RECUPERAÇÃO DE RECURSOS EM ESTAÇÕES DE TRATAMENTO DE ÁGUAS RESIDUAIS: UMA PERSPECTIVA DE ECONOMIA CIRCULAR

Vítor J.P. Vilar

vilar@fe.up.pt

CERVEIRA
VILA DAS ARTES

Aquamuseu
do rio minho

Interreg
España – Portugal
Cofinanciado por la Unión Europea
Cofinanciado pela União Europeia

blue water

ALiCE
ASSOCIATE LABORATORY IN CHEMICAL ENGINEERING

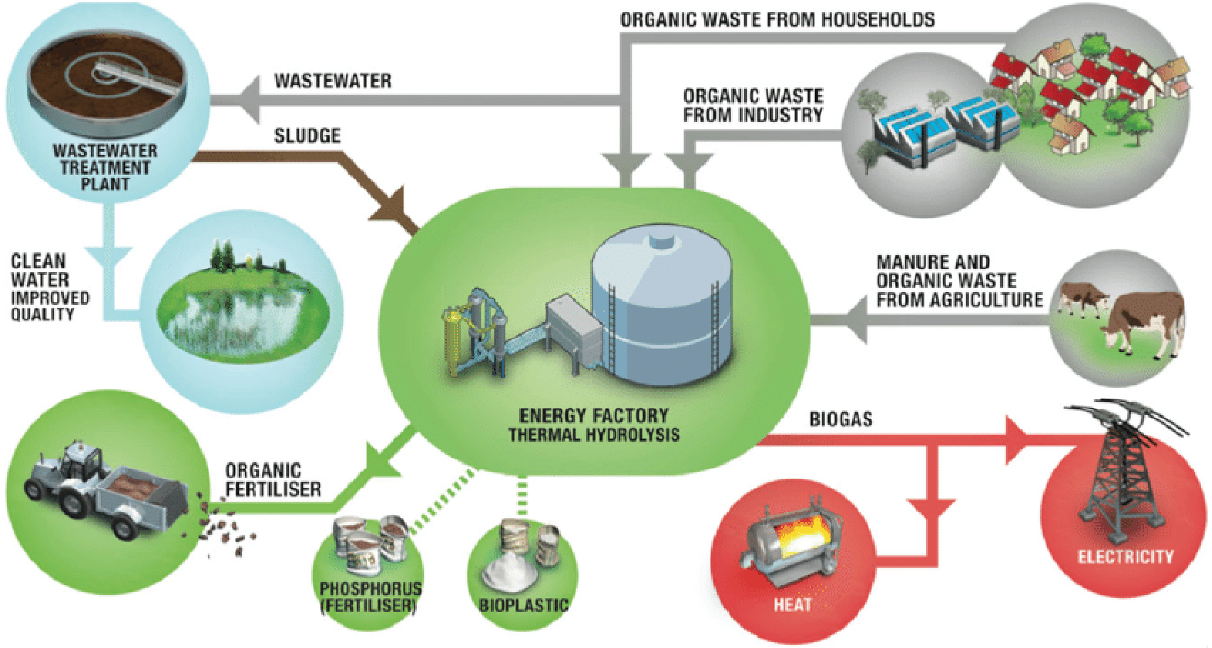
U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

10 DE ABRIL 2026

SRE CM
LABORATORY OF SEPARATION AND REACTION ENGINEERING
LABORATORY OF CATALYSIS AND MATERIALS

INTRODUCTION

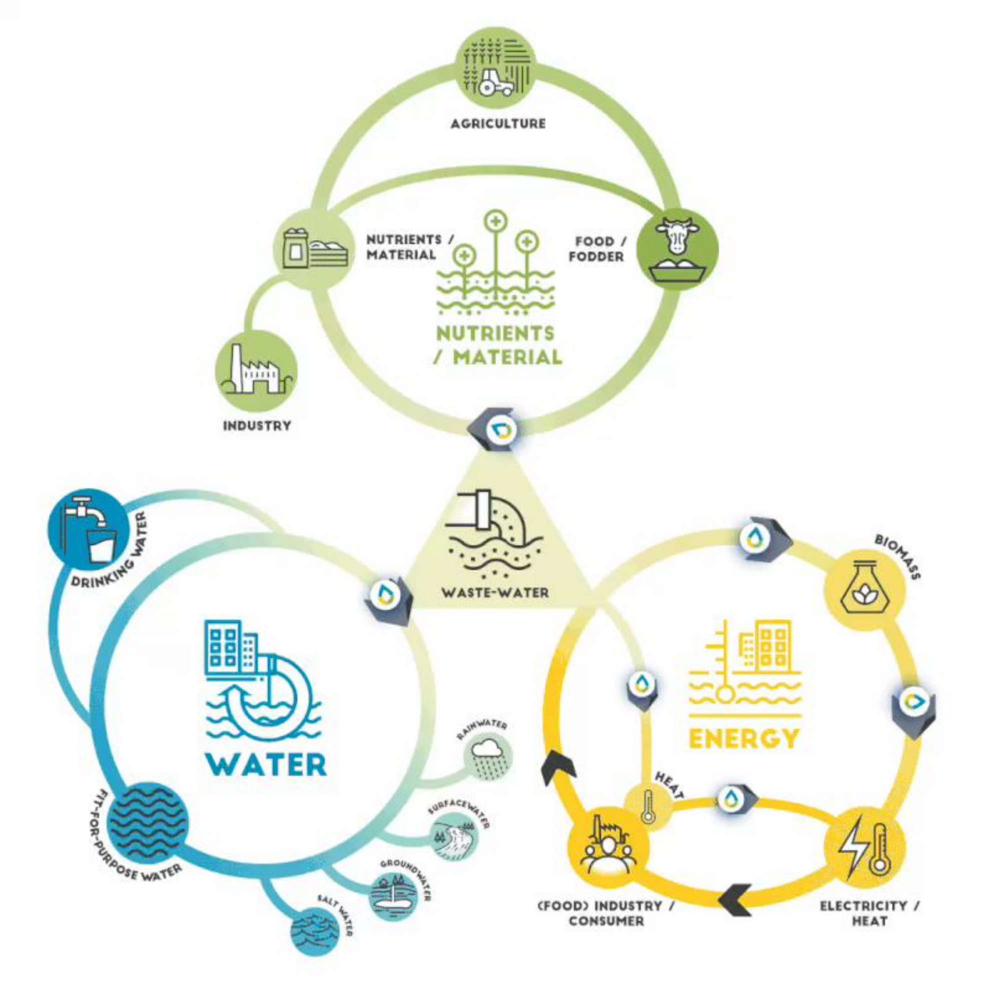
- Although the original goal of wastewater treatment was to protect water quality, today scarcity of resources and sustainability are driving major global changes
- The **N-E-W Paradigm** focuses on **Recovering Resources** such as **Nutrients**, **Energy** and **Water**, towards a **Circular and Self-Sufficient Bio-Based Economy**



NEW GENERATION OF SUSTAINABLE WWTPs

WWTPs 2.0

INTRODUCTION



NEW GENERATION OF SUSTAINABLE WWTPs

WWTPs 2.0

INTRODUCTION

European Commission

New EU Directive on Urban Wastewater Treatment (Directive (EU) 2024/3019)
Revised Regulation, Renewed Challenges

Wastewater treatment

- Nutrients removal (N: 80% removal or 8 mg/L; P: 90% removal or 0.5 mg/L; ≥ 150 000 p.e.)
- Obligation to all UWWTPs treating a load ≥ 150 000 p.e. to **apply quaternary treatment by 2045,** in order to **eliminate the broadest possible spectrum of micro-pollutants**.
- Promote the **reuse of treated wastewater** from all urban wastewater treatment plants **where appropriate**.

Energy neutrality and renewables

- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.

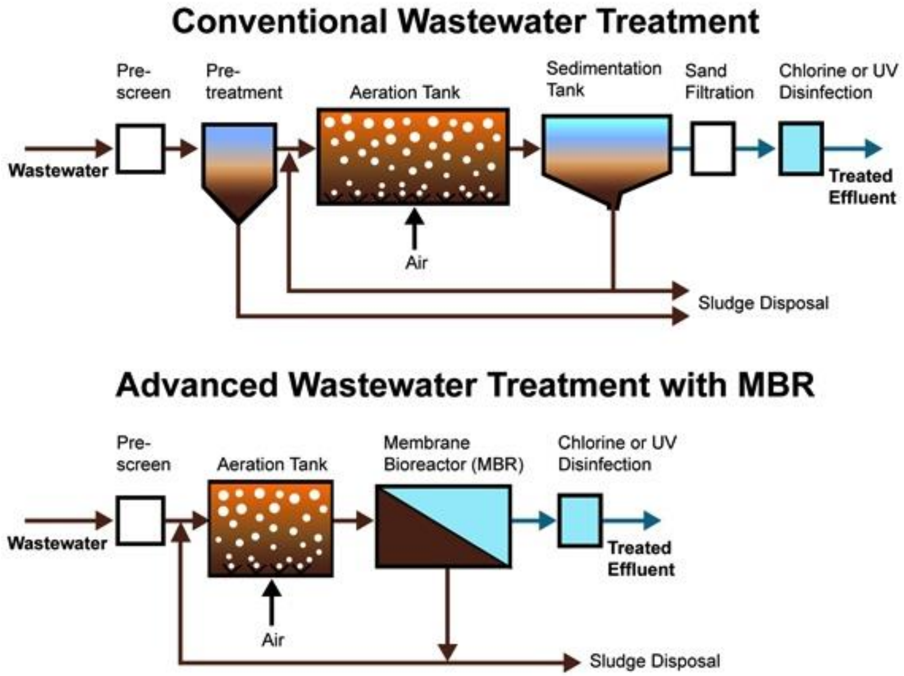
Wastewater surveillance and risk assessment

- Obligation **to monitor health parameters in urban wastewaters**: PFAS, Microplastics, Antimicrobial Resistance, Greenhouse Gases

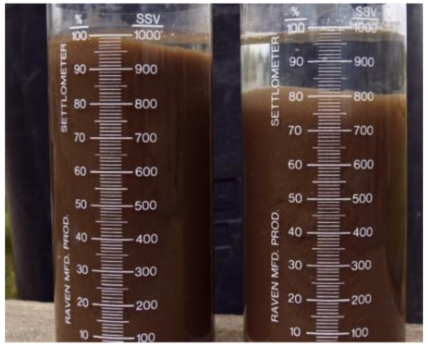
SECONDARY/TERTIARY TREATMENT

OBJECTIVES

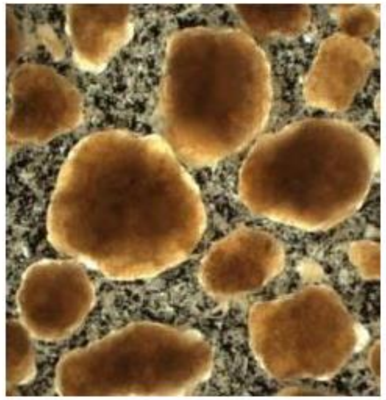
- Increase biomass concentration
- Reduce the footprint
- Ensure water quality

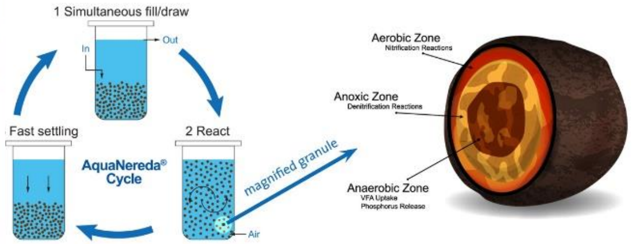


Activated Sludge



AquaNereda® Aerobic Granular Sludge Technology

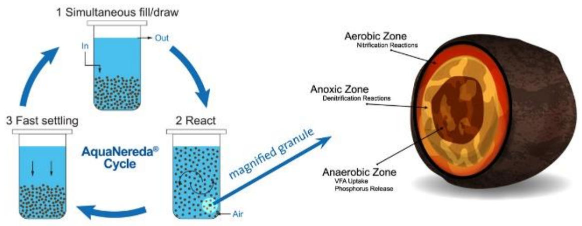


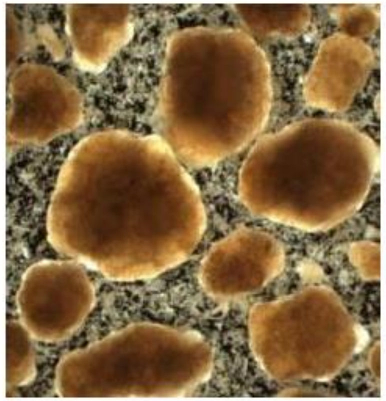


SECONDARY/TERTIARY TREATMENT

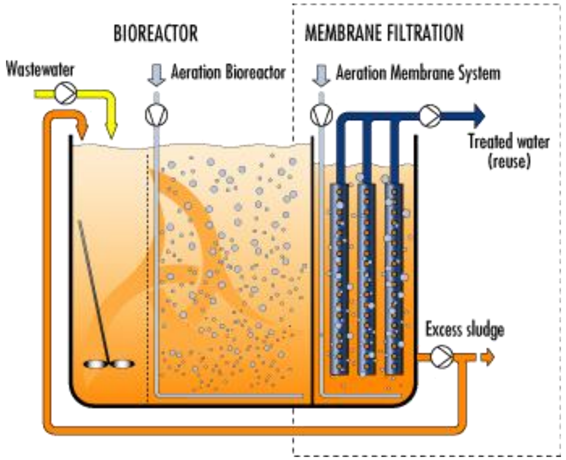
<u>OBJECTIVES</u>

- Increase biomass concentration
- Reduce the footprint
- Ensure water quality





AquaNereda® Aerobic Granular Sludge Technology



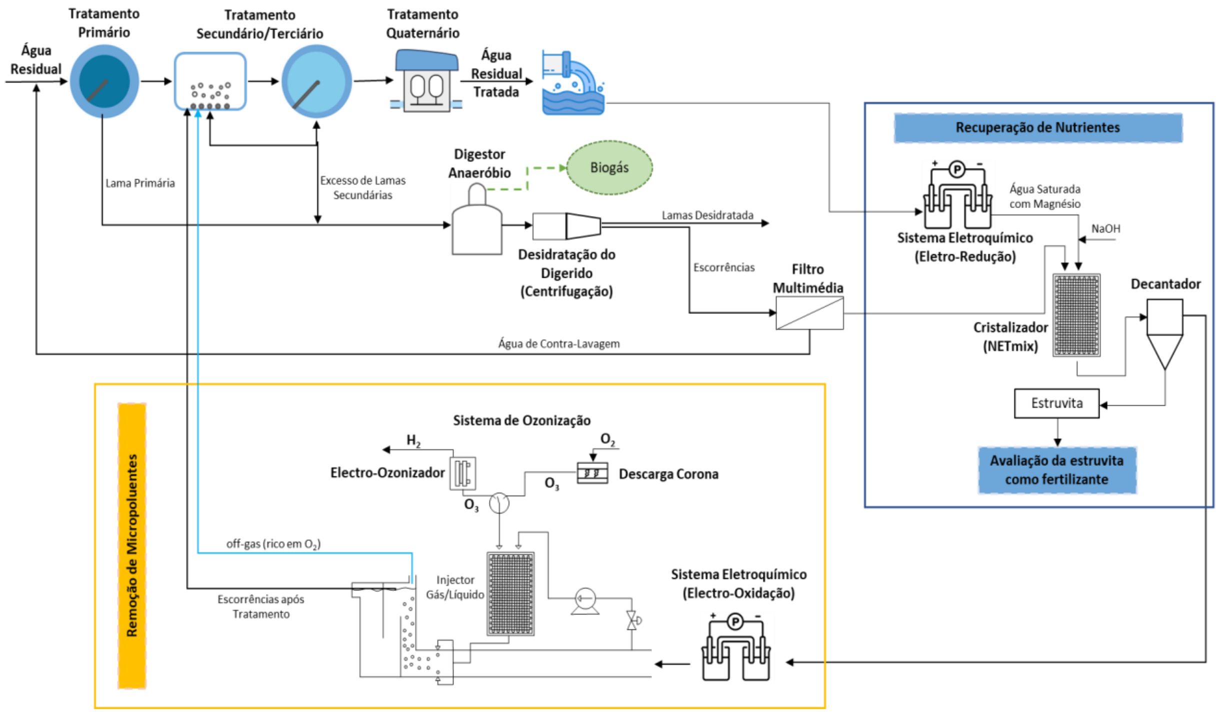
<u>MBR</u>
Membrane Biological Reactor

<u>MBBR</u>
Moving Bed Biofilm Reactor

RENURE PROJECT

Processo integrado e circular para a REcuperação de NUtrientes e remoção de micropoluentes de águas Residuais

COMPETE 2030 | PORTUGAL 2030 | Cofinanciado pela União Europeia



Objectives

- Foster nutrients recovery from sidestream digestate by **crystallization** using a **NETmix crystallizer**;
- **Electro-ozonizer** using the NETmix static mixer.
- **Gas (ozone)/liquid (water) injector** based on the NETmix static mixer to enhance the ozonation process for CECs removal.

Research Team

Vítor Vilar

Francisca Moreira

C. Cruzeiro

P. Marrocos

A. Olivera

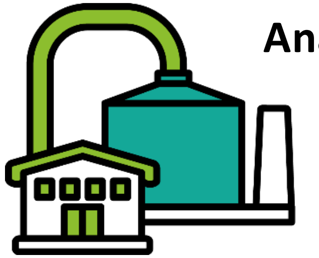
L. Cullen

Partners

VENTIL AQUA | U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO | ALiCE ASSOCIATE LABORATORY IN CHEMICAL ENGINEERING | SRE CM ASSOCIATE LABORATORY LABORATORY OF SEPARATION AND REACTION ENGINEERING LABORATORY OF CATALYSIS AND MATERIALS

LiquidMining project

Extraction of EU strategic raw materials from wastewater and brines using a cutting-edge technology



Anaerobic digestion

Digestate
Liquid fraction

Sidestream digestate

Nutrient-rich by-product

15 **P** Phosphorus

7 **N** Nitrogen

Idea

Nutrient recovery by **struvite** crystallisation[1]

$MgNH_4PO_4{\cdot}6H_2O$ → Slow-release fertiliser

Objectives

- Foster nutrients recovery from sidestream digestate by **crystallization** using an **oscillatory flow crystallizer** (OFC);
- Develop of a **low footprint crystallizer** combining computational modelling and experimental studies;
- Evaluation of **alternative sources of Mg and Ca** to bring down the costs of the crystallization process.

Research Team

Vítor Vilar

A. Ferreira

C. Cruzeiro

L. Sena

Partners

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
ALiCE ASSOCIATE LABORATORY IN CHEMICAL ENGINEERING
SRE CM ASSOCIATE LABORATORY LABORATORY OF SEPARATION AND REACTION ENGINEERING LABORATORY OF CATALYSIS AND MATERIALS
Lepabe Laboratory for Process Engineering, Environment, Biotechnology and Energy
AdP VALOR Grupo Águas de Portugal
efacec

[1]Muys, M., *et al.* Science of the Total Environment, 417 (2020). doi: 10.1016/j.scitotenv.2020.143726

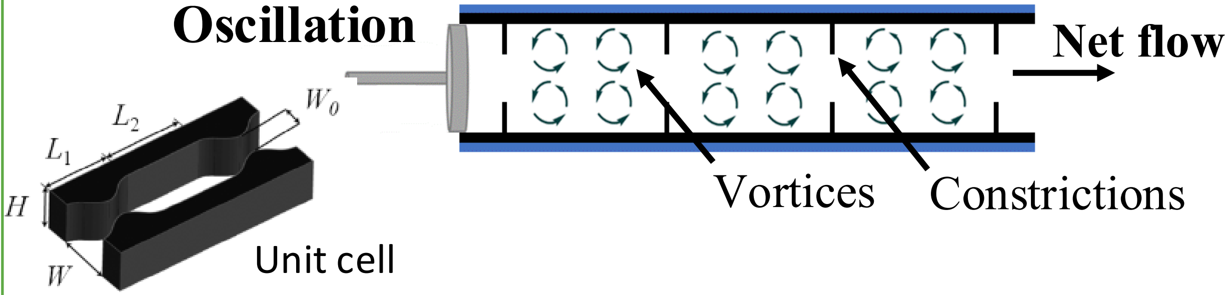
LIQUIDMINING PROJECT

Extraction of EU strategic raw materials from wastewater and brines using a cutting-edge technology

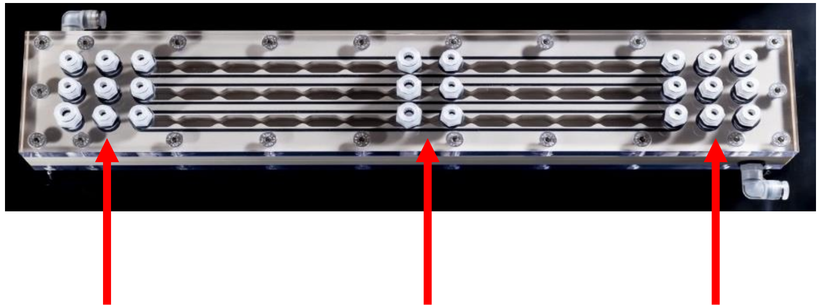
Oscillatory Flow Crystalliser Planar-OFC[2,3]

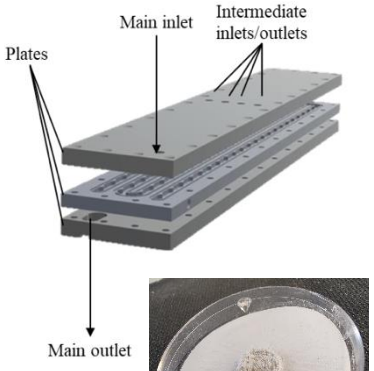
	Traditional Crystalliser	Planar-OFC
Mass and heat transfer		
Product quality		
Scale-up		
Portability		

A series of well-mixed tanks with plug flow behaviour



Operated Continuously

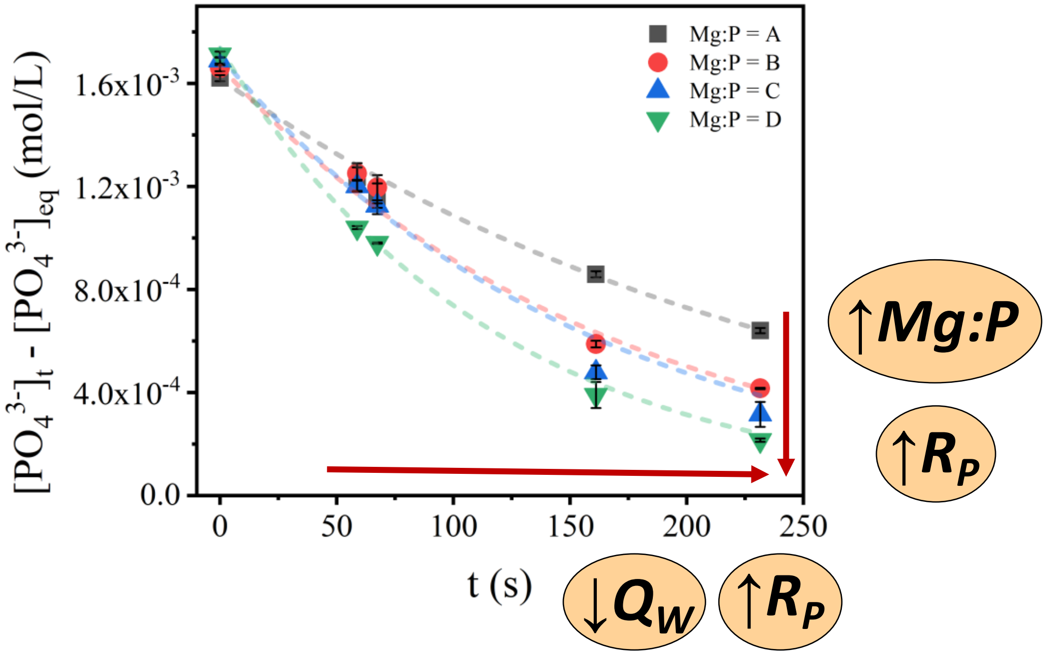




[2] Cruz, P. C., Silva, C. R., Rocha, F. A., and Ferreira, A. M. Ind. Eng. Chem. Res., 60 (2021). doi: 10.1021/acs.iecr.0c04991
[3] OFR TECH Process Intensification, LDA, 'Oscillatory flow plate reactor'. Available: https://www.ofrtech.com/

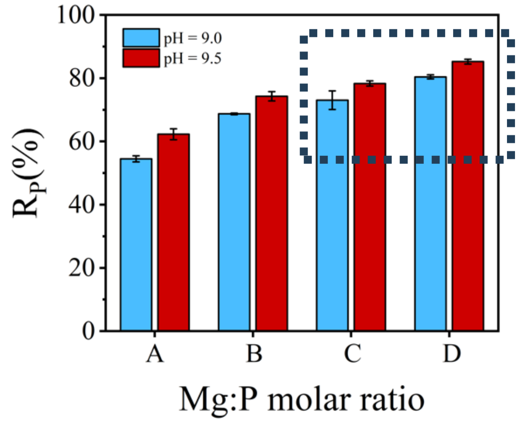
LIQUIDMINING PROJECT

Effect of Mg:P initial molar ratio and net flow rate (Q_W) on struvite production rate and phosphorus recovery (R_P)



The struvite production rate in the planar-OFC strongly depends on the initial magnesium concentration and the residence time.

Effect of final pH on the recovery rate of phosphorus



- ✓ Increasing the final pH enhances struvite precipitation and overall production yield;
- ✓ Operating at a lower final pH reduces reactant consumption.

Crystallisation process – general outputs

Production of **1.1** kg struvite/m^3

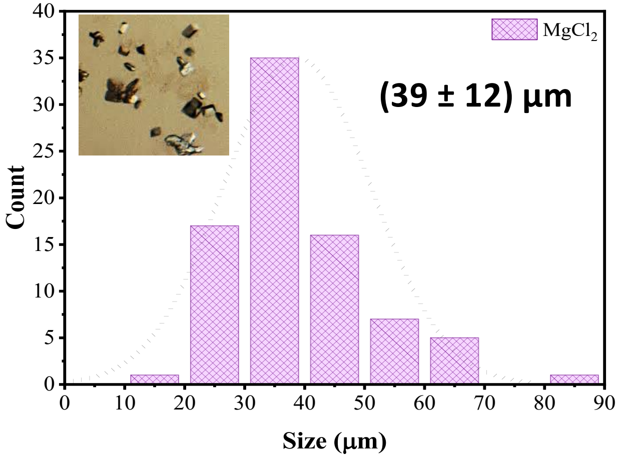
Recover **>90%** of phosphorus

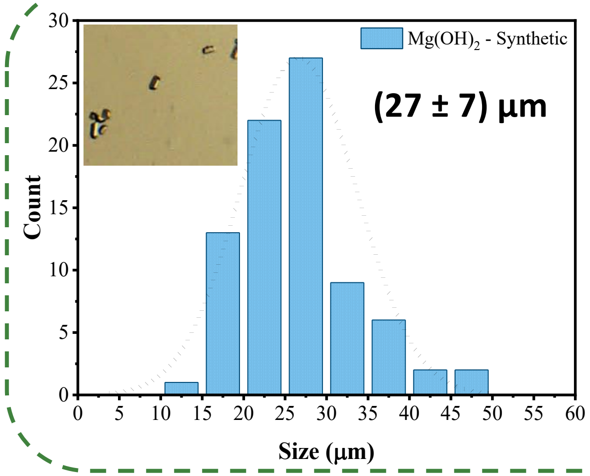
At least **10 times faster** than conventional processes!

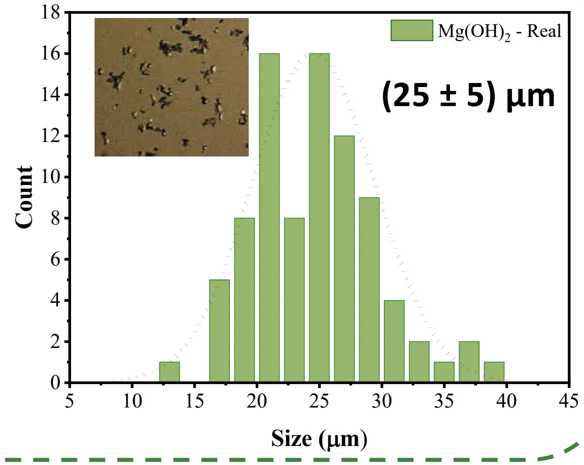
Struvite Crystallisation using Mg Salt Recovery from Brine

Target pH → 9; Hydraulic Retention Time ≈ 4 min; Tested molar ratio → 1.6 Mg:1.0 P. $[MgCl_2]_{control}$ = 100.94 mM; $[Mg(OH)_2]_{synthetic}$ = 99.37 mM; $[Mg(OH)_2]_{real}$ = 53.48 mM

Trial	NH_4^+	Mg^{2+}	PO_4^{3-}	Mg Source Dose	NaOH Dose	Struvite Yield
$MgCl_2$ - Control	4.0% (± 0.1)	45.0% (± 0.1)	93.36% (± 0.02)	**0.475 kg m^{-3}**	0.019 kg m^{-3}	**0.69 kg m^{-3}**
$Mg(OH)_2$ - Synthetic	8.90% (± 0.2)	**50.98% (± 0.02)**	91.61% (± 0.01)	0.290 kg m^{-3}	0.017 kg m^{-3}	0.68 kg m^{-3}
$Mg(OH)_2$ - Real	**13.24% (± 0.03)**	30.2% (± 0.1)	**94.07 (± 0.01)**	0.296 kg m^{-3}	**0.020 kg m^{-3}**	0.66 kg m^{-3}







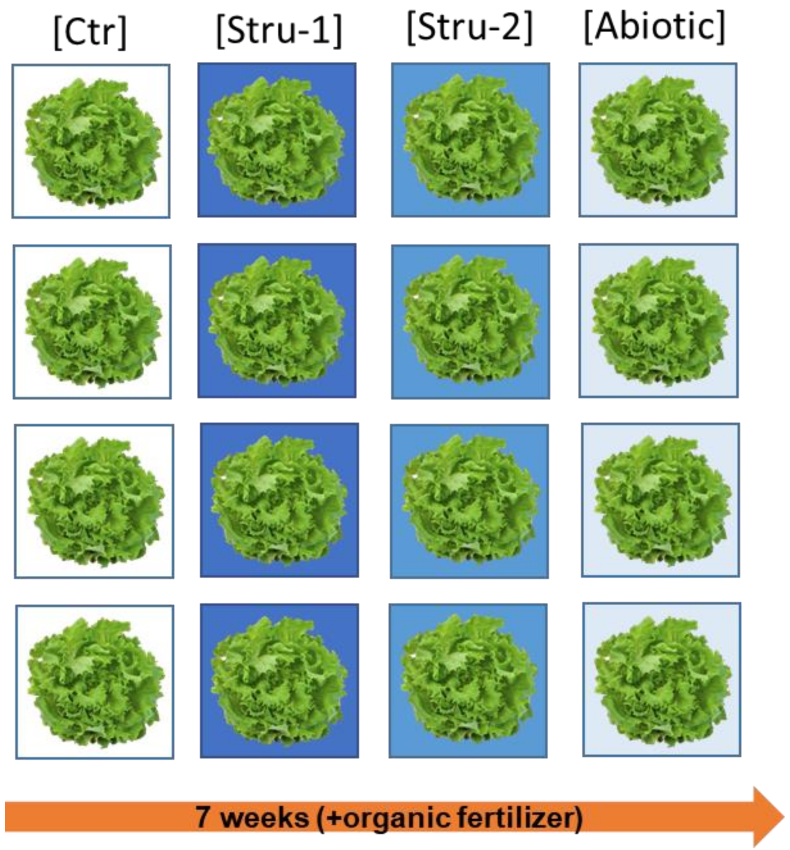
Larger crystals → Desirable for fertiliser applications

Narrow crystal size distribution, likely due to **Ca^{2+} and other impurities** incorporated into the Mg source.

Smaller, more uniform struvite crystals. Refined process control.

LIQUIDMINING PROJECT

CROPS PRODUCTION



INTRODUCTION

European Commission

New EU Directive on Urban Wastewater Treatment (Directive (EU) 2024/3019)
Revised Regulation, Renewed Challenges

Wastewater treatment

- Nutrients removal (N: 80% removal or 8 mg/L; P: 90% removal or 0.5 mg/L; ≥ 150 000 p.e.)
- Obligation to all UWWTPs treating a load ≥ 150 000 p.e. to **apply quaternary treatment by 2045,** in order to **eliminate the broadest possible spectrum of micro-pollutants**.
- Promote the **reuse of treated wastewater** from all urban wastewater treatment plants **where appropriate**.

Energy neutrality and renewables

- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.

Wastewater surveillance and risk assessment

- Obligation **to monitor health parameters in urban wastewaters**: PFAS, Microplastics, Antimicrobial Resistance, Greenhouse Gases

INTRODUCTION

European Commission

Table 3: Requirements for quaternary treatment of discharges from urban wastewater treatment plants referred to in Article 8 (1) and **or from urban wastewater treatment plants serving agglomerations referred to in Article 8**(~~3~~4).	
Indicators	Minimum percentage of removal **in relation to the load of the influent**
Substances that can pollute water even at low concentrations (see Note 1)	80 % (see Note 2)

Note 1: The concentration of the organic substances referred to in points (a) and (b) shall be measured.

(a) Category 1 (substances that can be very easily treated):

- (i) Amisulprid (CAS No 71675-85-9),
- (ii) Carbamazepine (CAS No 298-46-4),
- (iii) Citalopram (CAS No 59729-33-8),
- (iv) Clarithromycin (CAS No 81103-11-9),
- (v) Diclofenac (CAS No 15307-86-5),
- (vi) Hydrochlorothiazide (CAS No 58-93-5),
- (vii) Metoprolol (CAS No 37350-58-6),
- (viii) Venlafaxine (CAS No 93413-69-5);

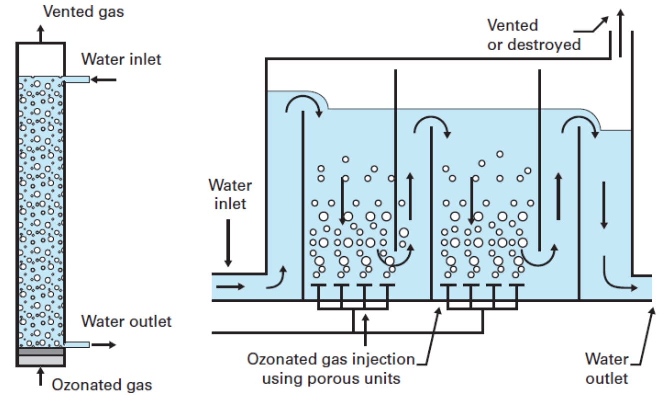
(b) Category 2 (substances that can be easily disposed of):

- (i) Benzotriazole (CAS No 95-14-7),
- (ii) Candesartan (CAS No 139481-59-7),
- (iii) Irbesartan (CAS No 138402-11-6),
- (iv) mixture of 4-Methylbenzotriazole (CAS No 29878-31-7) and ~~5~~6-methyl- benzotriazole (CAS No 136-85-6).

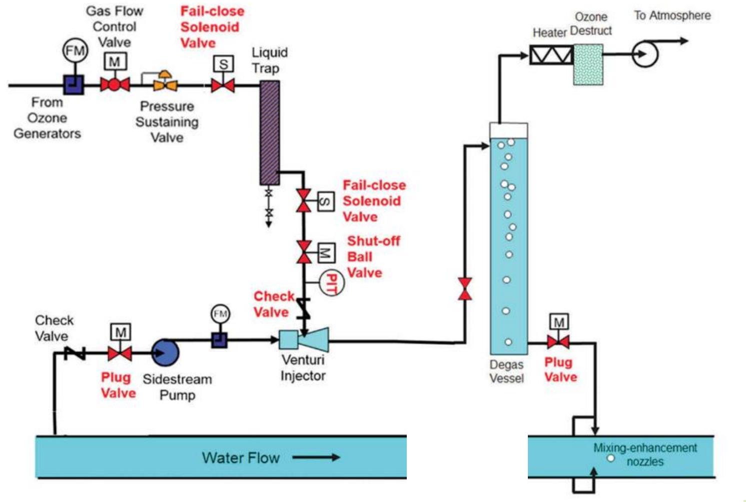
Note 2: **The percentage of removal shall be calculated for at least six substances**. The number of substances in category 1 **shall be twice** the number of substances in category 2. If less than six substances can be measured in sufficient concentration, the competent authority shall designate other substances to calculate the minimum percentage of removal when it is necessary. The average of the **specific** percentages of removal of all **single** substances used in the calculation shall be used in order to assess whether the required **80 % minimum percentage** of removal has been reached.

QUATERNARY TREATMENT

Ozonation



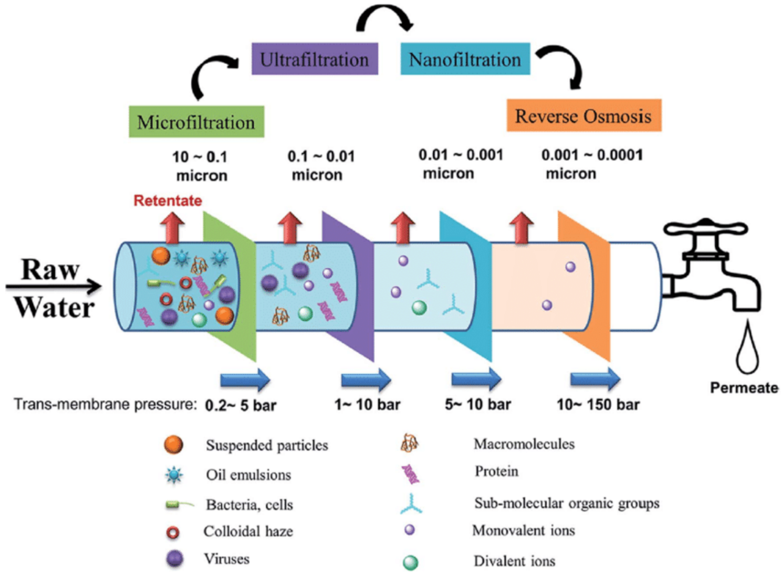
Bubble Diffusers



Sidestream configuration

Adsorption

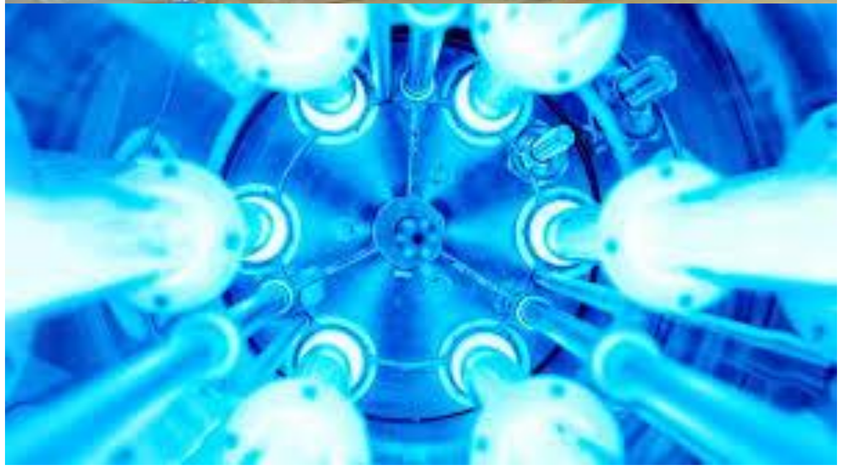
Membrane Filtration



QUATERNARY TREATMENT

Advanced Oxidation Processes

UVC/H_2O_2; O_3/ H_2O_2; O_3/ H_2O_2 /UVC



INTRODUCTION

European Commission

New EU Directive on Urban Wastewater Treatment (Directive (EU) 2024/3019)
Revised Regulation, Renewed Challenges

Wastewater treatment

- Nutrients removal (N: 80% removal or 8 mg/L; P: 90% removal or 0.5 mg/L; ≥ 150 000 p.e.)
- Obligation to all UWWTPs treating a load ≥ 150 000 p.e. to **apply quaternary treatment by 2045,** in order to **eliminate the broadest possible spectrum of micro-pollutants**.
- Promote the **reuse of treated wastewater** from all urban wastewater treatment plants **where appropriate**.

Energy neutrality and renewables

- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.

Wastewater surveillance and risk assessment

- Obligation **to monitor health parameters in urban wastewaters**: PFAS, Microplastics, Antimicrobial Resistance, Greenhouse Gases

EU Regulation 2020/741 on minimum requirements for water reuse

Uses of Reclaimed Water with a **“fit-for-purpose”** approach (minimum requirements set depending on the **food crop category** and **irrigation technique**) and protection of local public health and of the environment (the key risk management tasks)

Table 1 – Classes of reclaimed water quality and permitted agricultural use and irrigation method

Minimum reclaimed water quality class	Crop category (*)	Irrigation method
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation (**) or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy and seeded crops	All irrigation methods (***)

INTRODUCTION

EU Regulation 2020/741 on minimum requirements for water reuse

Uses of Reclaimed Water with a **“fit-for-purpose”** approach (minimum requirements set depending on the **food crop category** and **irrigation technique**) and protection of local public health and of the environment (the key risk management tasks)

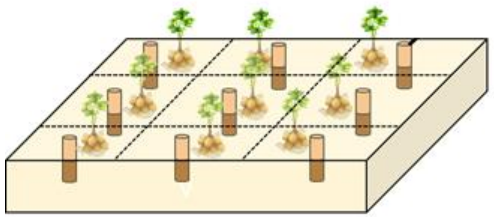
Table 2 – Reclaimed water quality requirements for agricultural irrigation

Reclaimed water quality class	Indicative technology target	Quality requirements				
		E. coli (number/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	*Legionella* spp.: < 1 000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/EEC (Annex I, Table 1)	In accordance with Directive 91/271/EEC (Annex I, Table 1)	-	
C	Secondary treatment, and disinfection	≤ 1 000			-	
D	Secondary treatment, and disinfection	≤ 10 000			-	

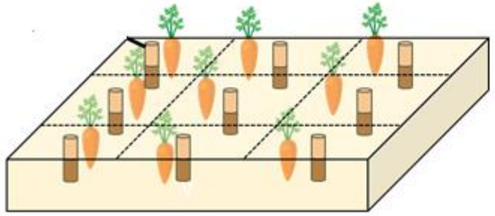
CROPS PRODUCTION

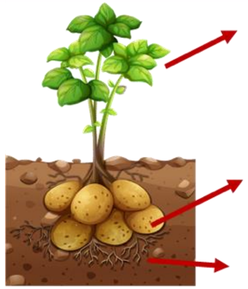
Gravel layer → Sand layer → Silty loam

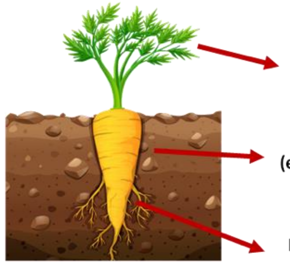
Potatoes



Carrots







INTRODUCTION

European Commission

New EU Directive on Urban Wastewater Treatment (Directive (EU) 2024/3019)
Revised Regulation, Renewed Challenges

Wastewater treatment

- Obligation to all UWWTPs treating a load ≥ 150 000 p.e. to **apply quaternary treatment by 2045,** in order to **eliminate the broadest possible spectrum of micro-pollutants**.
- Promote the **reuse of treated wastewater** from all urban wastewater treatment plants **where appropriate**.
- Nutrients removal (N: 80% removal or 8 mg/L; P: 90% removal or 0.5 mg/L; ≥ 150 000 p.e.)

Energy neutrality and renewables

- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.

Wastewater surveillance and risk assessment

- Obligation **to monitor health parameters in urban wastewaters**: PFAS, Microplastics, Antimicrobial Resistance, Greenhouse Gases

INTRODUCTION

European Commission

Energy neutrality and renewables

- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.
  - (a) 20 % of the total annual energy used by such plants by 31 December 2030;
  - (b) 40 % of the total annual energy used by such plants by 31 December 2035;
  - (c) 60 % of the total annual energy used by such plants by 31 December 2040;
  - (d) 100 % of the total annual energy used by such plants by 31 December 2045.
- All renewable energies produced by the urban wastewater treatment plants operators', whether **on-site or off-site**, such as **hydraulic, solar, thermal, wind energy or biogas**, should be taken into account. A **maximum share of 30% of energy**, not directly linked to urban wastewater treatment activities or operators' activities, **may be purchased from external sources**.
- However, initiatives to achieve energy neutrality **should not lead to an increased emission of methane and nitrous oxide**.

INTRODUCTION

New EU Directive on Urban Wastewater Treatment (Directive (EU) 2024/3019)
Revised Regulation, Renewed Challenges

Wastewater treatment

- Obligation to all UWWTPs treating a load ≥ 150 000 p.e. to **apply quaternary treatment by 2045,** in order to **eliminate the broadest possible spectrum of micro-pollutants**.
- Promote the **reuse of treated wastewater** from all urban wastewater treatment plants **where appropriate**.
- Nutrients removal (N: 80% removal or 8 mg/L; P: 90% removal or 0.5 mg/L; ≥ 150 000 p.e.)

Energy neutrality and renewables

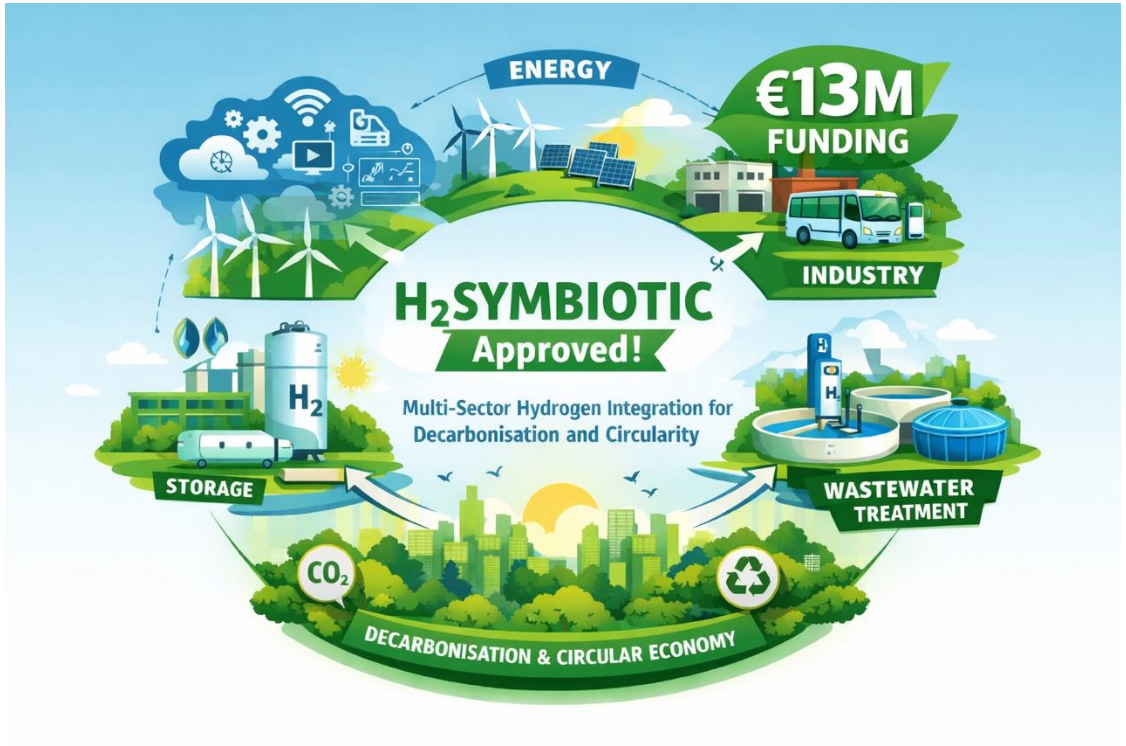
- Introduce an **energy neutrality target**, meaning that **by 2045** urban wastewater treatment plants will have to produce the energy they consume, with progressive intermediate targets.

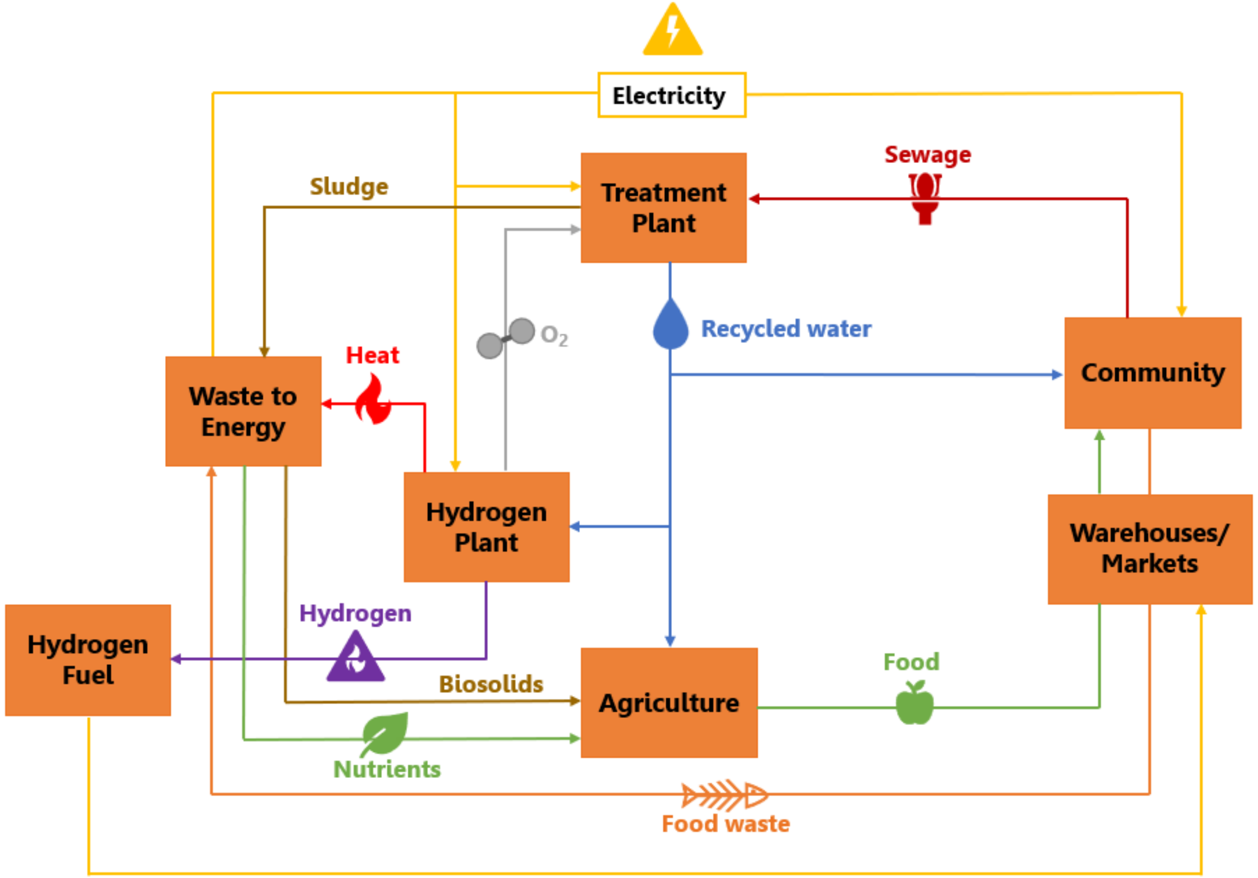
Wastewater surveillance and risk assessment

- Obligation **to monitor health parameters in urban wastewaters**: PFAS, Microplastics, Antimicrobial Resistance, Greenhouse Gases

H2SYMBIOTIC AGENDA

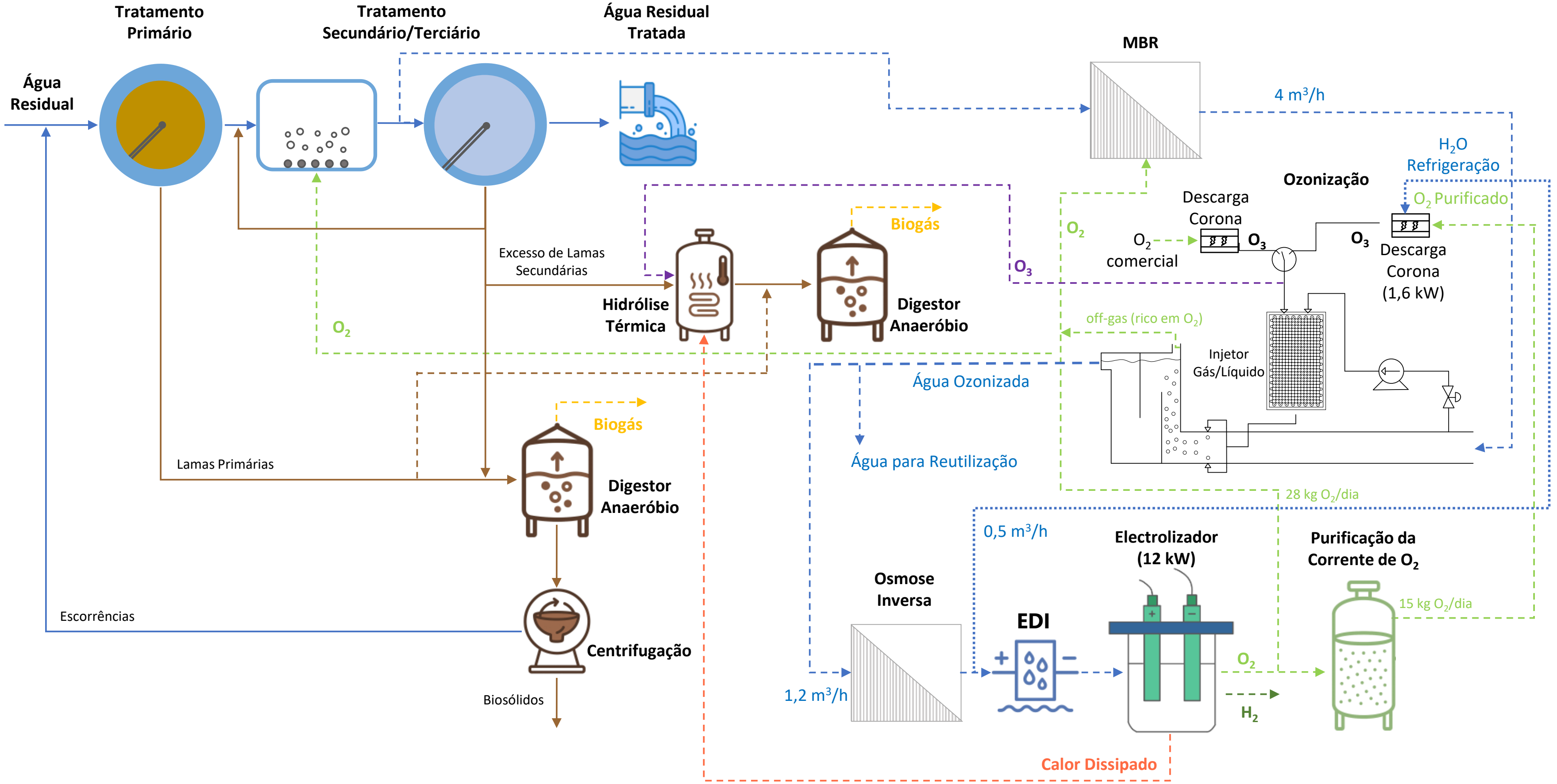
WasteWater Hydrogen to Power - WWH2P





H2SYMBIOTIC AGENDA

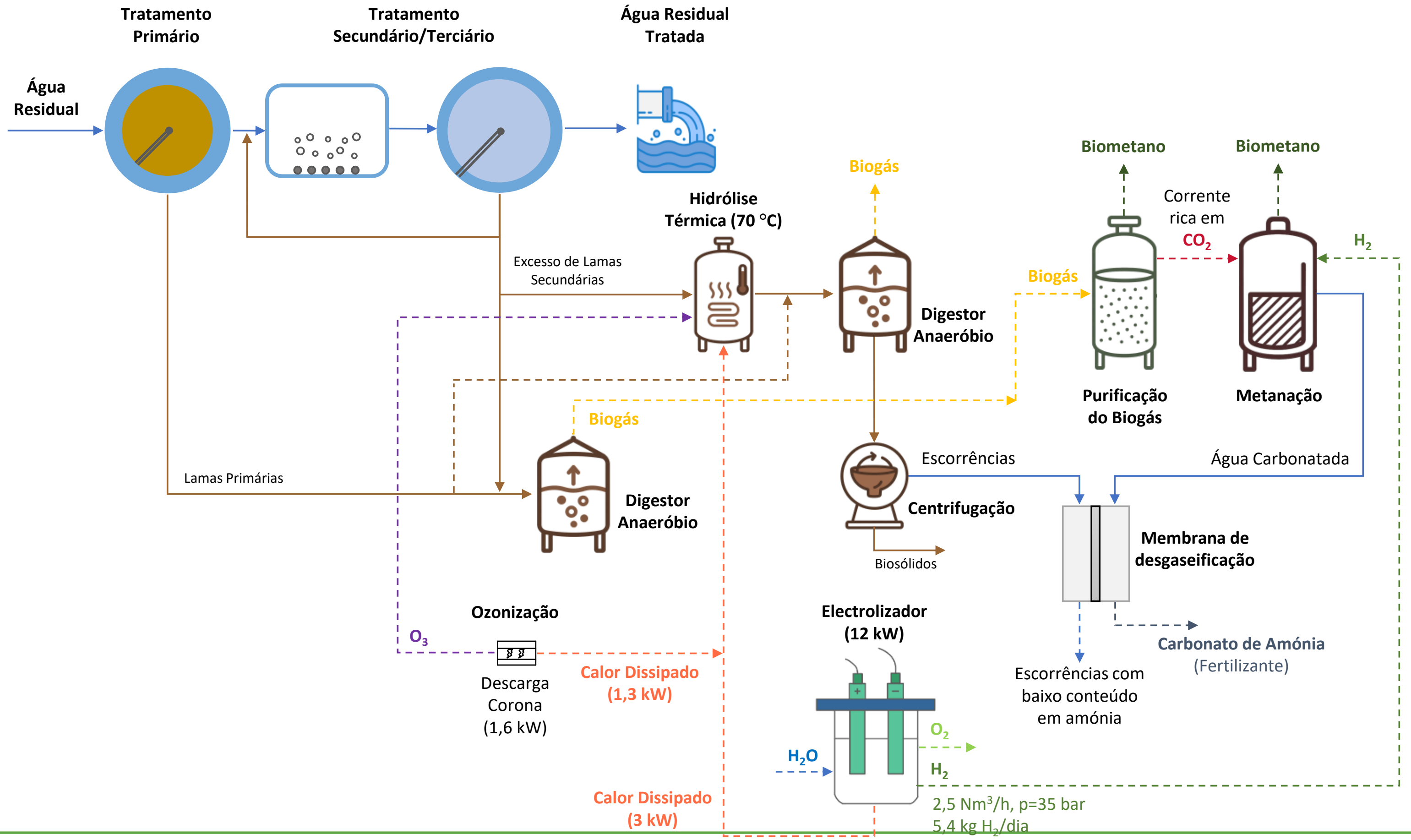
WasteWater Hydrogen to Power - WWH2P



ALiCE
SRE CM

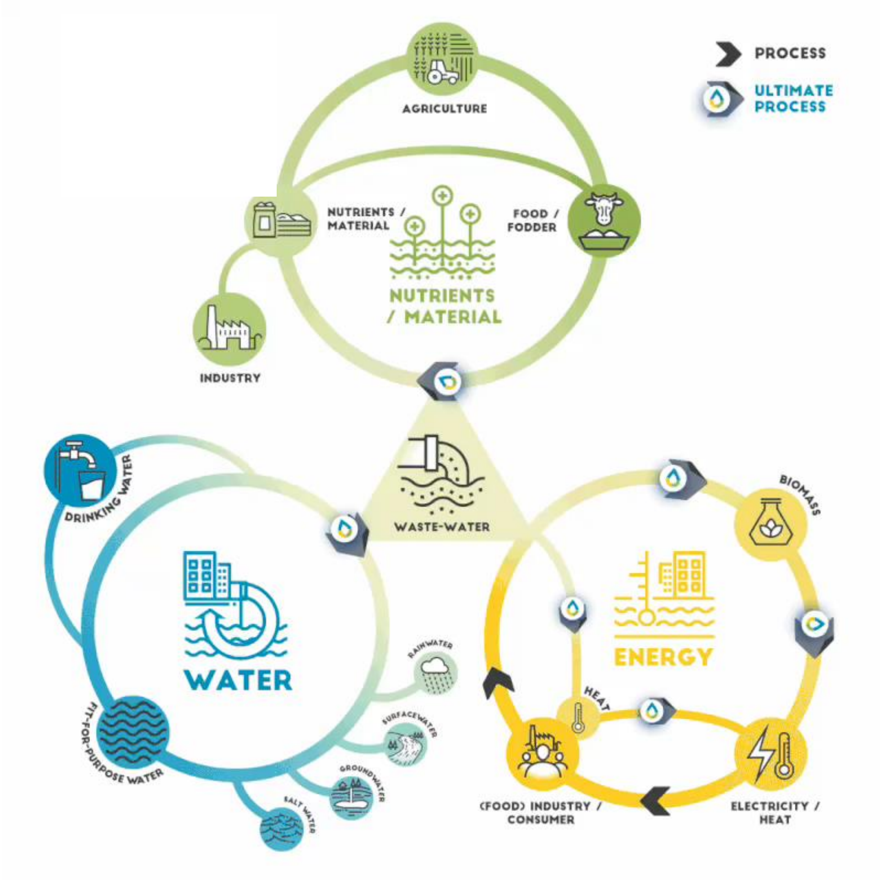
H2SYMBIOTIC AGENDA

WasteWater Hydrogen to Power - WWH2P



CONCLUSIONS

ADVANCED TREATMENT TECHNOLOGIES ↔ PROCESS INTEGRATION & INTENSIFICATION



Acknowledgements

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

ALiCE ASSOCIATE LABORATORY IN CHEMICAL ENGINEERING

SRE CM LABORATORY OF SEPARATION AND REACTION ENGINEERING LABORATORY OF CATALYSIS AND MATERIALS

lepabe Laboratory for Process Engineering, Environment, Biotechnology and Energy

cet Partnership

Water4All Water security for the planet

biodiversa+ European Biodiversity Partnership

Interreg España – Portugal Cofinanciado por la Unión Europea Cofinanciado pela União Europeia

blue water

fct Fundação para a Ciência e a Tecnologia

PRR Plano de Recuperação e Resiliência

REPÚBLICA PORTUGUESA

Financiado pela União Europeia NextGenerationEU

PORTUGAL 2030

Cofinanciado pela União Europeia

Faculdade de Engenharia da Universidade do Porto | Rua Dr. Roberto Frias s/n | 4200-465 Porto, Portugal | T. +351 220 414 567 | alice.info@fe.up.pt | www.alice.fe.up.pt

Vítor Vilar
vilar@fe.up.pt

Thank You For Your Kind Attention