Mid-term report on nutrients removal and recovery solutions

Deliverable D2.3

INNOVATIVE DECISION-MAKING TOOL FOR DEFINING THE MOST SUITABLE MANURE MANAGEMENT STRATEGIES TO ACHIEVE A SUSTAINABLE LIVESTOCK FARMING SYSTEM DURING THE WHOLE VALUE CHAIN

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EXECUTIVE SUMMARY

This deliverable presents the mid-term assessment of nutrient removal and recovery strategies developed within the NUTRITIVE project, covering primary treatment, post-treatment, and application level. The work focuses on selected technologies, as stated in the Description of Action (DoA), evaluated at laboratory and pilot scales, treating either pig or cow manure.

At the primary treatment level, microalgae-based systems were investigated for their capacity to recover nutrients directly from piggery livestock. Lab-scale results demonstrate that *Nannochloropsis oceanica* can successfully grow in diluted wastewater, achieving complete nitrogen removal at low dilution (10%) and up to 59% with a dilution of 30%. Maximum nitrogen consumption rates reached approximately 0.85 $mM \cdot d^{-1}$, confirming microalgae's potential to simultaneously treat effluents and produce biomass suitable for valorisation as a biofertilizer. However, process performance was influenced by wastewater composition (highlighting the presence of solids), and further optimization is required, particularly regarding nutrient balance for biomass growth.

At the post-treatment stage, several complementary technologies were assessed to enhance nutrient recovery from anaerobic digestate. Electrocoagulation (EC) demonstrated feasibility for phosphorus removal using iron electrodes, although efficiency was limited (16% P removal and 64% COD reduction). The formation of a thin layer of material on the iron electrode surface might lead to suboptimal conditions and highlight the need for further optimization of operational conditions (e.g., pH, current density, other electrodes, retention time...). Membrane-based processes, particularly ceramic membrane distillation (CMD), showed strong potential for water recovery and nutrient concentration, producing a clean permeate suitable for reuse. Experimental data is still not available, as is the case for its combination with the previous EC. Nitrogen recovery technologies exhibited promising performance at the pilot scale, with air ammonia stripping achieving up to 67% ammonium removal and producing fertilizer-grade ammonium sulphate. In parallel, preliminary data from innovative electrochemical systems showed ammonia recovery without chemical inputs, generating higher-value products such as ammonium hydroxide or ammonium bicarbonate. Additional technologies, purple phototrophic bacteria, drying processes, and pulse combustion are under development (no results available) and are expected to improve nutrient recovery and process integration further.

At the application level, the project explores the use of recovered nutrients as bio-based fertilizers. Microalgae- and PPB-derived products show strong potential to enhance crop productivity, nutrient-use efficiency, and soil quality, while reducing reliance on mineral fertilizers. Field trials are projected to the second part of the project, as microalgae and PPP-enriched biomass still need to be produced. Similarly, recovered mineral salts, such as struvite and ammonium sulphate, have demonstrated agronomic equivalence to conventional fertilizers and offer additional environmental benefits, including reduced nutrient losses. Salts recovered within Nutritive will be tested in the Atlantic and in high-rainfall conditions where information remains scarce.

Overall, the results confirm the potential of combining biological, physicochemical, and thermal technologies to enable efficient nutrient recovery and valorization within a circular economy framework. While several technologies have already demonstrated promising performance, further optimization, integration, and pilot-scale validation are required to enhance robustness and scalability. The outcomes of this work contribute to advancing sustainable nutrient management strategies and reducing the environmental impact of livestock waste.

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1. INTRODUCTION

Livestock farming is a key primary sector, accounting for 40% of total agricultural activity in Europe, with a total value of products of €170 billion. However, there is an increasing concern due to livestock farming's contribution to environmental pollution since it generates more than 1.4 billion tonnes/year of manure, leading to significant greenhouse gases (GHG) and air pollutants emissions (NH_3, NO_X) as well as to soil and water contamination caused by hazardous manure chemicals and biological contaminants (called here emerging contaminants). In this context, extensive efforts have been made for years to determine the detrimental impact of farming systems and to develop abatement methods for implementation. Despite significant advancements, many fundamental issues remain beyond the scope of existing legislation.

The main objective of NUTRITIVE is to develop a decision-making tool (DSS, decision support system) able to define the most efficient and sustainable (across its three pillars: environmental, economic, and social) manure management strategies for a given livestock farm, limiting manure air emissions as well as soil and water contaminants. This will allow the formulation of technical guidelines and recommendations that will support policymakers with enhanced knowledge to establish requirements for future European policies.

To fulfil this objective, the project is divided into six work packages (WPs): WP1 Up-to-date inventory; WP2 Novel management strategies/technologies investigation; WP3 Modelling and Life Cycle Assessment (LCA); WP4 Guidelines formulation; WP5 Communication, dissemination, and exploitation; WP6 Management (Figure 1).

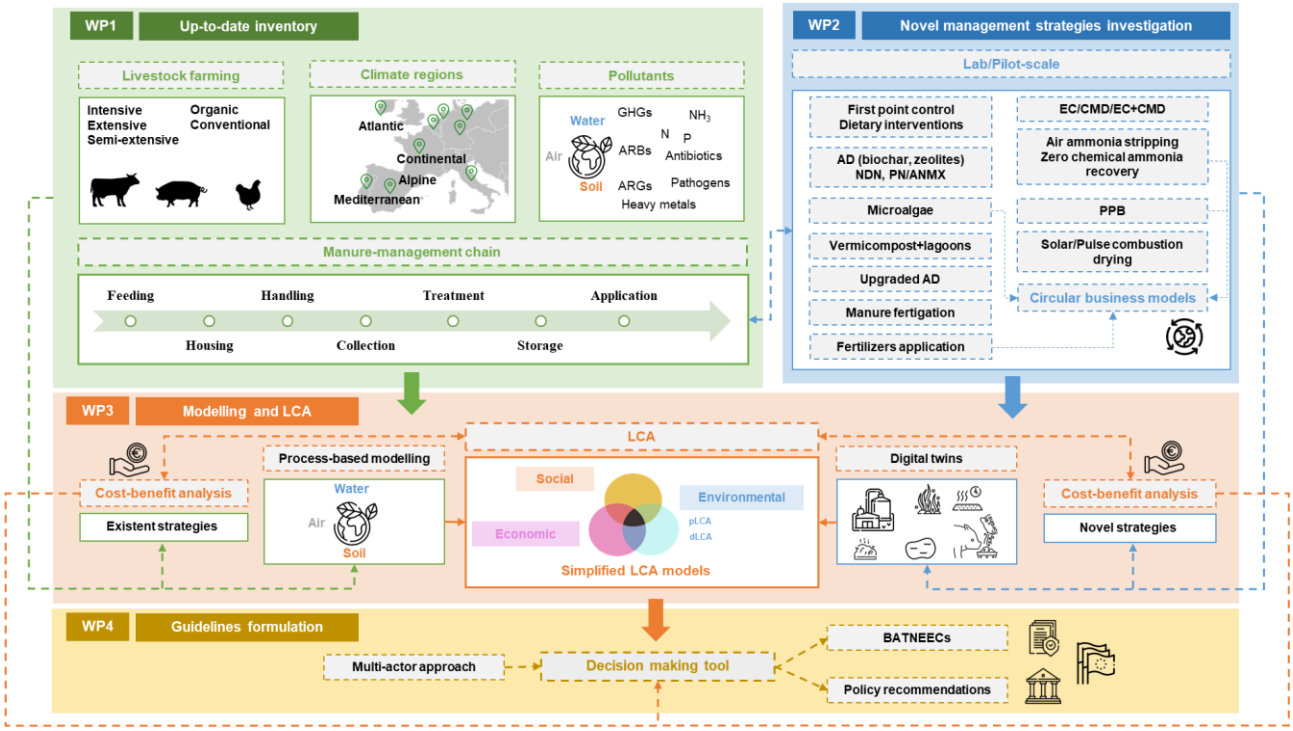

Figure 1. NUTRITIVE methodology.

NUTRITIVE anticipates widespread adoption of the project outcomes, with the consortium as a baseline: 22 partners (4 Chinese) from 8 countries across Europe, covering 6 climatic regions (2 Chinese), representing the whole supply chain, from animal feed to soil application.

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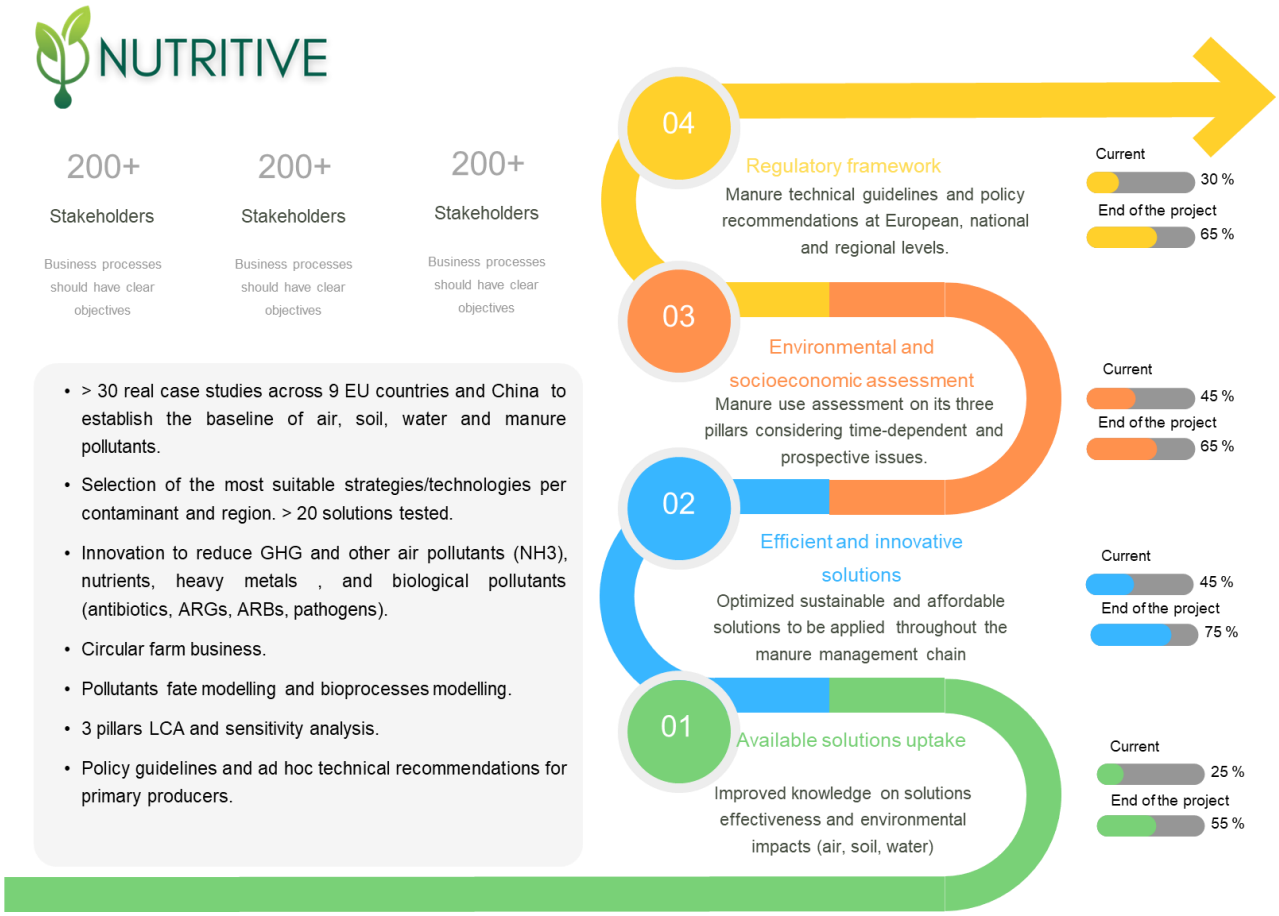

Figure 2. NUTRITIVE overview.

This mid-term report will focus on the progress of the efficient and innovative technologies from WP2, specifically nutrient removal and recovery (Task 2.2). They are classified according to the main treatment objective as: i) primary treatment, ii) post-treatment, and iii) application level.

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2. Nutrients removal and recovery - Primary treatment strategies

2.1. S/T9: Microalgae culture

2.1.1. Introduction

Among the innovative approaches being explored to treat livestock wastewater effectively, cultivating microalgae in nutrient-rich effluents offers a promising, cost-effective, and environmentally friendly method for biological remediation. This technique effectively removes excess nutrients and contaminants while capturing atmospheric CO_2 and converting it into valuable algal biomass. The resulting biomass can be transformed into fertilizers, plant biostimulants, or precursors for added-value bio-based products. Experimental results have shown that *Scenedesmus sp*., a widely studied freshwater alga, can remove up to 55.3 mg/(L·d) of ammonium nitrogen and between 0.1 and 0.9 mg/(L·d) of phosphate from piggery wastewater (Ji et al., 2013). Likewise, *Chlorella* species cultivated together with *Scenedesmus* achieved nutrient removal efficiencies of 92% for ammonium nitrogen and 80% for phosphorus (Guo et al., 2020). When used as soil amendments, microalgae biomass facilitates the slow release of nutrients, thereby promoting improved plant development and agricultural productivity (Guo et al., 2020).

Building on this concept, the current study seeks to evaluate the potential of *Nannochloropsis Oceanica*, a much more robust microalga than those previously studied, to grow in livestock effluents as an alternative nutrient source. This work is carried out in the framework of the Document of Agreement (DoA). For this purpose, it aims to evaluate the feasibility and optimize the growth conditions of *Nannochloropsis Oceanic*a cultivated in piggery wastewater (PWW) to assess its potential for nutrient removal and biomass production. The produced biomass will be assessed for its suitability as a biofertilizer or growth-promoting agent, aiming to substitute the direct application of the untreated liquid fraction of pig manure with a safer, more effective, and ecologically sustainable product.

2.1.2. Methodology

Due to the high ammonia concentration in raw PWW, dilution was necessary using the A4F industrial medium, which contains 20 g/L salt. Two wastewater formulations with different initial ammonium concentrations were prepared by diluting PWW to 30% and 10% (v/v) in A4F medium. The A4F medium alone served as the control, with additional nutrients added as needed. Culture media were inoculated with *Nannochloropsis Oceanic*a to an initial optical density (OD_{600}) of 0.5, using cells centrifuged at 3500 rpm for 10 minutes and resuspended in the test media to minimize nutrient carryover. Parallel assays were conducted using centrifuged PWW as well. Analyses were performed at defined timepoints (t_0, t_1, t_2) and included measurements of OD_{600}, pH, ammoniacal nitrogen (NH_4^+), nitrate (NO_3^-), dry weight (g/L), cell density (cells/mL), and microscopic evaluation of cell morphology and integrity.

All experiments were conducted in batch mode at approximately 23 °C with a maintained salinity of 20 g/L. Cultures were aerated continuously with air supplemented with 0.5 % CO_2 as the carbon source. The pH was maintained between 7 and 8, and cultures were exposed to continuous illumination (24-hour photoperiod) at a light intensity of 150 – 155 µmol/(m²·s). Each culture flask contained 900 mL of culture medium.

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2.1.3. Results

The capability of *N. Oceanica* to grow under conditions containing piggery wastewater (PWW) was evaluated. For this, the cell physiology of *N. Oceanica* was evaluated using microscopy. Under the growth conditions tested with PWW, cells appeared healthy and able to survive (Figure 3).

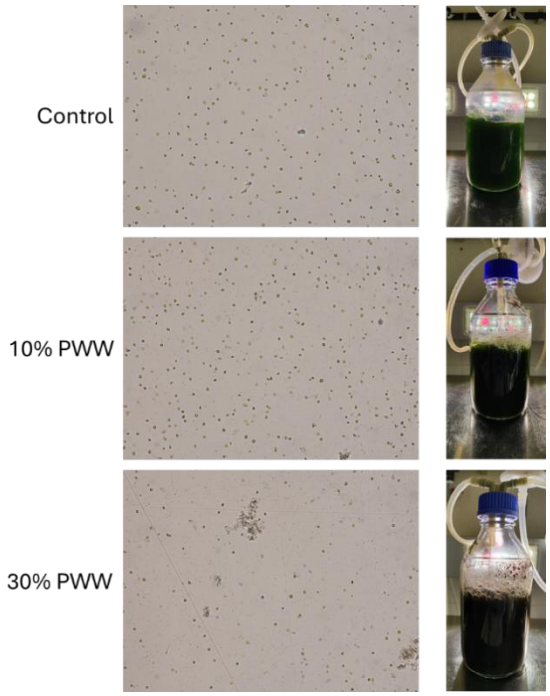

Figure 3: Example of macroscopic and microscopic photos of N. Oceanica grown in the tested conditions after 7 days of cultivation

To quantify the cellular growth of *N. Oceanica,* the salt-free dry weight of the culture was analysed. However, due to the high concentration of suspended solids in the medium, this parameter could not be used to assess growth, especially under the 30 % PWW condition (Figure 4, Panel A). To overcome this issue, the PWW was centrifuged prior to cultivation. This was expected to resolve the suspended solids hindering the growth assessment by dry weight. However, even after centrifugation, this behaviour persisted in the dry weight analysis (results not shown). Thus, cell growth was evaluated by counting the cells using a Neubauer chamber in the following experiments (Figure 4, Panel B).

From our preliminary results using 10 % PWW, we could reach a productivity of 1.14×10^7 cell/(mL·d) in the first 11 days, compared with 1.60×10^7 cell/(mL·d) obtained in the control. In the 30 % effluent condition, a productivity of 3.61×10^6 cell/(mL·d) from day 3 to day 21 was achieved, which was the lowest productivity among all conditions tested.

After centrifugation, using 10 % PWW condition, a productivity of 9.29×10^6 cell/(mL·d) in the first 11 days was obtained, while in the 30 % PWW condition, was obtained from day 3 to day 21 3.41×10^6 cell/(mL·d). While the 30 % PWW condition appears unaffected by centrifugation, using centrifuged 10 % PWW results in reduced productivity compared with raw PWW (Figure 4, Panel B).

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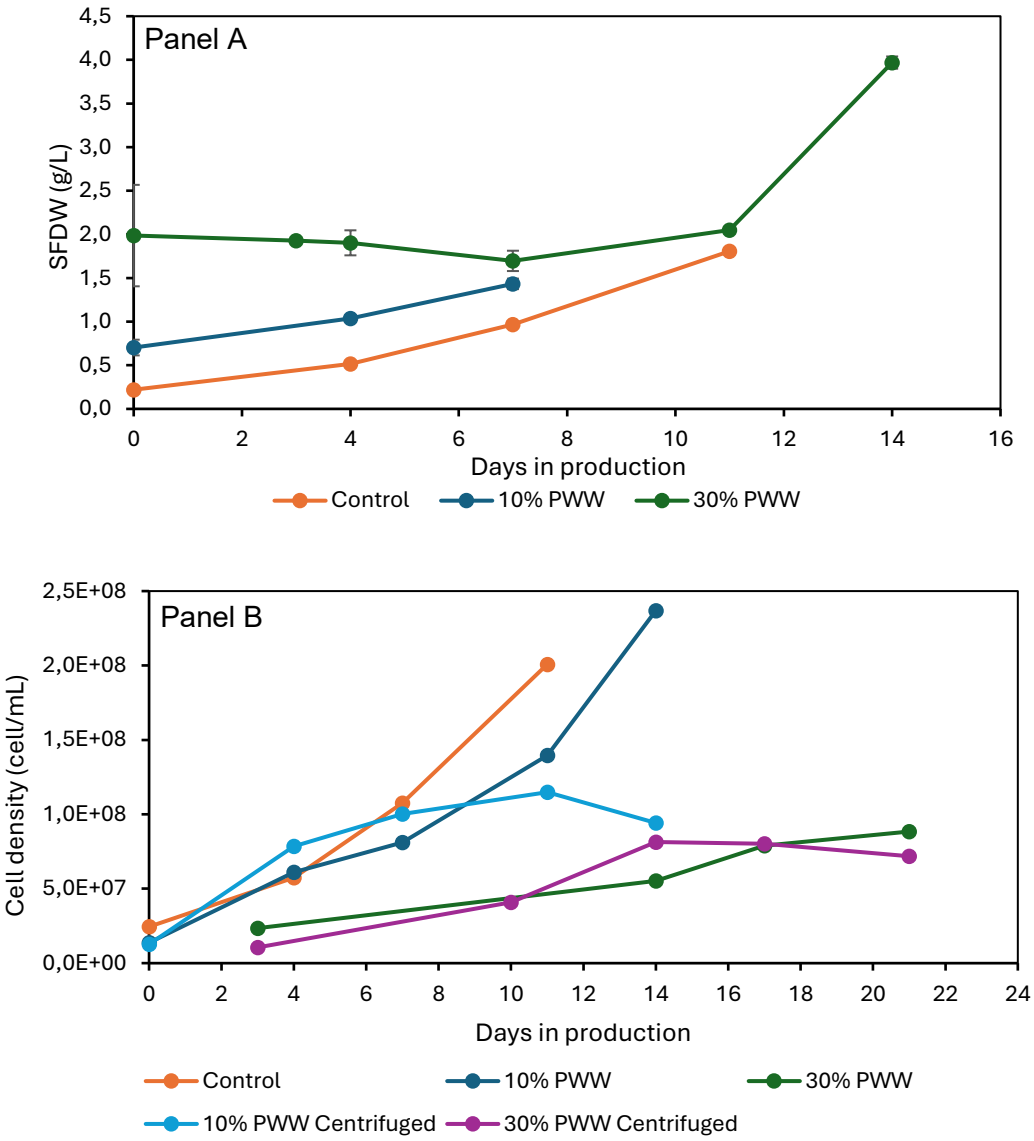

Figure 4: N. Oceanica growth using raw and centrifuged PWW as a nutrient source. Panel A - Growth was followed using salt-free dry weight (g/L); Panel B - Growth was followed using a Neubauer chamber to determine cell density (cell/mL)

Despite the difficulties in following growth due to the presence of suspended solids, nitrogen consumption was determined (Figure 5).

For these results, the sum of nitrate (NO_3^--N) and ammonia (NH_4^+-N) is shown as the total N content. Note that in the control, the N source is NO_3^-, whereas in the PWW tests, it is mainly NH_4^+. It was possible to observe a clear decrease in N content in the media, indicating that *N. Oceanica* is using this compound to grow. In the first 11 days, we observed consumption rates of 0.85 mM/d and 0.48 mM/d for the 30% and 10% PWW conditions, respectively, while the control showed a rate of 0.56 mM/d (Figure 5). Thus, suggesting that *N. Oceanica* can remove N from PWW. In the case of cultivations using centrifuged PWW, under the condition using 10 % PWW, a consumption of 30 mM/d was obtained in the first 11 days, while in the condition using 30 % effluent, 0.34 mM/d was achieved in the first 14 days (Figure 5). These results show that using raw piggery wastewater leads to greater N consumption from the medium.

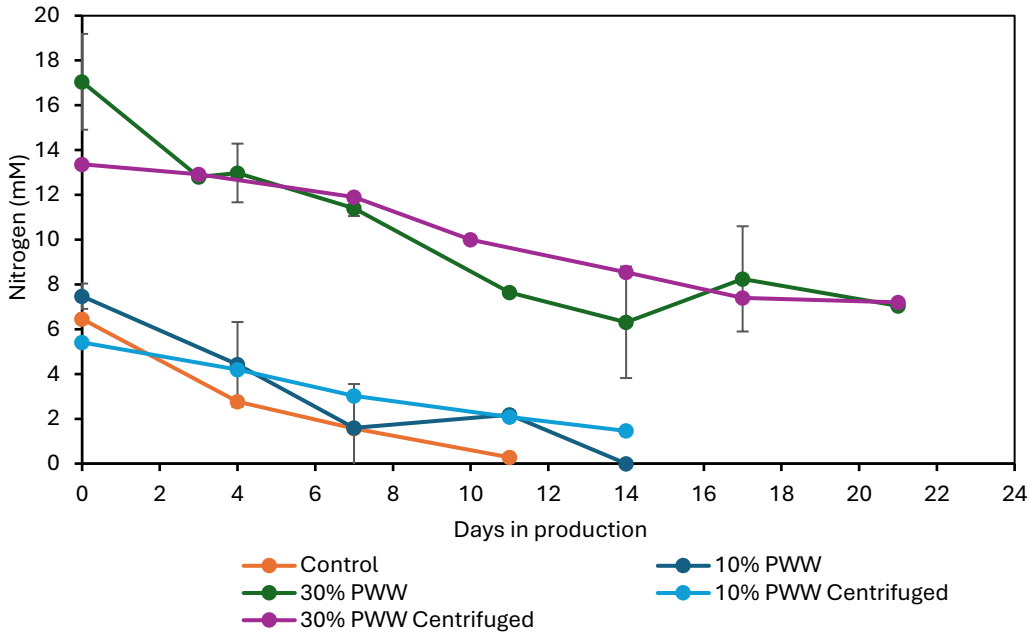

Figure 5: Nitrogen consumption by N. Oceanica grown in 10 % and 30 % raw and centrifuged PWW.

Similar results were obtained when evaluating the percentage of consumption taking into consideration the initial N and the final N in the medium (

Table 1). Overall, N removal was higher in the 10 % PWW condition, and centrifugation of the PWW reduced N removal from the medium.

Unfortunately, the removal of phosphorus (P) from PWW could not be determined due to interference in the measurement method used at A4F. Further tests will include P quantification in the microalgal culture medium with PWW using other, more suitable measurement methods.

Table 1: Initial and final concentration of N in the different growth conditions.

Condition	Initial N (mM)	Final N (mM)	N Removal (%)
Control	6.46	0.28	95%
10 % PWW	7.47	0.00	100%
30 % PWW	17.05	7.05	59%
10 % PWW centrifuged	5.41	1.46	73%
30 % PWW centrifuged	13.37	7.20	46%

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2.1.4. Conclusions and next steps

The results demonstrate that *N. Oceanica* can successfully grow in diluted PWW, exhibiting growth at both 10% and 30% PWW dilutions. The highest N consumption (~0.85 mM/day) was observed during the early stages in the 30 % PWW condition. However, complete nitrogen removal was not achieved in this case, indicating that other nutrients may limit the biological activity of *N. Oceanica.* Additionally, centrifugation of the wastewater generally resulted in reduced algal productivity and nitrogen consumption.

Regrettably, the phosphorus quantification method used in this study could not be optimized, preventing reliable conclusions on phosphorus uptake. Future work should prioritize refining phosphorus measurement techniques to accurately monitor its consumption. Furthermore, it will be important to identify the limiting nutrient(s) responsible for incomplete nitrogen removal and to investigate further the effects of PWW pre-treatment on *N. Oceanica* growth.

These preliminary findings require validation through additional experimentation. Due to the presence of suspended solids, future biomass growth assessments should rely on cell counting rather than dry weight measurements to ensure accurate evaluation.

3. Nutrients removal and recovery post-treatment strategies

3.1. S/T10 Electrocoagulation (EC)

3.1.1. Introduction

Phosphorus (P) is a key nutrient in agricultural systems, but also a major contributor to eutrophication when discharged into water bodies without prior conditioning. Anaerobic digestate, particularly its liquid fraction, often contains high concentrations of soluble phosphorus (mainly as orthophosphate), which must be removed or recovered to comply with environmental discharge limits and support circular economy goals.

Electrocoagulation (EC) is an electrochemical treatment process that uses sacrificial metal electrodes (typically made of iron or aluminium) to generate coagulants in situ. These coagulants destabilize and aggregate phosphorus-containing particles, promoting their removal via precipitation and further sedimentation. EC offers several advantages over conventional chemical coagulation, including reduced chemical usage, lower sludge production, and adaptability to varying wastewater compositions.

Recent studies have demonstrated the effectiveness of EC for phosphorus removal and recovery in various wastewater matrices. Jiang et al. (2023) achieved 93.9 % phosphorus removal from small rural domestic sewage using industrial iron electrodes, with low energy consumption (0.25 kWh/m³) and stable performance over 10 days of continuous operation. Similarly, Inna et al. (2025) reported 100% phosphorus recovery from slaughterhouse wastewater under optimized conditions, using both iron and aluminium electrodes. Their study highlighted the influence of key operational parameters such as pH, current density, inter-electrode distance, and stirring speed. It demonstrated that EC can be tailored to different wastewater types for efficient nutrient recovery. Additionally, Reza et al. (2024) provided a comprehensive review of EC applications for phosphorus removal in decentralized wastewater systems, emphasizing their simplicity, cost-effectiveness, and potential for integration into rural sanitation strategies.

In addition to P removal, EC has potential for recovery, especially when combined with downstream processes such as membrane distillation or struvite precipitation. The formation of flocs

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rich in iron or aluminium phosphates opens opportunities for valorisation as fertilizers or soil amendments.

While showing potential, EC performance depends heavily on operational parameters, including electrode material, current density, reaction time, pH, and conductivity. Optimization is essential to maximize phosphorus removal while minimizing energy consumption and electrode degradation. In the NUTRITIVE project, EC is being evaluated as a post-treatment strategy for nutrient recovery from anaerobic digestate, with initial trials already conducted and further testing planned. Although EC is an established technology, working with real matrices and optimising parameters at laboratory scale places this activity at TRL 4-5, corresponding to validation under controlled conditions with real influents.

3.1.2. Methodology

Two preliminary EC trials were carried out using a bench-scale setup comprising a sacrificial iron anode and a graphite cathode, both with an effective surface area of 48 cm² and separated by a 10 cm gap (Figure 6). The liquid fraction of anaerobic digestate, obtained by centrifugation, was used as the feed solution. A power supply was used to apply constant voltages of 5 V and 15 V in the first and second experiments, respectively. Both trials were conducted over 90 minutes, with data recorded at 10-minute intervals to monitor process dynamics. Key operational parameters were tracked throughout the experiments, including pH, electrical conductivity, current intensity, voltage, temperature, and chemical oxygen demand (COD).

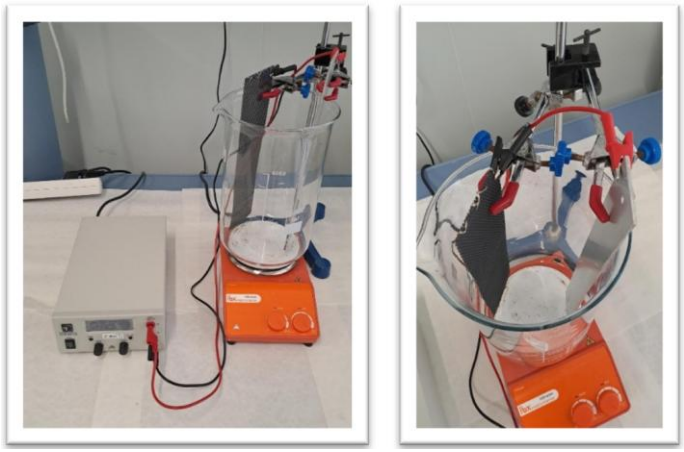

Figure 6: Bench-scale electrocoagulation set-up.

3.1.3. Results

In the first experiment (5 V, Figure 7), the current remained relatively low (0.52 A initially, decreasing to 0.38 A), and phosphorus removal was limited, resulting in a reduction of approximately 16.8 % in PO_4^{3-} concentration. COD decreased by 20.1 %, and ammonium by 9.8 %. No visible floc formation was observed, although foam generation and biofilm development on the iron anode were noted. The absence of flocs suggests insufficient coagulant generation or suboptimal operating conditions.

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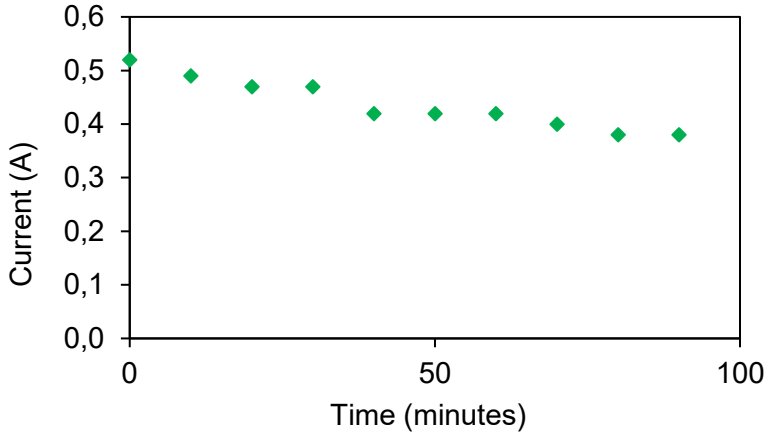

Figure 7: Current evolution during the EC trial at 5 V

In the second experiment (15 V), the current was significantly higher (starting at 1.42 A, Figure 8), and the system exhibited more pronounced foam formation and a higher temperature increase (up to 44.6 °C). However, phosphorus concentration in the supernatant increased after treatment (from an initial concentration of 121.1 mg P/L to 136.7 mg P/L), possibly due to resolubilization. COD reduction was more substantial, reaching 64.5 %, and ammonium levels dropped significantly (from 1027 mg N/L to 80 mg N/L). These results indicate that higher voltage enhances organic matter removal but may not directly improve phosphorus recovery without further optimization.

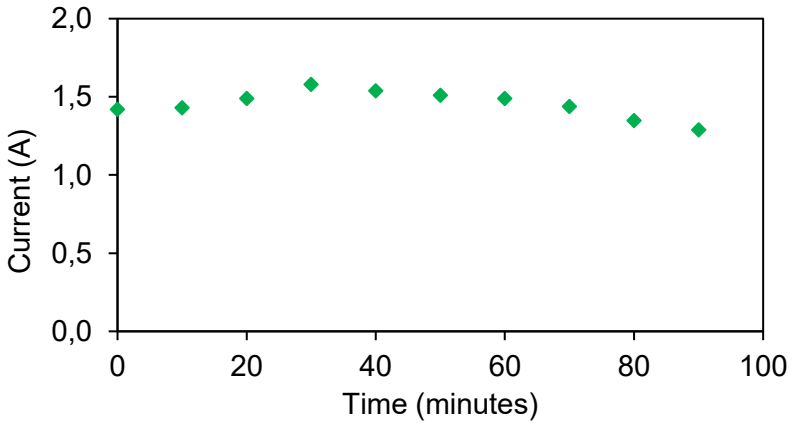

Figure 8: Current evolution during the EC trial at 15 V.

Biofilm formation on the iron anode (Figure 9) was observed in both experiments, but was more prominent in the first. This layer may act as a barrier to electron transfer and, over time, reduce the rate of iron dissolution, contributing to electrode passivation. Literature suggests that strategies such as chloride addition, pulsed current, or mechanical cleaning may help mitigate this effect and maintain EC performance during extended operation.

Overall, the trials confirmed the feasibility of EC for digestate treatment but highlighted the need for parameter optimization. The literature suggests that phosphorus removal efficiency in EC is highly sensitive to current density, pH, and electrode configuration. Thus, further investigation is needed to improve the experimental setup and the EC efficiency.

Progress in the EC activity has been moderate because the arrival of the manure samples was delayed, preventing the simultaneous initiation of EC and NDN experiments. This approach reduces

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the number of required characterisations and ensures the use of a common influent across technologies. Nonetheless, to avoid further delays in the overall timeline, it has been decided to proceed with the EC setup and begin the activity.

Figure 9: Biofilm formation on a sacrificial anode

3.1.4. Conclusions and next steps

The preliminary electrocoagulation trials demonstrated the feasibility of using iron electrodes for the post-treatment of anaerobic digestate, with moderate removal efficiencies for phosphorus and organic matter. The first experiment (5 V) showed limited phosphorus reduction (~16.8 %) and poor COD removal (~20 %). In comparison, the second experiment (15 V) achieved a greater COD reduction (~64.5%) but did not improve phosphorus recovery, possibly due to resolubilization.

A thin layer of material was observed adhering to the iron anode during both experiments, particularly in the first trial at 5 V. This deposit resembled a biofilm or corrosion layer and may be composed of iron oxides, hydroxides, or organic matter from the digestate. Its formation suggests active electrode dissolution and interaction with the matrix, but its exact composition remains unknown and requires further characterization. The presence of this layer could affect electrochemical performance by increasing resistance or contributing to electrode passivation, thereby reducing long-term efficiency. These results highlight the need to further optimize operational parameters to enhance phosphorus recovery.

Next steps in the NUTRITIVE project will include:

- Optimization of EC parameters, including pH adjustment, current density, and retention time.
- Testing alternative electrode materials, such as aluminium, to compare removal efficiencies and sludge characteristics.
- Quantification of floc formation and sedimentation, including mass balance and phosphorus speciation in the solid phase.
- Assessment of electrode passivation, including strategies for mitigation (e.g., chloride addition, pulsed current).

These actions aim to improve the efficiency and robustness of EC as a post-treatment strategy for nutrient recovery, contributing to the circular management of digestate and compliance with environmental discharge regulations.

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3.2. S/T11: Ceramic membrane distillation (CMD)

3.2.1. Introduction

Ceramic membrane distillation (CMD) is a thermally driven separation process that uses hydrophobic ceramic membranes to recover water and concentrate nutrients from digestate. CMD operates at moderate temperatures (typically 40 – 80 °C) and ambient pressure, making it compatible with low-grade heat sources such as solar or waste heat. Compared to polymeric membranes, ceramic membranes offer superior thermal and chemical stability, mechanical strength, and resistance to fouling and wetting. These properties make CMD particularly suitable for treating high-strength waste streams, like digestate, which contain elevated levels of organic matter, ammonia, and phosphorus (Alessandro & Macedonio, 2025).

Recent developments in CMD include the use of surface modification techniques to enhance membrane hydrophobicity and anti-wetting performance. CMD is increasingly being considered for decentralized water treatment and resource recovery applications, aligning with circular economy principles (Bian et al., 2025). As the aim is to assess performance and stability in a controlled environment before further scaling up, this activity is also classified as TRL 4-5. Profess in the CMD activity has been limited because its execution is planned to start after the completion of the initial EC tasks and the stabilisation of sample availability.

3.2.2. Methodology

Preliminary CMD trials will be conducted using real digestate pig slurry samples coming from the 30 L anaerobic digestion plant located at AINIA. This source ensures consistency and relevance to real agricultural waste treatment scenarios.

A bench-scale CMD unit will be employed, equipped with:

- Temperature control (feed and permeate side).
- Flow regulation (crossflow velocity).
- Hydrophobic ceramic membranes.
- Sensors for pH, conductivity, and temperature.

Key parameters to monitor:

- Transmembrane flux (L/(m²·h)).
- Temperature gradient across the membrane.
- pH and conductivity of feed and permeate.
- Concentrations of NH_4^+, PO_4^{3-}, and COD in permeate and retentate.

Cleaning protocols will include citric acid rinses to mitigate fouling.

3.2.3. Results

Recent literature confirms CMD's high efficiency in nutrient separation and water recovery:

- Water recovery rates between 30 % and 50 % are achievable depending on feed composition and operating conditions. Alessandro and Macedonio (2025) highlight that ceramic membrane distillation systems can achieve high permeate fluxes when parameters such as membrane porosity, thickness, and thermal conductivity are optimized.
- Phosphorus is not recovered in the permeate during ceramic membrane distillation due to its non-volatile nature. However, CMD effectively retains and concentrates phosphate

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ions in the retentate, which can later be valorised or recovered through precipitation or other downstream processes.

- Ammonium transfer is influenced by pH; higher pH promotes NH_3 volatilization and permeation. Bian et al. (2021) demonstrated that the increase in free ammonia (FA) concentration correlates with NH_3 transfer across membranes, facilitating its recovery in thermal processes such as CMD.
- Membrane fouling is manageable with periodic acid cleaning, and ceramic membranes show excellent durability under harsh conditions. Alessandro and Macedonio (2025) describe that citric acid cleaning is effective in restoring permeate flux in ceramic membranes, which also exhibit superior resistance to aggressive chemical environments and elevated temperatures.

CMD produces a clean permeate suitable for reuse (e.g., irrigation or process water) and a nutrient-rich retentate that can be valorised as fertilizer. Its compatibility with low-grade heat sources and resistance to fouling make it a promising technology for treating pig slurry digestate in agricultural settings.

3.2.4. Conclusions and next steps

CMD is a promising technology for simultaneously recovering water and concentrating nutrients from digestate. The next steps in this field are:

- Conduct CMD trials with digestate at varying pH (6 – 9) and temperatures (50 – 80 °C).
- Evaluate membrane performance, flux decline, and cleaning efficiency.
- Characterize permeate for reuse (e.g., EC, NH_4^+, PO_4^{3-} and, COD) and retentate for nutrient valorisation.

3.3. S/T12: Combination of EC and CMN

3.3.1. Introduction

The EC and CMN offer a synergistic approach to digestate treatment. EC effectively removes suspended solids and precipitates phosphorus, significantly reducing the organic load and the fouling potential of downstream membrane processes. CMN complements EC by recovering clean water and concentrating residual nutrients such as ammonia and phosphorus, thanks to its thermal stability and resistance to aggressive feed compositions. This hybrid strategy aligns with zero-liquid discharge and resource recovery goals, enhancing treatment efficiency, membrane longevity, and overall sustainability. Similar integrated approaches have been successfully applied to other high-strength wastewaters, demonstrating improved performance and reduced fouling in membrane distillation systems when preceded by EC (Sardari & Wickramasinghe, 2015; Jebur et al., 2021).

The sequential combination of electrocoagulation and membrane distillation integrates two technologies in a configuration that has not previously been validated with real influents at the laboratory scale. While each technology has a known maturity level, coupling them introduces additional operational and stability uncertainties. Therefore, the combined activity is likewise positioned at TRL 4-5, aligned with laboratory-scale validation of innovative process configurations. The combined EC-CMD configuration will be addressed once sufficient progress has been made in both individual technologies. Advancing sequentially ensures that the

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operational windows of EC and CMD are well established before evaluating their integrated performance, thereby reducing the risk of instability and rework.

3.3.2. Methodology

The combined process will follow a two-stage configuration:

1. EC pre-treatment of digestate using aluminium or iron electrodes under optimized conditions (e.g., current density optimization, pH adjustment, etc.).
2. Treatment of the EC supernatant using hydrophobic ceramic membrane by CMN process.

Comparative trials will be conducted:

- With and without EC pre-treatment
- Monitoring flux, fouling, and nutrient rejection in CMN

3.3.3. Results

Although no experimental data are yet available for this specific configuration with digestate, similar setups in wastewater treatment have shown promising results, supporting the benefits of the EC + CMN combination.

- EC achieves phosphorus removal efficiencies > 90 – 99 %, depending on current density and retention time (Inna et al., 2025; Jiang et al., 2023).
- EC reduces COD and suspended solids, mitigating membrane fouling in CMN (Vasudevan et al., 1997).
- CMN following EC shows improved flux stability and reduced cleaning frequency (Sardari & Wickramasinghe, 2015).
- The combination may lower energy demand by reducing organic load before thermal treatment (Jebur et al., 2021).

3.3.4. Conclusions and next steps

The EC + CMD combination is expected to enhance nutrient recovery and water reuse from digestate. It leverages EC's ability to remove phosphorus and CMD's capacity to recover clean water and concentrate residual nutrients. Next steps are:

- Design and execute integrated EC + CMD trials using digestate.
- Compare CMD performance (flux, fouling, rejection) with and without EC.
- Assess overall nutrient recovery, water quality, and operational feasibility.

3.4. S/T13: Air ammonia stripping

3.4.1. Introduction

This project applies air ammonia stripping to the liquid fraction of manure-derived digestate or pig manure using the Ammonia Mining Unit (AMU) developed by DETRICON. The system uses a two-step process involving heat and pH adjustment, achieved by stripping CO_2 to increase pH naturally. Ammonia-rich air is then scrubbed with sulfuric acid to produce ammonium sulphate ($(NH_4)_2SO_4$). The unit treats 1 m³ of liquid per hour, monitoring NH_4-N removal, NH_3 balance, and product quality parameters including nitrogen, TSS, COD, and sulphur content. The Ammonia Mining Unit is a commercially available technology, corresponding to a high Technology Readiness Level (TRL 8–9).

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3.4.2. Methodology

The air ammonia stripping process will be conducted using the Ammonia Mining Unit developed by DETRICON, which is designed to treat 1 m³/h of the liquid fraction from digestate or pig manure. The methodology consists of the following steps:

1. Pre-treatment and pH adjustment

   The liquid feedstock will first undergo CO_2 stripping to naturally elevate the pH, optimizing conditions for ammonia volatilization. Heat will be recovered and applied to further enhance NH_3 release.

2. Two-step stripping process

   The pre-treated liquid will pass through a two-stage air stripping system where ammonia is transferred from the liquid to the air phase.

3. Gas scrubbing

   The NH_3-enriched air will be directed into a scrubber. Sulfuric acid (H_2SO_4) will be used to capture NH_3 as ammonium sulphate ($(NH_4)_2SO_4$).

4. Monitoring and analysis

   The system will be continuously monitored for:

   - Influent and effluent NH_4^+-N concentrations to assess removal efficiency.
   - Quality of recovered salts, analysing total nitrogen (N), total suspended solids (TSS), chemical oxygen demand (COD), and sulphur content.

During the pilot operation, the NH_3 concentrations in the air phase will be measured once to ensure and validate mass balance closure.

3.4.3. Results

Initial trials and bibliographic data confirm that the Ammonia Mining Unit (AMU) is effective in recovering ammoniacal nitrogen from manure-derived liquids. Under real operating conditions in Aalter (Belgium), the system achieved a 67 % NH_4-N removal rate.

In the NITROMAN-project, the recovered ammonium sulphate ($(NH_4)_2SO_4$) was analysed and found to meet fertiliser-grade standards in terms of nitrogen content and purity.

3.4.4. Conclusions and next steps

The air-ammonia stripping process using the AMU offers a practical and scalable solution for nitrogen recovery from manure. The next steps include conducting tests at the pilot installation in Aalter and optimising process parameters (e.g., temperature, pH) to improve efficiency.

3.5. S/T14: Zero chemical ammonia recovery

3.5.1. Introduction

A zero-chemical ammonia recovery process will be applied to the liquid fraction of decanted manure-derived digestate or pig manure. Using an electrochemical membrane system with a capacity of 1 m³/h, ammonia (NH_3) will be recovered in the form of ammonium hydroxide and transformed into ammonium bicarbonate (NH_4HCO_3) without the use of external acids. The system operates in a closed loop, with internal acid recycling, resulting in negligible emissions. NH_4^+-N removal and the quality of the recovered salt will be monitored, focusing on nitrogen content, TSS, COD, and sulphur. The final product will be validated by ARESA as a fertilizer in S/T19. The zero chemical ammonia recovery technology is currently at pilot scale development (TRL ~6).

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To produce ammonium bicarbonate, two process routes are being explored:

1. Electrochemical recovery followed by CO_2 reaction
2. Evaporation-condensation followed by CO_2 reaction

Both approaches aim to convert recovered ammonia into NH_4HCO_3 efficiently and without external chemical input; CO_2 from the ammonia stripping process can be used. The optimal route will be selected based on product quality, energy efficiency, and risk of contamination (e.g., sulphate presence).

3.5.2. Methodology

The zero-chemical ammonia recovery will be implemented using an electrochemical membrane system designed to treat 1 m³ per hour of the liquid fraction from decanted manure-derived digestate or pig manure. The process involves the following steps:

1. Electrochemical separation

   The liquid feedstock is introduced into the electrochemical membrane unit. Ammonia (NH_3) is separated and converted into ammonium ions (NH_4^+), which are bound with internally recycled carbonates to form ammonium bicarbonate (NH_4HCO_3) in solution.

2. Closed-loop operation

   The system operates in a closed loop, with no external chemicals required. Acid used in the capture process is regenerated and recycled within the unit, eliminating chemical input and minimizing emissions.

3. Product recovery

   The NH_4HCO_3 solution is collected as the final product and serves as a potential nitrogen-rich fertilizer.

4. Alternative routes for NH_4HCO_3 formation

   Two production routes for ammonium bicarbonate are being tested:

   - Route 1: Electrochemical recovery followed by CO_2 reaction, where ammonia is first recovered electrochemically and then reacted with CO_2 to form NH_4HCO_3.
   - Route 2: Evaporation-condensation followed by CO_2 reaction, where ammonia is concentrated via thermal separation before CO_2 conversion.

Both routes aim to produce a high-quality NH_4HCO_3 solution suitable for fertilizer use. The presence of residual sulphate and other impurities will be closely monitored.

5. Monitoring and quality analysis

   Throughout the process, the following parameters will be monitored:

   - NH_4^+-N removal efficiency (influent vs. effluent)
   - Mass balance of nitrogen
   - Quality of the recovered NH_4HCO_3 solution, including:
     - Total nitrogen (N)
     - Total suspended solids (TSS)
     - Chemical oxygen demand (COD)
     - Sulphur (S) content

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6. Validation

   The recovered product will be validated by ARESA in S/T19 for its suitability and effectiveness as a fertilizer.

3.5.3. Results

Preliminary analysis of the zero-chemical ammonia recovery system indicates promising results for sustainable nutrient recovery. The electrochemical membrane unit successfully recovered NH_4-N in the form of ammonium hydroxide (NH_4OH). This product has a higher market value than conventional ammonium sulphate, and the internal recycling of sulfuric acid reduces the need for external acids.

Performance tests showed the following NH_4 recovery rates:

- Synthetic ammonium sulphate reference: 2.12 kg NH_4^+/day
- Aalter pilot: 3.12 kg NH_4^+/day
- Hooglede pilot: 0.432 kg NH_4^+/day

Based on these results, the Aalter-sourced ammonium sulphate will be used in future trials.

3.6. S/T15: Purple Phototropic Bacteria (PPB) culture

3.6.1. Introduction

Purple phototropic bacteria (PPB) have emerged as a promising technology for manure treatment, as they can recover nutrients while minimizing environmental impact. Under anaerobic conditions, PPBs can fix organic matter, nitrogen, and phosphorus from manure, converting them into protein-rich biomass that can be used as microbial protein or as a biofertilizer, depending on the NPK ratio. Moreover, due to their metabolic versatility, PPB can also fix CO_2 and thus, potentially have zero GHG emissions. PPBs stand out as a promising technology for slurry treatment due to their ability to efficiently recover nutrients such as nitrogen and phosphorus, reaching up to 60% and 70% of their dry weight (Zarezadeh et al., 2019). One of the key operational parameters is light, because PPB require near-infrared light for efficient photoheterotrophic growth (Hulsen et al., 2022). Access to light is hindered by the manure's turbidity, which limits PPB growth and overall process performance, thereby reducing biomass productivity.

3.6.2. Methodology

PPB will be operated in an anaerobic reactor, supplied with continuous stirring and infrared illumination. The inoculum will be obtained from an existing laboratory reactor. In this case, operational parameters such as light exposure, hydraulic retention time (HRT), total organic carbon (TOC), and nitrogen concentrations in the feed will be studied to improve microbial performance. Although the Document of Agreement (DoA) initially foresees the operation of a 10-25 L bioreactor, in this study, a 2 L bioreactor will be used.

3.6.3. Results

No results are currently available, as the activities corresponding to PPB will be performed during the year 2027.

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3.6.4. Conclusions and next steps

The PPB activities will begin at the start of 2027. This technology is currently at level 2 of technological maturity. Therefore, the first steps upon startup will consist of batch assays to obtain as much information as possible about PPB's performance in contact with slurry.

3.7. S/T16: Solar Drying (SD)

3.7.1. Introduction

One of the most relevant challenges in the manure management chain lies in the high volume to be treated, due to its high-water content. High volumes increase the cost of each step in the management chain, limiting its use in agriculture and hindering proper manure management. However, manure/digestate storage and direct land application may lead to emissions of Volatile Organic Compounds (VOCs), greenhouse gases, and water eutrophication (Battista & Bolzonella, 2019; Salamat et al., 2020).

In addition, fertilizer consumption in Europe has increased by 6.9% for nitrogen and 21.9% for phosphorus since 2010, continuing a decades-long trend (Liu et al., 2015). Recovering biobased fertilizers from animal manure is a key strategy for reducing reliance on synthetic fertilizers and promoting sustainable agriculture. Anaerobic digestion (AD) is effective for treating livestock manure, producing renewable biogas, and enabling nutrient recycling via digestate. Likewise, the nutrients contained in manure could be recycled for agricultural use, using concentration technologies. Additional valorisation pathways include ethanol production, nutrient-enriched microalgae, and membrane-based nutrient recovery. Therefore, further processing is needed to enhance fertilizer efficiency and mitigate environmental impacts (Morey et al., 2023).

Some regions of the world with high livestock production density are exposed to high levels of solar radiation, such as Spain. Various biomass-drying technologies have been developed to harness solar energy, with greenhouse-based systems among the most efficient. These structures trap shortwave solar radiation and retain longwave thermal energy, creating optimal drying conditions. Moisture is removed via natural convection or forced ventilation. However, the combination with solar caption structure, ventilation, and sweeping system conforms the infrastructure to the solar drying (SL) system (Prenafeta-Boldú et al., 2021).

However, the direct SD process results in the spontaneous release of ammonia (NH3) into the atmosphere due to increased pH and temperature. To reduce uncontrolled gas emissions, raw manure must be acidified, shifting the balance from volatile species (NH_3) to more stable species (NH_4). Additionally, methane (CH_4) emissions are produced by methanogen archaea during the storage and treatment of manure. The acidic treatment (pH = 5.5) reduces methane emissions by 63-99%, inhibiting methanogen growth (Morey et al., 2023).

The SD technology allows pathogen reduction in by-products, ensuring the safety of agricultural products. The sanitisation is achieved through the combination of continuous medium-high temperature (40-60 °C) and UV radiation. Thanks to these benefits, the SD has been used to treat high-pathogen-content residues such as sludge, sewage, manure, or digestate (An-nori et al., 2022).

3.7.2. Methodology

Each SD trial will be conducted using a pilot-scale setup located at the IRTA Torre Marimon research centre (Figure 10). The system comprises one solar dryer, an aeration unit, and a biofilter. IRTA recommends conducting at least two simultaneous trials per material to ensure statistical robustness.

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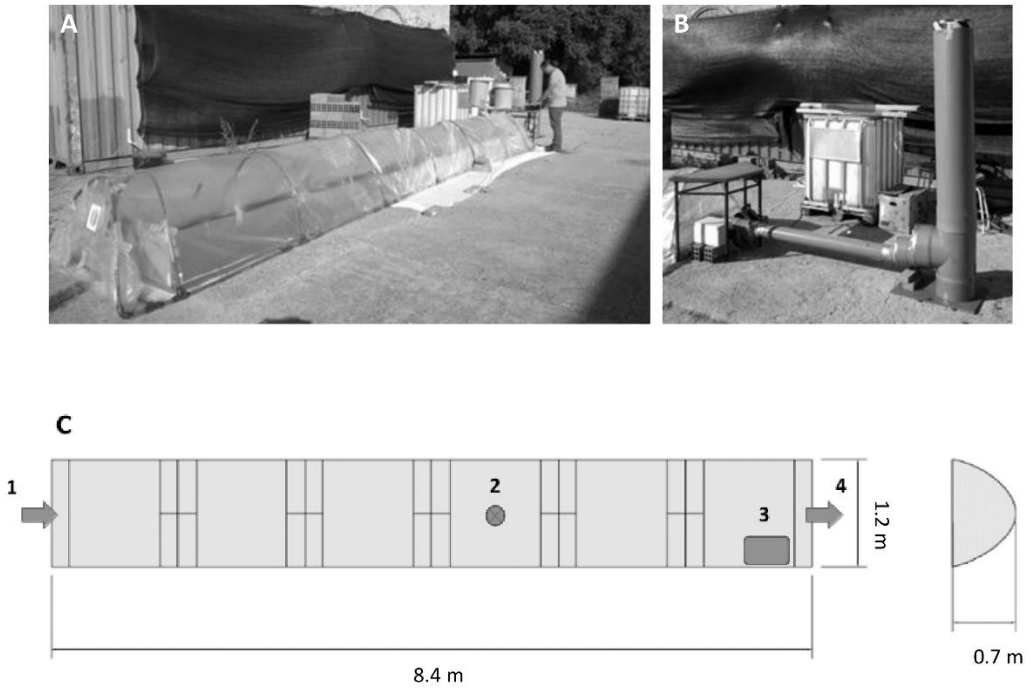

Figure 10: Pilot-scale solar drying greenhouse (A) and the biofilter for treating the exhaust gases (B), and schematic representation (C) of the greenhouse design and dimensions: air inlet (1), indoor temperature and relative humidity sensor (2), mass scale (3)

Each trial will involve weekly sampling, during which IRTA personnel will collect both solid and gaseous samples. Solid samples will be taken from within the pilot system, while gaseous samples will be collected at the inlet, interior, and outlet of both the dryer and the biofilter. Solid samples will be characterized for dry matter content, organic matter concentration, pH, total nitrogen, and ammoniacal nitrogen. Gaseous samples will be analysed for methane and nitrous oxide concentrations using chromatographic methods. Hydrogen sulphide and ammonia concentrations will be measured in situ using a portable electrochemical sensor.

Operational parameters, such as airflow rates, material quantities, and air characteristics (temperature and humidity) inside and outside the dryer, will be recorded. Based on the characterization data and flow measurements, the following will be determined: moisture loss and emissions of carbon, nitrogen, and sulphur throughout the trial. Greenhouse gas emissions from each unit (dryer and biofilter) will be estimated accordingly. Therefore, the assay will last between 6 months and 1 year, depending on the weather.

This assay will be realised over a raw manure sample of 100 L. The IRTA technical team of the IRTA experimental farm will collect the sample. After the collection, the raw manure sample will be characterized using the following parameters:

- Total solids (TS)
- Organic matter (OM)
- pH
- Total Carbon (TC)
- Total Nitrogen (TN)
- Total Phosphorus (TP)
- Total Ammonia Nitrogen (TAN)
- Nitrate (NO_3^-)

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- Nitrite (NO_2^-)
- Sulphates
- Phosphates

The scale, technology selection, and substrate and process characteristics enable this technology to reach a TRL of 7-8.

3.7.3. Results

Actually, no results have been produced yet, as the drying activity will be carried out during the second half of 2026. As a result of this activity, an organic concentrated fertilizer will be produced by solar drying of manure.

3.7.4. Conclusions and next steps

The start of the drying assay will be planned for 2026, likely after the first quarter. However, thanks to the planned operation, it is hoped that the SD can be evaluated inside the complete manure management chain.

3.8. S/T17: Pulse Combustion

3.8.1. Introduction

As in the SD case, an increase in livestock production increases the volume of manure to be treated. This fact is especially relevant in pig production, which has a significant influence on the primary sector. Pig manure is produced in higher quantities by animals in comparison with other manures by place (Loyon, 2018), which makes it necessary to establish high-capacity, high-efficiency treatment systems for the concentration of slurry. Usually, extensive technologies with low energy and reactive demand, such as SD or microalgae treatment, have been used. However, substrate production is usually produced in high-tension regions with a large number of livestock exploitations, such as Catalunya and Aragon in Spain. The low surface availability necessitates the adoption of intensive technologies despite their higher energy consumption, such as Pulse Combustion Spray Drying (PCSD).

PCSD is a drying system that uses the combustion force to volatilize the water contained in the substrate. In PCSD, a fuel-air mixture is ignited in a chamber, generating pressure waves that cyclically open and close the inlet valve. The term "pulse combustion" refers to the intermittent combustion of gaseous fuel in pulse combustion engines, as opposed to the continuous combustion typical of conventional burners. These waves produce sonic pulses that atomize the feed into fine droplets for drying. PCSD performance depends on fuel-air supply rate, fuel type, feed properties, and tailpipe length (Zinn 1992). Compared to continuous combustion systems, PCSD offers (Romo et al., 2024):

- Enhanced heat and mass transfer (up to 40 % higher thermal efficiency).
- Shorter residence times, enabling higher temperatures and lower emissions (NO_x, CO, SO_x).
- Suitability for heat-sensitive and viscous materials, with reduced equipment footprint.

Despite previous experience in food processing, PCD-manure treatment requires parameter adjustments to accommodate the new substrate. Likewise, the process must be assessed in terms of the quality of the produced powder, GHG emissions, and energy consumption to ensure the successful implementation of the technology. The typical substrates for this technology are food industry products, for which this technology has a TLR9. However, its application to livestock manure is currently at a TRL of 4–5.

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3.8.2. Methodology

The PCSD will be realised by EKONEK (Guipuzcoa, Spain) in its semi-industrial installations (Figure 11). The industrial drying process, as PCSD, requires preliminary testing before project design. Although drying itself is relatively straightforward, many design parameters depend on the material's behaviour once dried—such as adhesiveness, hygroscopicity, density, tendency to float or agglomerate, and whether specific specifications are met. These characteristics, known as drying behaviour, are influenced by drying conditions.

Therefore, when working with new materials, multiple drying trials are typically necessary. This progressive evaluation is referred to as product development. Likewise, the PCSD assay will be constituted by the following tasks:

1. Raw manure and/ or Digestate Sample collection with a mass of 100 - 150 kg and a low total solids content.
2. Processing and characterization of the samples
3. Operational parameters adjustment to adapt the process for the selected sample.
4. Dryer start-up and drying process.
5. Drying process evaluation through operational parameters, and mass and energy balance.
6. Product collection and characterization to quality evaluation.

Figure 11: Ekonek's 70 kW PCSD equipment.

3.8.3. Results

No results have been produced yet, as the drying activity will be developed during the second half of 2026. As a result of this activity, an organic concentrated fertilizer will be produced by the Pulse Combustion drying of raw manure. However, previous assays conducted by EKONEK with raw digestate yielded the results shown in Table 2, indicating a weight loss of 54%.

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Table 2: Previous results of PCD over raw digestate of pig manure.

Parameter	Units	Feedstock characteristic	Products obtained
Total Solid (TS)	%	4.5	90.5
Density	g/cm^3	1.03	-
pH		8.64	-
Viscosity	cP	2,126	-
Weigh	kg	71.4	1.6

3.8.4. Conclusions and next steps

The start of the drying assay will be planned for 2026, likely after the first quarter. However, thanks to the planned operation, the PCD is expected to be evaluated within the complete manure management chain.

4. Nutrients removal and recovery at the level of application

4.1. S/T18: Fertilizers based on microalgae and PPB application

4.1.1. Introduction

Microalgae and purple phototrophic bacteria (PPB; often purple non-sulphur bacteria, PNSB) can valorise residual nutrients into biomass rich in N, P, S, and bioactive compounds. These organisms enable the production of circular biofertilizers that can partially replace mineral inputs and enhance nutrient-use efficiency. Reviews and recent field or semifield studies report improved yields, enhanced N and P uptake, greater soil organic carbon, and, in some cases, reduced GHG and air pollutant emissions compared with conventional fertilization, although responses depend strongly on species, formulation, dose, and local soil-climate conditions (Nwoba et al., 2023; Dagnaisser et al., 2022; Zhang et al., 2024).

4.1.2. Methodology

Field trials will be established to compare the agronomic performance of microalgae, PPB, and a conventional NPK fertilizer under local conditions, while accounting for soil type. Treatments will be applied to maize and grassland, using a minimal replicated design to ensure statistical robustness while keeping the experimental layout simple and feasible. Key parameters, including agricultural yield, nutrient uptake, and basic soil indicators, will be assessed to evaluate whether bio-based fertilizers can partially replace mineral inputs.

4.1.3. Results

Several studies confirm the potential of microalgae to act as biofertilizers. For example, microalgae-based fertilizers in orchards improved yield and quality, soil C/N fractions, and even influenced GHG emissions (Zhang et al., 2024). Broader reviews highlight their role in enhancing nutrient-use efficiency and crop resilience (Nwoba et al., 2023; Dagnaisser et al., 2022).

For PPB, species such as *Rhodopseudomonas palustris* have been shown to enhance rice yield and reduce CH_4 emissions in paddy systems (Yamprai et al., 2015), while other field trials have demonstrated improved photosynthesis and yield parameters in rotation crops (Tu et al., 2023). Recent work shows that liquid PPB inoculants can reduce mineral inputs without yield penalties (Lee et al., 2025).

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Despite these promising results, evidence under Atlantic, high-rainfall conditions remains scarce, highlighting the need for local validation in Galicia (Nwoba et al., 2023).

4.1.4. Conclusions and next steps

Microalgae and PPB have strong potential to maintain crop productivity with reduced mineral fertilizer inputs while improving soil and environmental performance. Next steps for ARESA include securing product supplies, asking for expert advice on trials in maize and grassland under Atlantic conditions, and integrating agronomic and environmental KPIs into a decision matrix for farmer recommendations.

4.2. S/T19: Application of recovered salts

4.2.1. Introduction

Nutrient recovery technologies yield concentrated salts suitable as fertilizers: struvite ($MgNH_4PO_4 \cdot 6\ H_2O$), K-struvite ($MgKPO_4 \cdot 6\ H_2O$), and recovered ammonium sulphate (AS). Struvite is a slow-release P source, with reduced leaching and runoff risks. K-struvite adds potassium and has shown promising agronomic results in recent projects. Recovered ammonium sulphate provides both N and S and can directly replace synthetic fertilizers (Margenot et al., 2020; Pérez-Piqueres et al., 2023; Bair et al., 2024; Endeshaw et al., 2019).

4.2.2. Methodology

Experiments will test the agronomic equivalence of recovered nutrient salts (e.g., struvite and ammonium sulphate) against a commercial NPK formulation. The trials will follow a streamlined, replicated design, focusing on yield, nutrient uptake, and soil fertility indicators. This minimal setup is intended to demonstrate whether recovered products can replace conventional mineral fertilizers under practical field conditions.

4.2.3. Results

Field trials and meta-analyses confirm that struvite provides yields and P uptake comparable to Triple Superphosphate/monoammonium phosphate, often with reduced P runoff (Margenot et al., 2020; Bair et al., 2024). K-struvite has shown promising results in cereals and mixed fertilization strategies (Kabdaşli et al., 2022; K-EcoFertilizer Project, 2019–2022).

Recovered AS has been tested in multiple European trials, demonstrating agronomic equivalence to conventional fertilizers while providing the added benefit of sulphur supply (Endeshaw et al., 2019; Meers et al., 2014).

4.2.4. Conclusions and next steps

Recovered nutrient salts represent credible alternatives to conventional fertilizers, combining agronomic effectiveness with clear benefits for circular economy strategies and environmental protection. The next steps will focus on securing batches of recovered salts supplied by project partners, establishing replicated field trials in maize and grassland across three representative soils, and systematically integrating agronomic, environmental, and economic indicators into a comprehensive evaluation framework.

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