Gas Networks Ireland

# PC4 Gas Innovation Fund Application Form

## Nutrient (N, P, and K) Recovery from Digestate Using Novel Electrodialysis

## Gas Networks Ireland Innovation Fund

## FINAL REPORT

| SECTION 1: PROJECT DETAILS |
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| **Project Title** | **Nutrient (N, P, and K) recovery from digestate using novel electrodialysis** |
| **Lead Grantee (Organisation)** | **University of Galway** |
| **Lead Grantee (Name)** | **Prof. Xinmin Zhan** |
| **Report Submission Date** | **11/11/2024** |
| **Project summary** | |

Gas Networks Ireland (GNI) aims to achieve a net-zero carbon gas network by 2050, with biomethane as a central pillar of this strategy. Biomethane is a renewable energy source produced via anaerobic digestion (AD) of biowaste and agricultural by-products. However, the digestate—a by-product of AD—requires effective management to support this ambition. While digestate is often used as a fertilizer through direct land spreading, this practice can lead to environmental risks such as nutrient leaching and runoff. To address these challenges, the University of Galway group has pioneered novel electrodialysis (ED) technologies to recover nutrients from manure digestate. ED is an electrically-driven membrane technology that selectively transports nitrogen (N), phosphorus (P), and potassium (K) ions from digestate into a concentrated product.

The primary objective of this project was to advance ED technology for nutrient recovery from digestate, thereby improving the sustainability of AD systems. To achieve this, the team designed and constructed a prototype ED system with a

processing capacity of 100 L/hr—the first of its kind globally for this purpose. Extensive testing across different membranes and cleaning protocols enabled the identification of optimal operational conditions, ensuring the long-term functionality of the ED technology. Furthermore, we developed an innovative anode-ED technology to allow in-situ disinfection and the removal of emerging contaminants, enhancing biosafety. A field trial is underway to validate the practical performance of the technology and assess its environmental sustainability through a life cycle assessment alongside a cost-benefit analysis.

The project's findings have been published in leading scientific journals. To broaden the impact, the team organized the "Digestate Management International Symposium," bringing together international experts to discuss advances in AD, nutrient recovery, and digestate management. Additionally, a PhD summer school was held from June 9-14, 2024, offering comprehensive academic and practical training on AD theory and digestate management. These efforts provided valuable knowledge to early-career researchers, underscoring the project's scientific contributions and building a foundation for further research, practical applications, and technology commercialization in digestate management.

This project has advanced sustainable AD operations, nutrient recycling, and bio-based fertilizer production. These achievements support Ireland's Climate Action Plan and contribute to GNI's net-zero strategy, promoting environmental sustainability and resilient energy systems.

# SECTION 2: FINAL TECHNICAL REPORT

## 1. Introduction

As the world intensifies efforts to combat climate change, achieving carbon neutrality has become a critical goal for many nations. In this context, Gas Networks Ireland (GNI) is working to deliver a net-zero carbon gas network by 2050 and to reduce emissions by gradually replacing natural gas with renewable biomethane. Biomethane is a carbon-neutral renewable gas produced through anaerobic digestion (AD), which breaks down organic material (organic waste) by microorganisms under anaerobic conditions. GNI is aligned and devoted to promoting biomethane production to reduce agricultural emissions and decarbonize the energy system, as published in the National Biomethane Strategy. This strategy sets an ambitious target of producing up to 5.7 TWh of indigenously produced biomethane by 2030, equivalent to 10% of Ireland's current natural gas demand [1].

GNI has committed to constructing more AD plants to support this biomethane strategy, utilizing biowaste and agricultural by-products to produce biomethane [2]. However, digestate, a by-product of AD and a residue after organic degradation, requires effective management. Land spreading of digestate is a common practice, as is using the digestate as fertilizer for crops. It, however, may lead to nutrient runoff, water pollution, ammonia volatilization, and GHG emissions [3]. Moreover, due to the nutrient imbalance of digestate, the adjacent land's capacity to receive digestate limits this practice. Those challenges would become more severe with the building of more AD plants. Nutrient recovery from digestate to produce commercial fertilizer offers a strategic solution. If nutrients are effectively recovered, it is estimated that at least 103 and 16 Kt of N and P could be recovered annually, equal to 28% and 38% demand for N and P fertilizers [4]. This could reduce GHG emissions by 14–65% by decreasing the demand for chemical fertilizers, as replacing 1 ton of chemical fertilizer with digestate saves approximately 4 tons of $CO_2$ emissions [5].

Nutrient recovery from digestate needs more reliable technologies. Existing methods face significant challenges due to the poor quality of digestate, such as severe membrane fouling during pressure filtration and low recovery rates in ammonia stripping and struvite precipitation [6, 7]. Recently, technologies based on the electrodialysis (ED) concept have been developed for nutrient recovery[8,9]. ED is an electro-driven, membrane-based technology that uses an electric field to separate charged ions from a feed solution. Unlike pressure-driven membrane filtration technologies, ED can avoid severe membrane fouling, making nutrient recovery from digestate possible. Although ED has been successfully applied in the industry for desalination, its application in nutrient recovery from wastewater is still relatively new. Our previous studies have demonstrated that ED could effectively recover wastewater from nutrients. However, the research remains primarily at the laboratory scale, and its potential for nutrient recovery from digestate needs further discussion and exploration.

The project aimed to develop novel ED technology for nutrient recovery from digestate to improve AD sustainability. To achieve this, we constructed a proto-type ED system with a capacity of 100 L/hour. The objectives of this project were to assess the technology at a large scale and evaluate its environmental and economic sustainability.

## 2. Project Outcomes

### 2.1 Academic achievement

The project team has thoroughly investigated the challenges of ED application in digestate treatment to pave the way for its practical implementation. The main findings led to the publication of several peer-reviewed papers in distinguished journals. These papers include:

- J Meng, L Shi, S Wang, Z Hu, A Terada, X Zhan. Membrane fouling during nutrient recovery from digestate using electrodialysis: Impacts of the molecular size of dissolved organic matter. Journal of Membrane Science, 10.1016/j.memsci.2023.121974, 2023
- W Cui, J Meng, S Wang, Z Hu, G Liu, X Zhan. 17β-estradiol (E2) removal in anode-electrodialysis (anode-ED) during nutrient recovery from pig manure digestate. Journal of Hazardous Materials, 10.1016/j.jhazmat.2023.132754, 2023
- J Meng, L Shi, Z Hu, Y Hu, P Lens, S Wang, X Zhan. Novel electro-ion substitution strategy in electrodialysis for ammonium recovery from digested sludge centrate in coastal regions. Journal of Membrane Science, 10.1016/j.memsci.2021.120001, 2021
- J Meng, X Shi, S Wang, Z Hu, DY Koseoglu-Imer, PNL Lens, X Zhan. Application of electrodialysis technology in nutrient recovery from wastewater: A review. Journal of Water Process Engineering, 10.1016/j.jwpe.2024.105855, 2024

### 2.2 Development of ED technology

#### 2.2.1 Demonstration of long-term operation

(1) Mechanism of membrane fouling

In manure digestate, the organic matter, consists of humic-like and fulvic-like substances, can foul anion-exchange membrane (AM) by electrostatic interactions [9]. However, the fouling mechanism is still unclear, particularly regarding which size of organic matter causes irreversible fouling. Our research indicates that large molecular pollutants (>10,000 kDa) only cause surface fouling, which is easily cleaned, while small molecular pollutants lead to irreversible internal fouling. Particularly pollutants with molecular sizes smaller than 10 kDa are of significant concern. Those findings provide a significant basis for controlling membrane fouling during ED in digestate treatment.

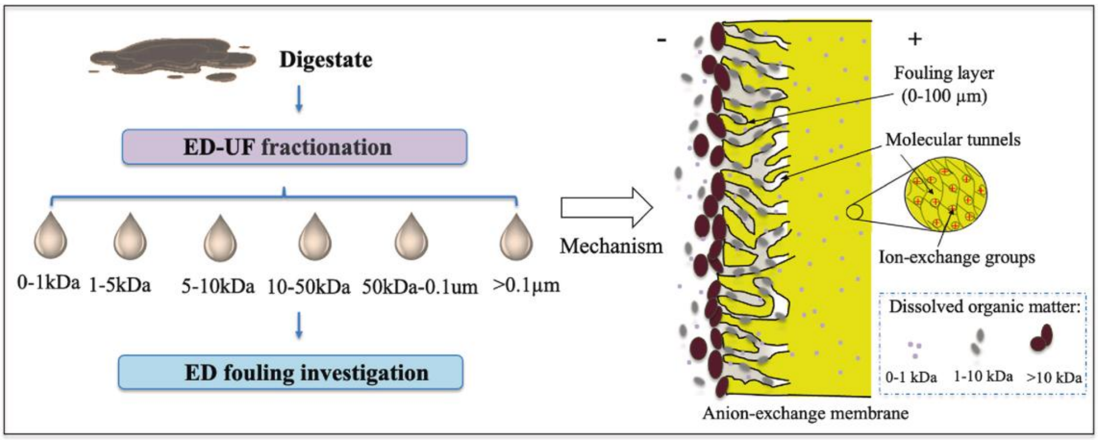


**Fig. 1**. Mechanism of membrane fouling by organic matter fouling with different molecular size.

(2) Fouling mitigation

To mitigate the membrane fouling, we practically investigated different strategy for fouling cleaning, including electrodialysis reversal (EDR) technology and chemical cleaning. EDR, by frequently reversing the polarities of electrodes, could be effective in mitigation of membrane fouling caused by particle aggregation, providing a self-cleaning mechanism. In addition, chemical deposition can be dissolved periodically during the reversal operation of electrodes, thereby remitting the risk of membrane scaling. Combined with periodical chemical cleaning, most of particles and DOM can be removed, but some organic matter, like tyrosine-like and humic-like substances, still fouled AM gradually. This type of fouling only occurred in the area close to the membrane surface, while the interior of membrane remained uncontaminated. Reversible fouling was cleaned by the acid solution, while the irreversible fouling resulted in the permanent loss of IEC. Nonetheless, the growth of irreversible fouling became insignificant after several cycles of EDR. Therefore, EDR was approved as an effective technology for mitigating inorganic fouling and organic fouling.

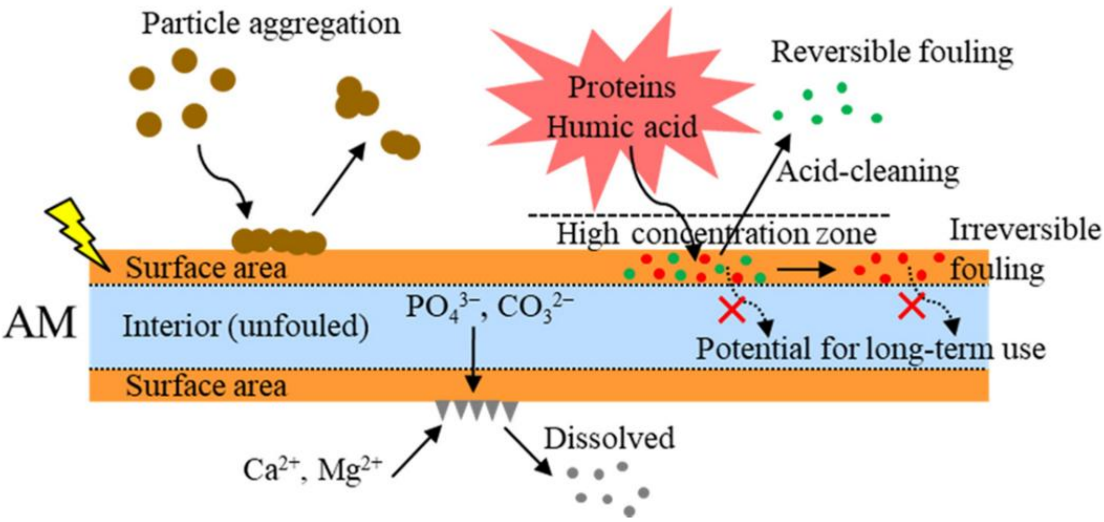


**Fig. 2**. Mechanisms of fouling mitigation in EDR during the nutrient recovery from pig manure digestate.

(3) Long-term operation of EDR for treating pig manure digestate

To demonstrate the feasibility of long-term operation of ED for treating manure digestate, a long-term operation was conducted, combined with chemical cleaning and EDR, as shown in Fig. 3. The ED has been operated with a treatment loading over 5000 L/m$^2$, which was significantly higher than all previously reports, exceeding by an order of magnitude. During the operation, ED had recovered more than 80% of $NH_4^+$ from digestate. The $PO_4^{3-}$ recovery ratio was not stable ranging from 40% to 90%, which resulted from the low and fluctuating concentrations of P in the digestate. After the ED operation, the membranes had no mechanical damage, but the integrity was destroyed as the change in the membrane surface morphology. The fouling did not destroy the membrane perm-selectivity, and the membranes still showed high performance in nutrient recovery. Overall, even with an increased membrane resistance at a treatment load of 5000.0 L/m$^2$, the ED system maintained efficient operation.

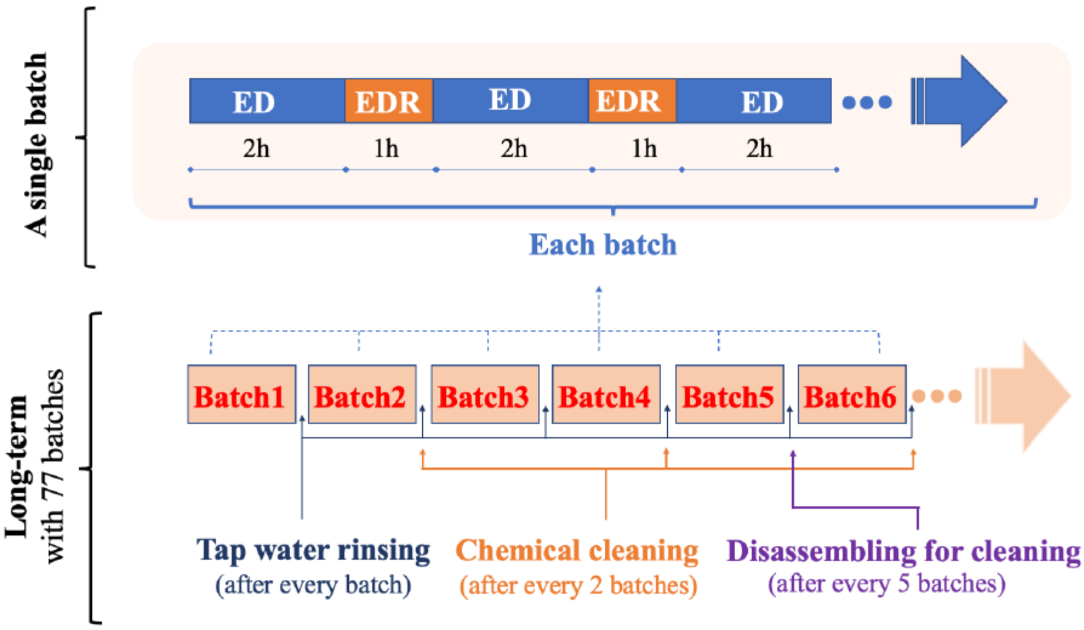


**Fig. 3.** Schematics of long-term EDR operation

### 2.2.2 Innovation of Anode-ED technology

Biosafety is a critical concern in digestate management. To address this, we developed Anode-ED technology for the removal of contaminants, including antibiotics (such as sulfadiazine, SD, and tetracycline, TC), pathogenic microorganism (E. coli and Enterococcus), and the natural estrogen 17β-estradiol, as depicted in Fig.4. Results indicated that $Cl_2$ generated at the anode played a key role in removing these contaminants, with SD and TC eliminated within 30 and 60 minutes, respectively, and E2 oxidation intermediates removed after 40 minutes, demonstrating a significant advantage over conventional ED. Additionally, gas bubbling in Anode-ED reduced membrane fouling. In terms of disinfection by-products, only 134 μg/L of trihalomethanes and 192 μg/L of haloacetic acids were detected in the effluent due to membrane sorption, which was far lower than the levels typically produced during conventional electrochemical oxidation and chlorination of wastewater. Overall, Anode-ED technology exhibits a strong capability to efficiently remove contaminants during nutrient recovery, significantly enhancing the biosafety of digestate treatment.

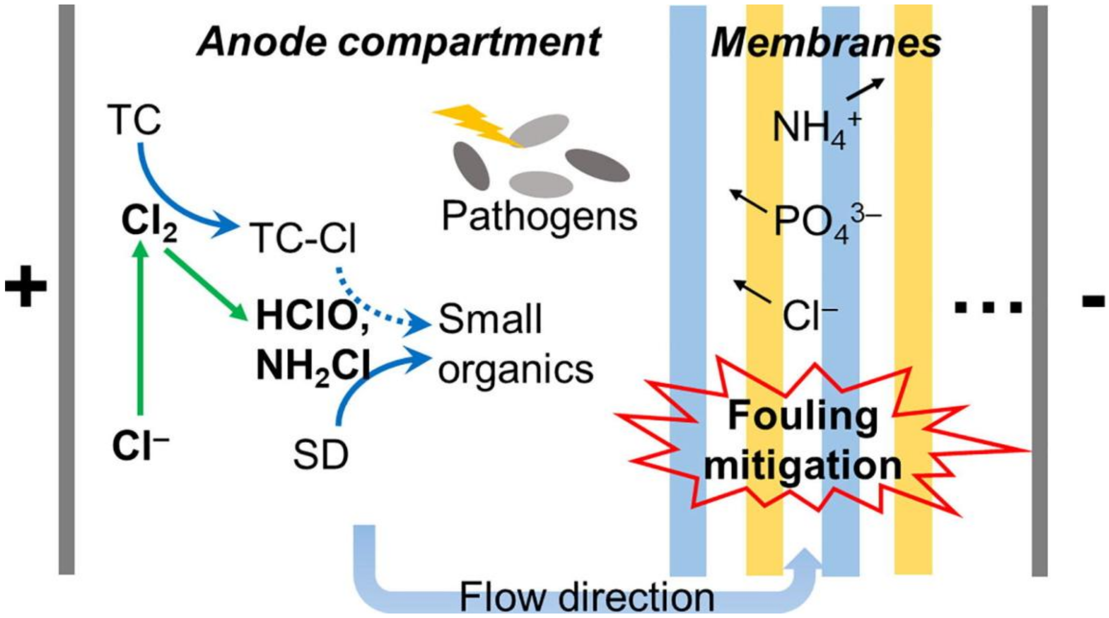


**Fig. 4**. Mechanism of contaminations removal in anode-ED

### 2.2.3 Development of novel electro-ion substitution strategy

Membrane fouling has been the primary challenge limiting the application of ED. To address this, we developed an electro-ion substitution modified electrodialysis (EIS-ED) system for nutrient recovery with minimal membrane fouling and scaling formation. In this system, the wastewater flowed between two cation-exchange membranes (CM), alongside the seawater providing $Na^+$ as the substitution of $NH_4^+$. According to the experimental data and modeling, EIS-ED recovered more than 70% of $NH_4^+$ from the wastewater with an energy consumption of 2.03 kWh/kg $NH_4^+$-N, which was 14% lower than the conventional ED. Membranes, solutions and electrodes were the three major contributors of the linear ohmic resistance in the EIS-ED process. EIS-ED significantly resisted membrane fouling by means of electrostatic repulsion between the CM and negatively charged compounds, including particles and dissolved organic matter, and membrane scaling was also mitigated. After a treatment of 20 L wastewater, no significant decrease of membrane ion-exchange capacity was observed in the EIS-ED, while a decrease of 5.3% was found in the conventional ED.

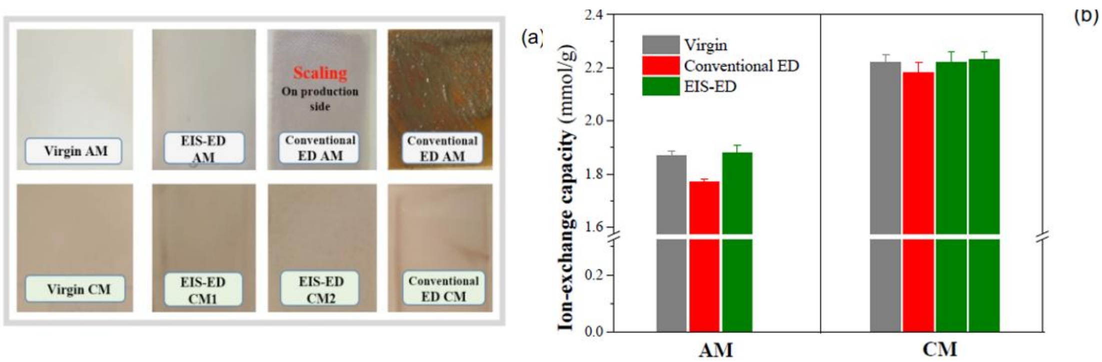


**Fig. 5**. Fouling mitigation in EIS-ED, by comparing to conventional ED.

## 2.3 ED pilot demonstration

Building on extensive laboratory research, we designed and constructed a pilot ED system tailored for nutrient recovery from digestate, with a processing capacity of 100 L per hour. The system's design includes a modular stack configuration, automatic and remote EDR control, precision flow control, and washing control. The design overses common challenges like membrane fouling and operational stability. More importantly, the system integrates programmable controls for real-time monitoring of parameters such as pH, conductivity, and temperature, ensuring consistent performance under varying input conditions.

After construction, the ED system was successfully tested in the laboratory, confirming its ability to efficiently recover nutrients from digestate at the anticipated loading. This system demonstrates a significant advancement in sustainable digestate management, reducing the need for synthetic fertilizers and offering a pathway for more sustainable nutrient recycling within the anaerobic digestion process. This system is now ready for demo on field in order.

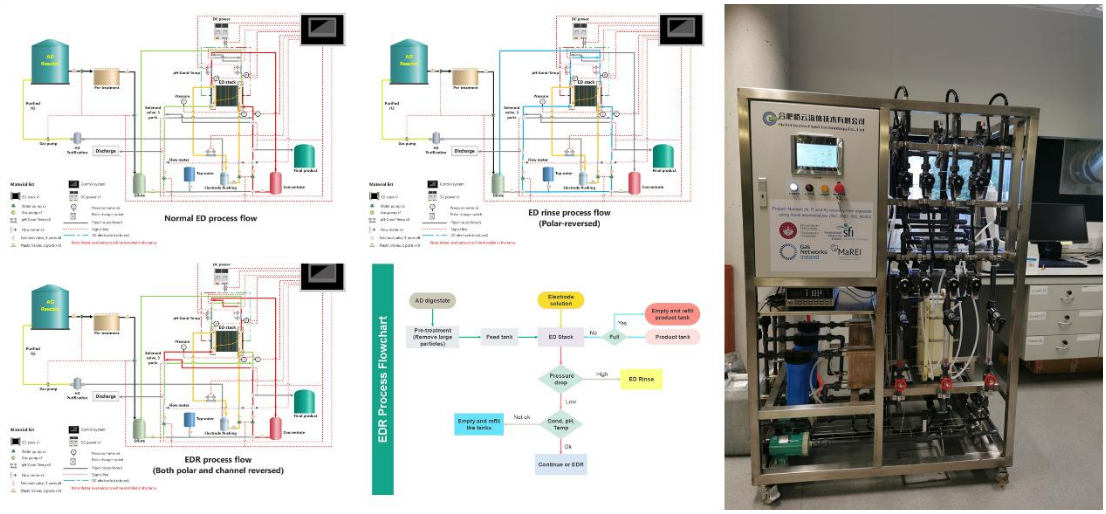


**Fig. 6**. Construction of ED system

## 2.4 Dissemination

(1) Digestate management international symposium

On 22 May 2024, the project team successfully organized the 'Digestate Management International Symposium' at the Menlo Park Hotel in Galway, Ireland. This event brought together international experts from institutions such as the University of Galway, Gas Networks Ireland, Teagasc, Agri-Food and Biosciences Institute (UK), International Water Association, Atlantic Technological University, and KTH Royal Institute of Technology, focusing on the latest advancements in anaerobic digestion and digestate management. The symposium had two main thematic sessions: Sustainability and Nutrient and Product Recovery, where experts discussed effective digestate management strategies to maximize biomethane production. This symposium served as a platform for showcasing project outcomes and laid a solid foundation for ongoing research and practical applications in digestate management.


**Fig. 7** Digestate management international symposium

(2) PhD summer school

From 9 June to 14, 2024, the project team successfully hosted a PhD summer school in Galway, bringing together distinguished researchers from internationally renowned universities and research institutions, including Teagasc, the University of Galway (Ireland), Istanbul Technical University (Turkey), University of Borås (Sweden), Case Western Reserve University (USA), and INRAE (France). This program provided participants with in-depth academic and practical training on AD theory and digestate management through lectures, interactive discussions, AD field visits, and lab tours. The summer school disseminated the project's findings to early-career researchers, enhancing their understanding of AD technology and its applications in sustainable agriculture and waste management. This event was a crucial platform for developing participants' practical skills and academic foundations, fostering future advancements in digestate management and sustainable practices.

**Fig. 8** Field visit to an anaerobic digestion plant during PhD summer school

(3) Conference presentation

The outcomes of this project have led to numerous conference presentations and invited talks, showcasing the advancements and challenges in nutrient recovery from digestate and the application of electrodialysis (ED) technology. Key presentations include:

- Xinmin Zhan: Anaerobic digestion for producing biogas from agricultural wastes and byproducts: economic and environmental considerations, FULLRECO4US Conference 2023, Istanbul, Turkey (**Keynote speaker**)
- Jizhong Meng, Xinmin Zhan: The application of electrodialysis technology in nutrient recovery from digestate. (Invited open seminar presentation, Institute of Microbiology and Biotechnology, University of Latvia, 2023)
- Jizhong Meng, Xinmin Zhan: Nutrient recovery from digestate using electrodialysis: feasibility and challenges. (Invited open seminar presentation, Institute of Innovative Membrane Materials, Istanbul Technical University, 2023)
- Jizhong Meng, Membrane fouling during nutrient recovery from digestate using electrodialysis: long-term operation, IWA AD18, Istanbul, Turkey (**Oral presentation**)
- Jizhong Meng, Nutrient recovery from anaerobic digestate, Workshop: Water and Nutrient Recovery Strategies, Thessaloniki, Greece (**Oral presentation**)
- Jizhong Meng, Xinmin Zhan, Anodic oxidation in electrodialysis for antibiotics and oestrogen removal during nutrient recovery from anaerobic digestate, Early Career Researcher Regional Symposium on Electrochemistry (2022), Belfast, UK. (**Poster**)
- Jizhong Meng, Ruoke Li, Lin Shi, Shun Wang, Xinmin Zhan. Feasibility analysis of electrodialysis technology for nutrient recovery as fertiliser from digestate in Ireland, International Symposium on Climate-Resilient Agri-Environmental Systems (2022), Dublin, Ireland. (**Oral presentation**)
- Jizhong Meng, Ruoke Li, Xinmin Zhan, Feasibility analysis of electrodialysis technology for nutrient recovery from digestate in Ireland, MaREI Symposium 2022. Galway, Ireland. (**Poster**)

## 3. Project Impact

This project has developed ED technology for digestate management, providing an innovative and sustainable solution for sustainable AD and GNI's biomethane strategy. The ED system efficiently recovers nutrients from digestate to produce bio-based fertilizers. This approach reduces environmental impacts associated with land-spreading—such as nutrient runoff, water pollution, ammonia volatilization, and GHG emissions—and enhances the sustainability of AD processes. By achieving closed-loop nutrient recovery, the project will decrease the reliance of the agricultural sector on chemical fertilizers, thereby mitigating risks of resource depletion and reducing greenhouse gas emissions in the farming sector. This aligns with Ireland's Climate Action Plan targets and supports GNI's vision of achieving a net-zero carbon gas network by 2050.

The project's dissemination efforts have laid a strong foundation for adopting and applying ED technology. Through organizing the Digestate Management International Symposium and a PhD summer school, the project has brought together experts and scholars in anaerobic digestion, nutrient recovery, and digestate management from national and abroad. These events provided early-career researchers and industry stakeholders with comprehensive academic training and practical insights, effectively communicating the project's results, and promoting the adoption of ED technology. Additionally, the construction of the pilot ED system provided a practical demonstration of sustainable digestate management options, showcasing the technology's feasibility and encouraging its implementation in real-world settings.

In the long term, this project is expected to contribute to a thriving, sustainable, circular bio-economy, supporting wealth creation and quality job opportunities in rural areas.

## 4. Conclusions

During this project, we successfully built and optimized an ED system with a treatment capacity of 100 L/h (which can be expanded to 500 L/hr), demonstrating the feasibility of ED for digestate management on a large scale. It thoroughly investigated the challenges of ED application in digestate treatment: long-term stability and high energy consumption. For stability, we tested various membrane cleaning protocols and used electrode reversal to reduce particle fouling, along with acid and base cleaning to manage organic fouling. To address energy consumption, we developed an energy-efficient anode-ED technology that can improve current efficiency and enable in-situ disinfection and antibiotic removal at the anode while recovering hydrogen at the cathode. The field trial is underway to validate practical performance and analyze this technology's environmental sustainability through a life cycle assessment, along with a cost-benefit analysis.

The project's outcomes have led to productive outputs. The team organized two events to disseminate outcomes: the Digestate Management International Symposium and a PhD summer school. These efforts highlight the project's scientific contributions to advance sustainable AD operations, nutrient recycling, and bio-based fertilizer production, aligning with environmental sustainability goals, Ireland's Climate Action Plan, and GNI's strategy.

## 5. Recommendations

Further optimization of the ED system's energy consumption is recommended to support large-scale applications. The anode-ED technology developed in this project has already demonstrated significant benefits by utilizing surplus anode energy for disinfection and antibiotic removal. Future considerations could include incorporating solar photovoltaic and other renewable energy sources to reduce operational costs and enhance overall energy efficiency, thereby improving the system's economic feasibility.

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Communications; Department of Agriculture, Food and the Marine. https://www.gov.ie/en/publication/d115e-national-biomethane-strategy/.
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