a]	€/year	0	389
CAPEX: for sludge fermenter [a]	€/year	0	449
OPEX: EE for aeration [b]	€/year	72060	54084
OPEX: Sludge disposal [c]	€/year	13607	7884
OPEX: Aluminium Polychloride (PAC)[d]	€/year	10439	0

(interest rate 4% was used for CAPEX)

[a] Payback time = 25 years; [b] 4 kWh/kgO_2, 0.2 €/kWh; [c] 400 €/kg$TS_{disposed}$; [d] €/tonAl 5500

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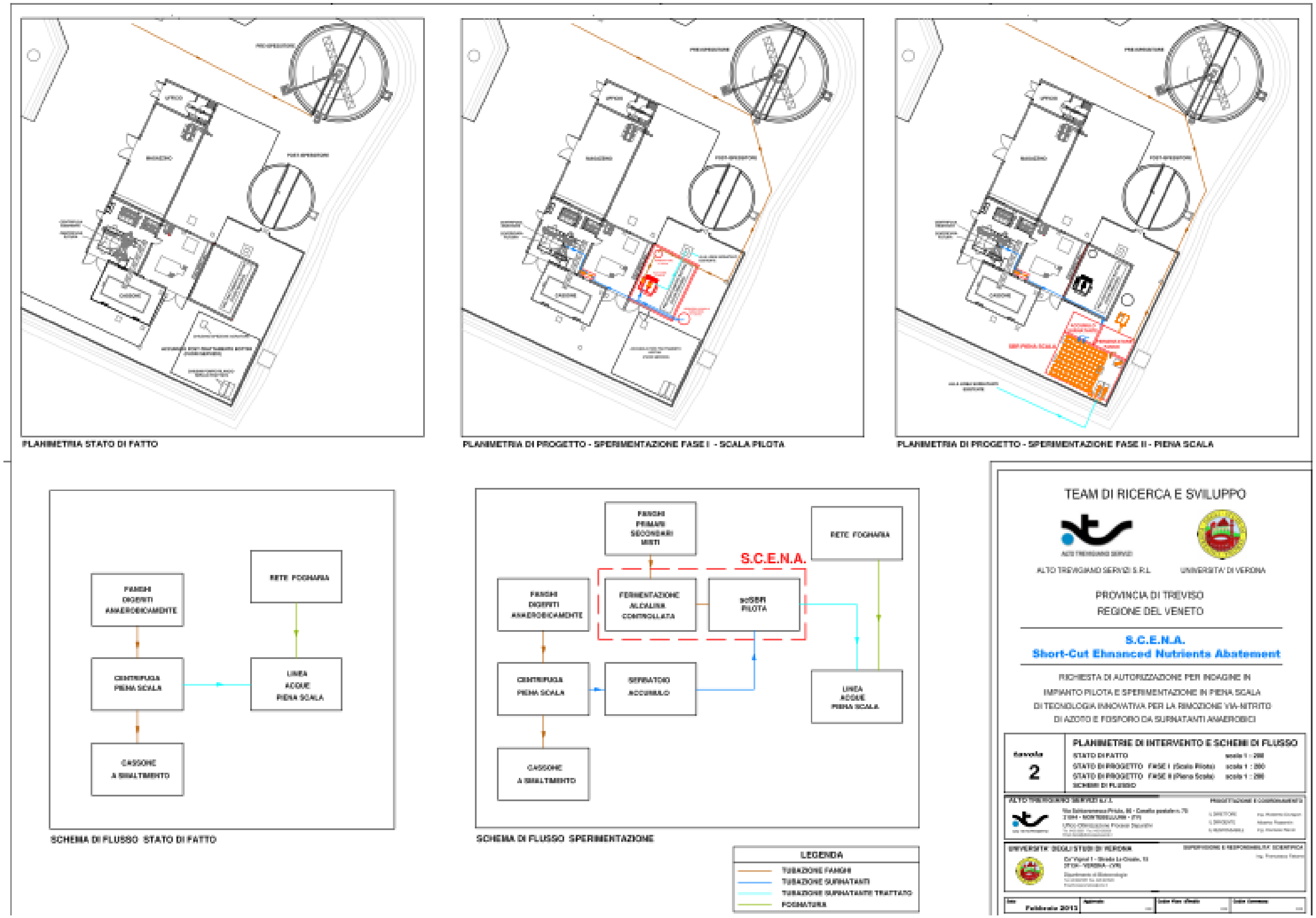
S.C.E.N.A. in full scale in 2014



Conclusions

-Short-cut nitrification and denititation (**SCND**) with external carbon source **is solid and reliable process** to treat liquid effluents originated from anaerobic (co)digestion;

The **short-chain fatty acids** produced by the fermentation of biowaste available in WWTPs may enhance the **simultaneous biological removal of nitrogen and phosphorus via-nitrite pathway**.

Alkaline fermentation optimize the production and separation of **BACS and use of alkali-silicates for pH buffering is effective**

FISH analysis confirmed a stable presence of nitrite-DPAO compared with the inoculum

PHA accumulating organisms were selected so as to leave perspectives to be presented later this afternoon

ALTO TREVIGIANO SERVIZI

the international water association

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EcoTechnologies for Wastewater Treatment

Technical, Environmental & Economic Challenges

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