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Sustainable Nutrient Recovery from Porcine Slurry: Agronomic Evaluation of Filtered and Ozonated Effluents in IoT-Enabled Aeroponic Lettuce Cultivation

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Abstract

Intensive porcine livestock production generates approximately 15 million cubic meters of slurry annually, exerting significant environmental pressure on groundwater and contributing to greenhouse gas emissions. The AEROFER project aims to mitigate this impact by demonstrating the conversion of nitrogen-rich waste into liquid fertilizers for soilless cultivation. Using an IoT-enabled aeroponic platform controlled by an ESP32 microcontroller, this study evaluated filtration (40-micron) and ozone-based stabilization (N-Amatic technology). Three lettuce varieties (*Lactuca sativa L.*)—*longifolia* (romaine lettuce), *capitata* (butterhead lettuce), and *capitata* (red leaf lettuce)—were grown to compare Filtered Slurry (FS) and Filtered-Ozonated Slurry (FOS) against a mineral control standard solution (SS). Results indicate that ozone treatment significantly reduces pathogenic load and odor while enhancing phosphorus availability, though it induces a slight reduction in potassium content. Agronomic data reveal variety-specific responses, and mass balance analysis shows the solutions are potassium-deficient, meeting only 32–64% of crop needs. In conclusion, while aeroponics is a viable tool for nutrient recovery and requires targeted mineral supplementation to achieve full parity with commercial fertilizers, it satisfies a substantial proportion of plant nutritional requirements. Consequently, it represents a sustainable approach to food production through waste recycling, contributing to a circular economy in the pig industry without apparent sanitary risks.

Keywords: circular economy; ozone treatment; slurry filtration; *Lactuca sativa*; soilless production; sustainable horticulture; water valorization

1. Introduction

The contemporary global agricultural landscape is defined by a paradoxical challenge: the urgent necessity to expand food production capabilities to sustain a projected population of nearly 10 billion by 2050, while simultaneously operating within the increasingly rigid constraints of planetary boundaries [1,2]. Traditional agricultural paradigms, heavily reliant on fertile soil and excessive freshwater consumption, are proving inadequate in the face of escalating climate volatility, soil degradation, and resource scarcity. One of the most critical resources under pressure is water, with agricultural irrigation currently accounting for over 70% of global freshwater withdrawals [3].

In regions such as the Mediterranean basin, which is identified as a climate change hotspot, the scarcity of water is coupled with the degradation of groundwater quality due to intensive livestock practices. Catalonia, as a major European hub for porcine production, exemplifies the environmental conflicts inherent in modern livestock intensification. The regional porcine population, exceeding 5 million places for fattening and over 600,000 sows, generates a massive volume of waste that is traditionally managed through land application as fertilizer. However, the spatial concentration of these farms has led to an excess of nitrogen beyond the land's assimilation capacity, resulting in approximately 40% of Catalonia's groundwater being contaminated with nitrates [4]. Furthermore, porcine slurry management is responsible for nearly 30% of all greenhouse gas (GHG) emissions attributed to the livestock sector in Spain [5]. Transitioning this "waste" into a "resource" is therefore not merely an economic opportunity but an environmental imperative for the sustainability of the territory.

Simultaneously, the global horticulture sector is grappling with a fertilizer crisis. The production of synthetic nitrogen fertilizers is an energy-intensive process highly dependent on natural gas, contributing significantly to global carbon emissions and leaving farmers vulnerable to geopolitical instability and price fluctuations. The European Union currently exceeds planetary boundaries for nitrogen and phosphorus flows by factors of 3.3 and 2, respectively, highlighting the urgent need for recovered nutrient sources [6–8].

In this context, the AEROFER project (AEROponics for the study of FERtilizer viability) proposes a radical departure from conventional land application of slurry by integrating advanced oxidation processes with aeroponic cultivation [9]. Aeroponics represents the pinnacle of soilless cultivation technology, wherein plants are grown with their roots suspended in a light-opaque chamber and periodically misted with a nutrient-rich aerosol [10]. This system offers several physiological and operational advantages over traditional soil-based and hydroponic systems [11]. Primarily, the maximum exposure of the root system to oxygen accelerates metabolic rates and nutrient uptake, leading to faster growth cycles and higher yields per unit of space. Moreover, aeroponics can reduce water use by up to 95% and fertilizer consumption by over 50% compared to soil cultivation, as the excess solution is recirculated and the misting protocol can be precisely tuned to the plant's transpiration needs [12].

However, the application of organic waste streams like porcine slurry in aeroponic systems is technically demanding. The high concentration of suspended solids, the risk of pathogen transmission, and the chemical instability of raw slurry can lead to the clogging of atomization nozzles and the development of anaerobic biofilms on root surfaces. The innovation of the AEROFER approach relies in the use of microfiltration to reduce the presence of particles and pathogens, and in the use of ozone (O_3) as a stabilizing agent. Ozone is a powerful oxidant capable of reducing pathogenic loads, oxidizing odor-causing compounds [13,14], and potentially altering the speciation of nutrients to enhance their bioavailability in recirculating systems. This study aims to evaluate the technical and agronomic feasibility of using filtered and ozonated porcine slurry as a primary nutrient source for lettuce (*Lactuca sativa L.*) grown in a vertical aeroponic setup. By integrating IoT-based monitoring and analyzing the differential responses of three commercial varieties, the research provides a comprehensive assessment of how recovered nutrients can be successfully deployed in high-tech, decentralized food production systems. This work aligns with the European "Farm to Fork" strategy and the Circular Economy Action Plan, offering a tangible solution for the sustainable management of agricultural externalities [15,16]. Furthermore, previous studies have already demonstrated the nutrient potential of organic liquid solutions for aeroponic cultivation systems [17].

2. Materials and Methods

The experimental design consisted in the use of three fertilizing solutions to produce three different varieties of lettuce. Two of them were the two types of porcine slurry and the third were a mineral solution as a blank. Three aeroponic towers were deployed, one for each fertilizing solution and eight units of each variety of lettuce were inserted in each aeroponic tower. Different environmental parameters were monitored as well as plant growing parameters. At the end of the experiment, plant production and characterization were conducted to assess differences between treatments. Figure 1 summarizes the experimental design and detailed description of each step is detailed in next sections.

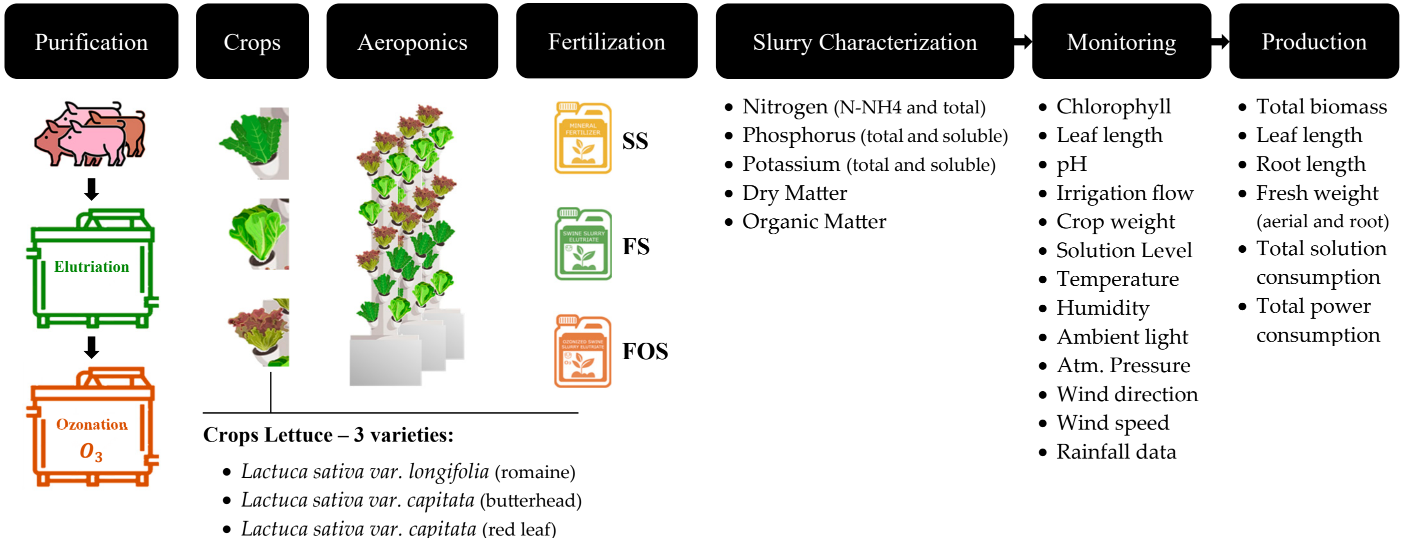


Figure 1. Integrated technical workflow of lettuce production by using treated porcine slurry.

2.1. *Advanced Oxidation and Mechanical Pre-treatment of Porcine Slurry*

The conversion of raw porcine slurry into a standardized fertilizer suitable for aeroponics requires a rigorous multi-stage treatment process designed to align the solution's physical and chemical properties with the requirements of high-pressure misting systems. The variability inherent in slurry composition—driven by animal life cycles, feeding regimes, and seasonal fluctuations—presents a significant hurdle for precision agriculture [18]. To address this, the AEROFER project utilizes the technology developed by N-Amatic Systems S.L. (Patent ES2845275), which focuses on mechanical refining and ozone purification [19].

2.1.1. Mechanical Separation and Particle Refinement

Raw slurry typically contains a high percentage of fibrous material and heavy organic matter that is incompatible with the fine orifices of aeroponic atomizers, which often measure less than 1 mm in diameter. The first stage of treatment involves mechanical separation using a 1,000-micron sieve to isolate the bulk solid fraction. This solid fraction is redirected toward composting, where it can be used to improve soil structure due to its high carbon-to-nitrogen ratio. The resulting liquid fraction, although clarified, still contains substantial suspended solids and colloidal matter. A second stage of pre-treatment follows, utilizing a filter-press with a 240-micron mesh to further reduce the particulate load. For the specific application in aeroponics, a final refinement stage is critical, where the liquid is passed through a 50-micron fine filter. This ensures that the slurry-derived solution can be circulated through the pump and delivered through the nozzles without immediate risk of mechanical failure as well as main pathogenic load is reduced.

2.1.2. Ozone Purification Technology

The defining innovation of the AEROFER methodology is the application of ozone-based stabilization. Ozone (O_3) acts as a potent biocide and oxidant, targeting the unique biological and chemical challenges of livestock waste. In the AEROFER demonstration, a portion of the filtered liquid was subjected to intensive ozonation to create the Filtered-Ozonated Slurry (FOS) treatment, while another portion remained as the Filtered Slurry (FS) control. From a microbiological perspective, the ozonation process is highly effective at neutralizing pathogens such as *Escherichia coli* and *Salmonella*, which are significant concerns for food safety in production for raw consumption. Furthermore, ozone treatment targets the viral load often present in porcine waste, including Porcine Circovirus Type 2 (PCV2) and Type 3 (PCV3), thereby reducing the biosecurity risks associated with waste recycling.

Chemical Oxygen Demand (COD) is used as a measure of the organic content in the solution. Analytical results show that the ozonated treatment (FOS) actually exhibited a similar COD level (48845 mg O_2/L) compared to the filtered treatment (40485 mg O_2/L). This initially counterintuitive result suggests that ozone treatment facilitates the breakdown of complex, insoluble organic matter into smaller, soluble organic fractions, effectively increasing the "chemical" demand even as it potentially stabilizes the solution for biological uptake.

2.1.3. Physicochemical Characterization

A comprehensive analysis of the two slurry treatments (FS and FOS) reveals the impact of the oxidation process on nutrient availability and solution density (Table 1). The physicochemical characterization of the slurry samples was conducted following standardized methodologies according to [20]. The ozonated treatment (FOS) resulted in a higher dry matter (*DM*) percentage (3.74%) compared to the FS treatment (3.33%), indicating that the process concentrates the solution through the removal of moisture or the addition of mineralized components.

Table 1. Physicochemical characterization of treatments.

Parameter	Filtered Slurry (FS)	Filtered-Ozonated Slurry (FOS)	Unit
Density	1008	1006	kg/m^3
Dry Matter (*DM*)	3.33	3.74	%
Organic Matter (*OM*)	63.4	64.8	% *DM*
Total Nitrogen (*TN*)	10.23	9.70	% *DM*
Organic Nitrogen	3.21	3.23	% *DM*
Ammoniacal Nitrogen	7.02	6.48	% *DM*
Phosphorus (*P*)	2.13	2.10	% *DM*
Potassium (*K*)	9.02	8.21	% *DM*
Calcium (*Ca*)	3.06	3.06	% *DM*
Magnesium (*Mg*)	1.24	1.22	% *DM*
Iron (*Fe*)	0.36	0.39	% *DM*
C/N Ratio	9.88	10.03	-
Nitrites	5.77	6.74	mg/kg
COD	40485	48845	mg O_2/L

Interestingly, the nitrogen forms show slight shifts; total nitrogen (*TN*) is marginally higher in the FS treatment, while organic nitrogen levels are almost identical. The ammoniacal nitrogen, which is readily available for plant uptake but susceptible to volatilization, represents approximately 67–68% of the total nitrogen in both treatments. The nitrates (not showed in Table 1) are lower than 50mg/L, which is a comparable value to the limit allowed to drinking water (Directive 2020/2184). Phosphorus levels remained consistent across both treatments (approx. 2.1% *DM*), but potassium (*K*) levels were lower in the FOS treatment (8.21% vs. 9.02% in FS), suggesting that the oxidation process may induce the precipitation of certain potassium salts or alter their solubility in the presence of ozone. Trace element analysis confirms the presence of Copper (*Cu*) and Zinc (*Zn*) at levels typical for porcine diets (around 390 mg/kg for *Cu* and 1,100 mg/kg for *Zn* in the ozonated fraction). While essential as micronutrients, their concentrations must be monitored to prevent phytotoxicity in recirculating systems. Safety-wise, heavy metals like Cadmium, Lead, and Mercury were found at extremely low levels or below detection limits, reinforcing the technical viability of the reclaimed solution.

2.2. Agronomic Evaluation and Plant Material Characteristics

The selection of appropriate crop species and varieties is vital for validating the efficiency of recovered fertilizers. Lettuce (*Lactuca sativa L.*) was chosen as the model crop for the AEROFER demonstration due to its economic importance, high sensitivity to nutrient imbalances, and suitability for vertical, high-density cultivation [21].

2.2.1. Varietal Adaptability and Characteristics

Three commercial varieties were selected to represent different growth habits and consumer preferences:

- *Lactuca sativa var. longifolia* (romaine lettuce): Characterized by upright, robust leaves with a marked central rib. This variety is generally considered high-yielding and requires a steady supply of nitrogen to maintain its crisp texture.
- *Lactuca sativa var. capitata* (butterhead lettuce): A butterhead variety with tender, smooth leaves. It is highly valued for its delicate flavor but is susceptible to tipburn and osmotic stress.
- *Lactuca sativa var. capitata* (red leaf lettuce): A curly-leaf variety known for its rapid growth and high environmental resilience. It serves as an excellent indicator for potential growth inhibition under sub-optimal nutritional conditions.

The experimental design followed a randomized block approach, with each tower level hosting one individual of each variety to ensure that spatial variations in light and mist distribution were accounted for in the statistical analysis.

2.2.2. Nutrient Solution Preparation and Conditioning

The fundamental comparison in this study was between a conventional mineral solution (Control) and the two slurry treatments (FS and FOS). The control solution was formulated using commercial fertilizers from the Terra Aquatica Tripart line (5-0-1, 3-1-6, and 0-5-4 formulations) to target an ideal NPK ratio of approximately 5:1:9. For the slurry treatments, the concentrated effluents were diluted with local municipal water to reach a target electrical conductivity (EC) and nutrient density compatible with lettuce cultivation. Based on the analytical characterization, a dilution ratio of 1:20 was employed. This dilution is essential not only to prevent osmotic stress on the plants but also to manage the high concentration of ammoniacal nitrogen, which can lead to toxicity in recirculating systems if not stabilized [22–26].

2.2.3. Nitric Acid Acidification and Nitrogen Enrichment

Porcine slurry naturally exhibits an alkaline pH (often > 8.0), which facilitates the conversion of ammonium (NH_4^+) to volatile ammonia gas (NH_3), resulting in nitrogen losses and the emission of unpleasant odors. To stabilize the solution and optimize the nutrient uptake environment, an acidification protocol was implemented to bring the pH down to a target value of 6.0. After evaluating various mineral acids, nitric acid (HNO_3) at 70% concentration was chosen. Unlike sulfuric or phosphoric acid, nitric acid provides a direct "top-up" of nitrogen in the form of nitrates (NO_3^-), which are the preferred nitrogen source for lettuce to achieve high growth rates and low oxalate content. The quantification of nitrogen added through acidification was calculated for mass balance: in the FS solution, 0.5 mL of HNO_3 (70% dilution) per liter of 1/20 diluted slurry contributed an additional 93.27 mg of N per liter; in the FOS solution, 4.0 mL of HNO_3 (70% dilution) per liter of 1/20 diluted slurry contributed 74.61 mg of N per liter. This dual-action step corrects the pH while addressing the relative nitrogen deficiency of porcine slurry.

2.2.4. Precision Irrigation Scheduling

To maximize water use efficiency and prevent root zone environmental stress, a tripartite irrigation schedule was established using a wifi-enabled digital timer:

- Peak Photosynthetic Period (08:00–18:00): 8 minutes of misting every 20 minutes to maintain high leaf turgor and support maximum transpiration.
- Twilight/Cool-down Period (18:00–22:00): 5 minutes every 30 minutes
- Nocturnal Period (22:00–08:00): 5 minutes every 45 minutes to prevent root dehydration while avoiding excessive cooling of the reservoir.

This precision timing, enabled by IoT integration, allows the system to respond to the plant's biological clock, ensuring that nutrient availability is always synchronized with the metabolic demand

2.2.5. Production and Composition Assessment

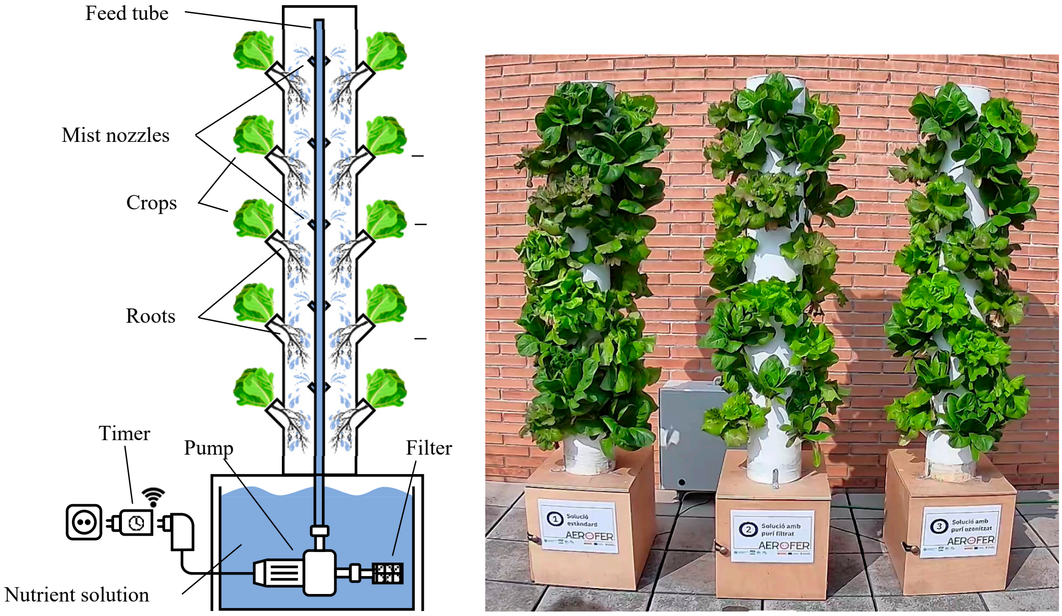
To assess the effects of the treatments on plant material, monitoring parameters during the experiment and at the end were performed:

- Periodical measurements: Along the experiment the content in chlorophyll of the plants was monitored as Chlorophyll Content Index (CCI), measured with an OptiSciences CCM200plus. Between 2 and 3 three plants of each variety in each aeroponic tower were chosen, and the chlorophyll content of 2-3 leaves of each plant was measured in a weekly basis. For the same plants, the length of the longest leaf was measured.

- Production assessment: At the end of the experiment, weight of each plant was performed for total, root and aerial part to assess production. Also, final values of leaves and root length of each plant were measured. The assessment of the consumption of nutrient solution for each aeroponic was also performed.
- Plant characterization: dry matter (80ºC until constant weight), organic nitrogen by Kjeldahl digestion (Selecta RAT-2) and quantification by potentiometry (Jenway Ion Meter 3345) with ammonia selective electrode (Jenway 3345), protein content by approach (organic nitrogen x 5), total phosphorus and potassium by acid solution of the ashes (loss on ignition in muffle furnace at 470ºC) with HNO3 3N and quantification by colorimetry for total phosphorus (Spectrometer Shimadzu UV-VIS 160) and flame photometry for total potassium (Flame photometer Corning 410).

2.3. IoT-Integrated Aeroponic Platform and Monitoring Framework

The AEROFER platform was designed to serve as a high-precision demonstration unit that marries structural simplicity with advanced sensorization. In aeroponics, the lack of a substrate buffer means that any failure in the irrigation system or shift in solution chemistry can result in plant wilting within hours. Therefore, a robust monitoring and control framework is essential for the successful deployment of unstable organic nutrients like porcine slurry.



(a) (b)

Figure 2. Structural design and operating principle of the AEROFER aeroponic platform: (a) Schematic representation of the internal misting mechanism, nutrient recirculation system, and automated timing control; (b) Experimental setup showing the three independent vertical towers, one for each treatment (SS, FS, and FOS) during the final stages of the lettuce cultivation cycle.

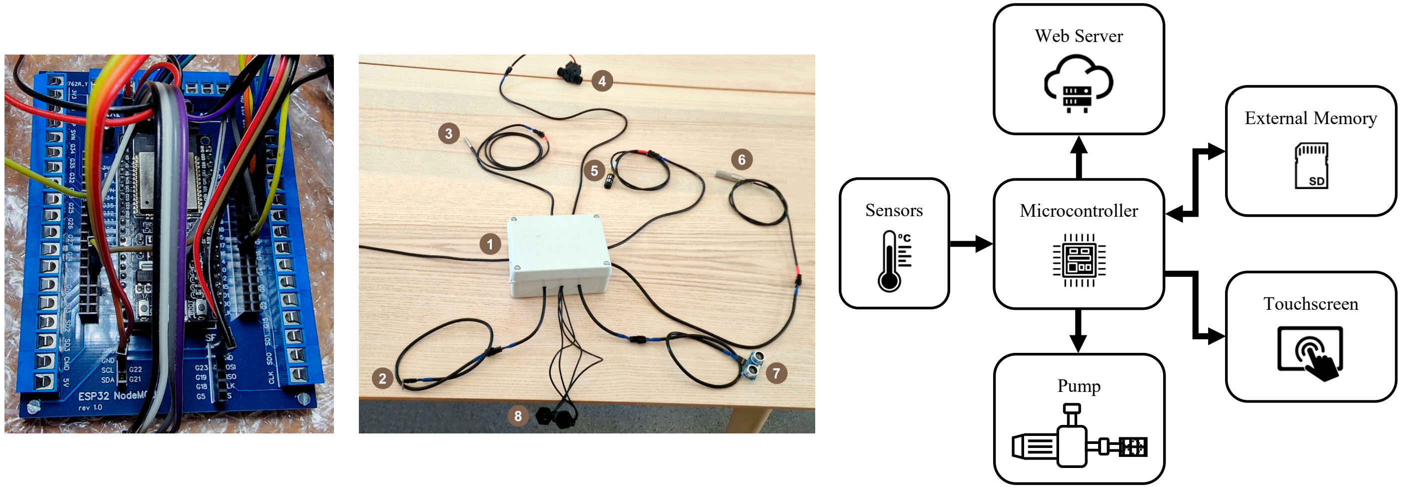
2.3.1. Structural Design and Modular Components

The experimental setup consisted of three independent vertical towers, each capable of supporting 24 plants [27]. These towers were constructed from food-grade PVC and modular plastic components to ensure durability and resistance to the corrosive nature of acidified slurry. The internal architecture of the towers, designed to ensure uniform misting of the suspended root systems, and the overall physical configuration of the experimental platform are illustrated in Figure 2. The spacing between towers (70 cm) was adjusted to minimize shading effects and allow for uniform ventilation, which is critical for preventing high humidity levels that favor fungal pathogens in the canopy. At the base of each tower, a 25-liter reservoir stored the nutrient solution. A high-pressure submersible pump delivered the solution through a central vertical pipe equipped with 18 high-efficiency atomizers per tower. This distribution ensures that every level of the tower receives an identical mist volume, promoting homogeneous plant growth. To maintain this growth, the system requires strict control of parameters such as pH, electrical conductivity, and misting frequency [28]. To mitigate the risk of nozzle blockage from biological biofilms or residual slurry particles, a 50-micron secondary filtration mesh was integrated into the return line of the slurry-fed towers.

2.3.2. IoT Sensor Array and Cloud Infrastructure

The AEROFER platform is integrated with a monitoring framework centered on a dual-microcontroller architecture using the ESP32, selected for its low power consumption, integrated Wi-Fi capabilities, and support for multiple peripheral interfaces. This system allows for high-precision acquisition and real-time visualization of the aeroponic system’s 'metabolism' from any location via a cloud interface. The sensor array tracks atmospheric conditions (ambient temperature (T) and relative humidity (RH) to calculate vapor pressure deficit (VPD)), root chamber microclimate (internal T and RH for thermal stability monitoring), and nutrient solution dynamics. Specific components include SHT20 and SHT40 digital sensors (± 0.3 ℃ and $\pm 3\%\ RH$ precision), a BH1750 sensor for solar radiation tracking, and a DS18B20 1-Wire probe for nutrient solution temperature. Physicochemical and volumetric dynamics are monitored through a PH-4502C module, an YF-S201 Hall-effect flow meter for irrigation auditing, and a redundant level-sensing system employing both capacitive (XKC-Y25-V) and ultrasonic (HC-SR04) technologies to prevent pump cavitation. Operational metrics also include total crop weight to monitor growth in real-time without destructive sampling [29].

Data synchronization is managed via the ESP32 using I^{2}C, SPI, and One-Wire protocols, with metrics transmitted to the ThingSpeak cloud server for longitudinal analysis and the generation of automated alerts. For instance, the system issues notifications if the pH drifts outside the 5.5–6.5 range or if irrigation failure is detected via the flow sensor. This level of automation is crucial for the future scalability of aeroponics in commercial and urban environments where labor costs are a constraint [30]. The technical implementation of the monitoring and control hardware, including the custom ESP32-based PCB and the integrated sensor array, is illustrated in Figure 3.



(a) (b) (c)

Figure 3. Implementation of the IoT monitoring and control hardware: (a) Custom ESP32-based printed circuit board (PCB) for multi-channel data acquisition; (b) Close-up of the integrated sensor array indicating: (1) the ESP32-based microcontroller system with wireless communication capabilities (Bluetooth and Wi-Fi), (2) ambient light level sensor, (3) nutrient solution temperature probe, (4) irrigation flow meter, (5) internal tube temperature and relative humidity sensor, (6) ambient temperature and relative humidity sensor, (7) nutrient solution level sensor, and (8) maximum and minimum level thresholds; (c) Logical architecture and data flow of the AEROFER IoT platform.

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2.3.3. Machine Learning and Predictive Analytics

A secondary goal of the AEROFER project's sensorization is to build a dataset for future machine learning applications. By correlating real-time sensor data (such as pH fluctuations and solution temperature) with the final crop yield and quality, predictive models can be developed to automate nutrient dosing and adjust misting schedules based on historical performance patterns [31,32]. This "smart" control system will be particularly valuable for managing porcine slurry, as the mineralization rate of organic nitrogen is highly sensitive to temperature and solution chemistry.

3. Results

The data generated provide a detailed view of the technical viability and the limitations of using treated pig slurry. By analyzing the chemical mass balance alongside crop yields, the study identifies critical bottlenecks that must be addressed for commercial implementation [33].

3.1. Solution Chemistry and Electrical Conductivity

Monitoring showed that the ozonated slurry (FOS) exhibited higher electrical conductivity (2.58 dS/m) than the filtered slurry (2.47 dS/m) at a 1/20 dilution (Table 2). This increase in *EC* is likely due to the oxidation of organic complexes, which releases mineral ions into the solution. Pre-acidification pH remained high in both treatments (approx. 7.9), confirming the absolute necessity of the HNO_3 buffering process.

Table 2. Characteristics of nutrient solutions at 1/20 dilution.

Parameter	Filtered Slurry (FS)	Filtered-Ozonated Slurry (FOS)	Unit
Density	1003	1002.5	mg/L
pH	7.86	7.90	-
Electrical Conductivity (*EC*)	2.47	2.58	dS/m
Total Nitrogen (*TN*)	53	46	mg/L
Soluble Ammoniacal Nitrogen (*SAN*)	130	170	mg/L
Available Phosphorus (*AP*)	30.9	55	mg/L
Available Potassium (*AK*)	180	160	mg/L

Chemical analysis demonstrates that FOS has significantly more assimilable phosphorus (*P*) than FS (55 mg/L vs 30.9 mg/L), reinforcing the hypothesis that ozone treatment facilitates mineralization. However, the lower assimilable potassium in FOS (0.16 g/L vs 180 mg/L) suggests a trade-off that may impact final crop quality.

3.2. NPK Mass Balance and Extraction Ratios

The fundamental goal of fertilization is to match the solution concentration with the crop's extraction needs. For lettuce, the required NPK ratio based on standard extraction rates is approximately 5.1 : 1 : 9.17 [33].

Table 3. Resulting NPK ratios after acidification.

Treatment	Resulting Nitrogen (*N*) Ratio	Resulting Phosphorus (*P*) Ratio	Resulting Potassium (*K*) Ratio
Ideal Target	5.1	1.0	9.17
FS (after acid)	7.24 (42% Excess)	1.0	5.83 (36% Deficient)
FOS (after acid)	5.59 (10% Excess)	1.0	2.92 (68% Deficient)

The mass balance analysis reveals a significant disparity (Table 3). The acidification process with nitric acid leads to a surplus of nitrogen, particularly in the FS treatment. Conversely, both slurry treatments are chronically deficient in potassium. This deficiency is extreme in the FOS solution, which provides only about 32% of the required potassium relative to the phosphorus content. This imbalance is a critical finding: porcine slurry is naturally "unbalanced" for leafy green production, and while ozonation improves safety and phosphorus availability, it exacerbates the potassium deficit. However, it is worth noting that the aim is to recycle a waste and it is proven that even the product does not cover the expected needs of nutrients the plants had grown.

3.3. Physiological Response: Chlorophyll and Biomass

The physiological health of the lettuce plants was monitored through non-destructive and post-harvest assessments to evaluate the impact of organic nutrient sources on metabolic activity. Despite the nutritional imbalances identified in the chemical analysis, all varieties achieved 100% survival across all treatments. The Chlorophyll Content Index (*CCI*), measured with an OptiSciences CCM200plus, served as a proxy for nitrogen assimilation and photosynthetic potential, showing a strong correlation ($R^2 \approx 0.95$) with leaf nitrogen levels.

Table 4. Biomass and stability overview by variety.

Variety	Parameter	Control (SS)	Filtered Slurry (FS)	Filtered-Ozonated Slurry (FOS)
Romaine lettuce	Total Fresh Weight (g)	246.00 Aa *	185.44 Aa	231.88 Aa
	Aerial Fresh Weight (g)	200.63 Aa	153.13 Aa	187.75 Aa
	Chlorophyll (CCI, 11/06)	27.19 Aa	27.26 Aa	28.01 Aa
Butterhead lettuce	Total Fresh Weight (g)	189.19 Aa	126.50 Aa	197.06 Aa
	Aerial Fresh Weight (g)	143.25 Aa	99.63 Aa	153.63 Aa
	Chlorophyll (CCI, 11/06)	16.40 Aa	13.79 Ba	17.47 Ba
Red leaf lettuce	Total Fresh Weight (g)	177.81 Aa	143.75 Aa	129.25 Ba
	Aerial Fresh Weight (g)	147.81 Aa	118.50 Aa	100.81 Ba
	Chlorophyll (CCI, 11/06)	29.18 Aa	15.25 Ba	15.20 Ba

* Uppercase letters compare varieties within a treatment; lowercase letters compare treatments within a variety (Tukey's HSD, $p < 0.05$).

Varietal responses to the ozonated treatment (FOS) were statistically distinct (ANOVA, $p < 0.05$). The romaine lettuce variety exhibited the highest stability across all treatments; its total fresh weight reached 246.00 g (± standard error) in the standard solution (SS) and maintained a statistically comparable 231.88 g in the FOS treatment (Table 4). Conversely, the red leaf lettuce variety showed significant growth inhibition under the ozonated treatment. Its total fresh weight dropped from 177.81 g in the SS to 129.25 g in FOS, a reduction marked as statistically significant (noted as 'Ba' in Table 4).

The chlorophyll data further highlighted this sensitivity. While romaine lettuce maintained high and consistent *CCI* values at harvest (reaching 28.01 in FOS), the red leaf lettuce variety experienced a drastic reduction in chlorophyll levels when grown with slurry-derived solutions. Its final *CCI* fell from 29.18 in the standard solution to just 15.20 in the FOS treatment. This suggests that while ozonated slurry is safe, its high Chemical Oxygen Demand (*COD*) or residual oxidation by-products may induce physiological stress in faster-metabolizing varieties like red leaf lettuce, leading to reduced biomass accumulation and lower chlorophyll density.

3.4. Nutrient Content of Harvested Tissue

Tissue analysis revealed that while nitrogen uptake was sufficient across all treatments, the potassium and phosphorus levels in the slurry-fed plants were significantly lower than those in the control group. In particular, the potassium content in red leaf lettuce leaves under FOS was below the optimal range for commercial quality. This confirms that the low potassium availability in the ozonated solution directly limits the final nutritional profile of the crop.

4. Discussion

The preliminary results of the AEROFER project demonstrates that porcine slurry can be repurposed for high-tech agriculture. The transition from waste to standardized fertilizer is a non-linear process involving complex interactions between mechanical filtration, chemical oxidation, and biological uptake. The scalability and sustainability of the proposed methodology needs an in-depth study.

4.1. The Paradox of Ozone Treatment

Ozone is a dual-edged sword in the context of nutrient recovery. On the one hand, it is highly effective at stabilizing the solution, reducing odors, and neutralizing pathogens, which are absolute requirements for the social acceptance and regulatory approval of waste-derived fertilizers. The increase in assimilable phosphorus in the FOS treatment highlights ozone's ability to "unlock" nutrients from complex organic matrices, potentially reducing the need for mineral phosphorus supplements.

On the other hand, the reduction in assimilable potassium and the increase in *COD* suggest that ozone treatment induces chemical shifts that may not always align with plant physiology. The higher *COD* in FOS indicates that the solution contains more soluble organic fragments. While these fragments can be beneficial for microbial diversity in the root zone, they also compete for dissolved oxygen in the recirculating reservoir. In an aeroponic mist, this competition can lead to localized oxygen stress at the root-air interface, especially for high-metabolism varieties like red leaf lettuce.

4.2. The Critical Need for Potassium Supplementation

The most significant bottleneck identified in this study is the NPK imbalance. Porcine slurry is inherently rich in phosphorus because a significant portion of the phosphorus in pig diets is excreted in forms like phytate, which are later mineralized in the waste stream. Conversely, the potassium levels in the effluent are consistently insufficient to meet the demands of fast-growing leafy greens.

This finding suggests that a "pure" organic slurry solution is not viable for commercial-grade aeroponics without hybrid supplementation. To maintain the circular economy principles of the AEROFER project, future research should explore the integration of other recovered organic streams. For example, the addition of potassium-rich fruit processing waste or the use of wood ash extracts could balance the slurry's NPK ratio without reintroducing synthetic chemicals.

4.3. IoT as the Enabler of Organic Precision Agriculture

The technical success of the AEROFER towers—specifically the lack of nozzle clogging and 100% plant survival—is directly attributable to the IoT monitoring system. In a mineral system, pH and EC drifts are relatively slow and predictable. In a slurry system, the solution is biologically "alive," with ongoing mineralization, bacterial activity, and thermal instability.

The ESP32-based alerts for pH and solution level provided the necessary "fail-safe" that allowed the organic nutrient experiments to proceed. Furthermore, the continuous logging of ambient and root-zone humidity allowed for the identification of periods of high fungal risk, which were mitigated through manual ventilation adjustments. The integration of these sensors into an automated feedback loop—where the pump frequency increases or decreases based on real-time tower weight—represents the next evolution in sustainable aeroponics.

4.4. Territorial and Socio-Economic Impact

The impact of the AEROFER project extends beyond the laboratory. By demonstrating that even a small percentage of porcine slurry can be converted into high-value horticultural products, the project offers a pathway for farm diversification. Calculations suggest that if only 3% of Catalonia's porcine census were linked to aeroponic systems, it could free up approximately 5,000 hectares of agricultural land currently dedicated to excessive slurry application. If scaled to 10%, the territorial relief would exceed 16,000 hectares, significantly reducing the pressure on vulnerable aquifers.

Furthermore, the 'clean' vertical towers of aeroponics are suitable for integration into urban environments and therapeutic settings, such as the Hospital de Bellvitge initiative [34]. This project, known as 'Rega(lem) salut mental,' implements horticultural therapy not only for psychiatry patients but also for those in cardiology, transplants, and persistent COVID-19 units, aiming to enhance emotional well-being, empower patients, and reduce social stigma. The inclusion of custom-built aeroponic systems could specifically address the spatial and water access limitations characteristic of urban hospital environments while fostering cognitive development and physical stimulation. Moreover, these systems can provide educational value for schools, illustrating the science of technology and circularity, while producing local, nutritious food with a near-zero carbon footprint from transport.

5. Conclusions

The AEROFER demonstration project successfully proves that porcine slurry, when subjected to mechanical refinement and ozone stabilization, is a technically viable nutrient source for aeroponic lettuce production. The integration of advanced oxidation processes effectively mitigates the primary environmental and mechanical risks associated with livestock waste recycling.

The study's principal conclusions include:

1. Technical Reliability: Mechanical filtration down to 50-microns combined with ESP32-based IoT monitoring ensures that slurry-derived nutrient solutions can be delivered via high-pressure misting systems without significant mechanical failure or nozzle clogging.
2. Varietal Sensitivity: While romaine lettuce variety exhibits high stability, the red leaf lettuce variety shows growth inhibition under ozonated slurry, highlighting the need for variety-specific nutrient management in organic systems.
3. Nutrient Balance Imperative: Porcine slurry is naturally unbalanced for horticulture, providing a nitrogen surplus but a chronic potassium deficiency (covering only 32–64% of needs). Ozonation further mineralizes phosphorus but appears to reduce potassium bioavailability.
4. Operational Safety: Ozone treatment effectively neutralizes pathogens (*E. coli*, virus PCV2/3) and stabilizes the solution, fulfilling the safety requirements for food crop production.
5. Circular Economy Scale: Scaling this technology to just 5–10% of the regional porcine census could release up to 16,000 hectares of agricultural base from nitrate over-application, significantly protecting groundwater resources.

To advance this technology toward commercial maturity, it is recommended that future implementations adopt a *Hybrid Nutrient Management* approach, where ozonated slurry serves as the base effluent, supplemented with targeted organic potassium sources to achieve a balanced NPK ratio. Additionally, the transition from cloud-based monitoring to fully automated AI-driven control will be essential for managing the dynamic chemistry of recovered organic solutions, ensuring high yields and nutritional quality in the next generation of resilient, circular agri-food systems.

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Abbreviations

The following abbreviations are used in this manuscript:

CCI	Chlorophyll Content Index	IoT	Internet of Things
COD	Chemical Oxygen Demand	NPK	Nitrogen Phosphorus Potassium
DM	Dry Matter	OM	Organic Matter
EC	Electrical Conductivity	PCV2	Porcine Circovirus Type 2
FOS	Filtered-Ozonated Slurry	PCV3	Porcine Circovirus Type 3
FS	Filtered Slurry	SS	Standard Solution
GHG	Greenhouse Gas	TN	Total Nitrogen

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