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# Enhancing industrial symbiosis in the value chain of anaerobic digestion

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**Abstract**

The goal of ALIVE project is to establish a robust, scalable, and efficient system that maximises the potential of anaerobic digestion for bioenergy production and in-situ nutrient recovery. By ensuring the effective employment of thermal hydrolysis and application of specialised anaerobic microbial consortia through bioaugmentation (a process where specific microorganisms are added to a biological system to improve or recover specific functions), followed by a membrane system, the project holds promise for maintaining and enhancing methane production efficiency and nutrient recovery in biogas plants worldwide, that utilise ammonia-rich substrates. This approach supports the generation of renewable energy and contributes to more sustainable waste management practices, aligning with broader environmental and economic goals. The production of biofertilisers and biostimulants from the recovered nutrients can potentially enable the standardisation and commercialisation of the process by scaling up the technology for widespread application.

**Keywords: Bioenergy production, Anaerobic digestion, Ammonia-rich biomasses, Ammonia toxicity, Nutrient recovery**

## 1. Introduction

Agro-livestock waste contains significant amounts of organic matter and valuable nutrients which, despite efforts to date, are not being utilised in the most efficient and environmentally sustainable way. Anaerobic digestion (AD) is an established technology that converts organic waste into valuable bioenergy in the form of biogas ($CH_4$), effectively preventing organic pollution. However, the recovery of valuable nutrients, particularly nitrogen, through AD technology can be inefficient, resulting in the pollution of aquatic and other ecosystems (Lamolinara et al., 2022).

Ammonia-rich biomasses, such as animal waste (e.g., from pigs, poultry, mink, etc.), are generated in vast quantities and require sustainable treatment options to mitigate their environmental impact. Ammonia is a byproduct of the decomposition of nitrogenous compounds and, even at moderate concentrations, can be toxic to methanogens, which are responsible for methane production during AD (Sihlangu et al., 2024; Yang et al., 2024). This toxicity can inhibit methanogenesis, the last step of AD process, leading to reduced biogas production and even process failure if ammonia levels become too high (i.e., 1.5 g $NH_4^+$-N $L^{-1}$) (Chen et al., 2008). As a result, many biogas plants using ammonia-rich substrates as feedstocks, operate under an "inhibited steady state" (Wang et al., 2024), resulting in methane production losses of up to 30%, due to the toxic effect of ammonia (Fotidis et al., 2017). In such cases, traditional AD process falls short, necessitating advanced solutions to reduce its environmental footprint.

The methodological approach of the ALIVE project addresses these challenges by employing focused pre-treatment methods, leveraging the capabilities of acclimatised methanogenic consortia (bioaugmentation) that can thrive in high-ammonia (>4.0 g $NH_4^+$-N $L^{-1}$) environments to counteract ammonia toxicity (Tian et al., 2019). This approach will, for the first time, be combined with an advanced membrane system for efficient nutrient recovery, significantly enhancing the overall efficiency of the AD process.

Therefore, the aim of the ALIVE project was to develop an innovative and integrated technology for the sustainable recovery and reuse of carbon and nitrogen contained in agro-livestock waste by upgrading them into high-value products such as biostimulants and biofertilisers, preventing pollution in an economically viable way. This innovative approach aims to boost methane production from various unwanted biomass sources while simultaneously protecting the environment and offering a cost-effective, user-friendly solution. The concept note and methodological approach are presented in the current manuscript.

## 2. Methodology

The methodological approach is described in the following investigative steps. Initially, a thermal hydrolysis stage (max 70°C) of ammonia-rich substrates (e.g., poultry manure) is implemented, followed by AD, under high ammonia concentrations (>4000 ppm), in continuous reactors (lab- and pilot-scale), where operating conditions are optimised and bioaugmentation is applied, so that methane production and yield remain unaffected. Afterwards, a filtration system (6-8 L $h^{-1}$ capacity) for ammonia recovery treats the produced digestate from the

AD of ammonia-rich substrates to recover dissolved nutrients. The system consists of the following two filtration stages: i) Reduction of digestate's solid content to less than 2% with three pre-filtration stages. In each filter, the filtrate is fed into the next filter while the concentrate is removed from the filtration system, ii) Final filtrate from stage one is pumped into a membrane system with a) Three-stage ultrafiltration, b) Two-stage nanofiltration, and c) Two-stage reverse osmosis.

A 40 L tank is used, and the concentrate is recirculated back to the feed tank until the volume is reduced to about one-tenth of the original. The microfiltration permeate is collected and fed into the ultrafiltration membrane system (with a pore size of 10 kDa) using a similar methodology in a 25 L vessel. The filtrate is then directed to the nanofiltration system and subsequently to a reverse osmosis membrane array. To recover the ammonia, sulphuric acid is used, which reacts chemically, and ammonium sulphate is produced, which can be used either directly as an inorganic fertiliser or as a raw material for manufacturing other types of fertilisers. Furthermore, the residual nitrogen from the filtrate serves in the next step as the feedstock for a microalgae system (pilot-scale closed photobioreactor). At this step, the recovery of nitrogen and phosphorus is implemented through microalgae cultivation, which is later used to produce hydrolysed protein solutions from the microalgae, rich in amino acids and peptides, that can be used as plant growth-promoting materials. Finally, the effectiveness of the produced biofertilisers and biostimulants, specifically, the microalgae as-is, the hydrolysed protein solution, and ammonium sulphate, is investigated as growth enhancement on plants to evaluate their ability to replace synthetic fertilisers.

## 3. Expected results

The overall concept is based on the optimisation of AD with ammonia-rich substrates (>4.0 g $NH_4^+$-N $L^{-1}$) and optimised nutrient recovery from the digestate, along with the development of biofertiliser and biostimulants production. The successful implementation of the ALIVE concept is expected to improve AD performance with ammonia-rich substrates by enhancing bioenergy yields, increasing process efficiency and economic viability, enabling the utilisation of low-value or unwanted biomass, and facilitating the production of marketable bioproducts. The membrane system used for nutrient recovery and separation, although it was refined regarding the different stages and achieves a final removal efficiency of up to 95% of the ammonia, requires further investigation regarding the operating parameters. Different types of dissolved inorganic nutrients can be separated based on their molecular size at various filtration stages. Ammonia, due to its molecular size, is usually captured successfully in the concentrate of the first and/or second reverse osmosis stage. Nevertheless, occasional membrane clogging, fouling, and even inadequate long-term maintenance can often result in inconsistent efficiencies.

## 4. Conclusion

Overall, the combined system with initial thermal hydrolysis and efficient AD under elevated ammonia concentrations (>4.0 g $NH_4^+$-N $L^{-1}$) (enhanced by bioaugmentation) results in a nitrogen-rich digestate which is afterwards effectively recovered by the membrane system. Nevertheless, the combined system of thermal hydrolysis, AD, and membrane system needs further investigation regarding certain operational parameters, which is deemed essential towards a promising potential standardisation of the process for simultaneous bioenergy production combined with nitrogen recovery to produce biofertilisers and biostimulants. These high-value products will significantly contribute to improving the competitiveness of biogas plants and the agri-food sector, reducing the use of synthetic fertilisers, and saving resources and energy.

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