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Developing a novel technology for slurry management by project-based learning

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Farming is responsible for 30% of global anthropogenic emissions. A novel technology, aligning with current regulations of covering slurry stores, has been developed for processing anaerobic digestate liquor, which is obtained from the screw press stage. Instead of using hazardous chemicals, such as sulfuric acid, to capture ammonia and greenhouse gases, the artifact contains calcium chloride as deliquescent salt. Preliminary simulations in Aspen Plus® v12 showed that the absorption of NH₃ and carbon dioxide during the solid–liquid separation was feasible and the resulting clean brine could be used as chemical amendment of untreated slurry. The characterization of the performance of the artifact was organized following a project-based learning active teaching method, for a group of 3 students (17-year-olds) of secondary education, as part of the In2ScienceUK program. The collection of empirical data allowed the contents of the curriculum to be contextualized, enhancing environmental awareness of participants. A titrimetric method was employed to determine the content of NH₃ and CO₂ in the brine, and the granulation of the dewatered liquor with the fibers of anaerobic digestate was investigated by determining the compression strength required to break the pellets. The operation capacity of the prototype was found to be 250 m³ of liquor per year, at a cost of £1/m³. The use of the filtered brine as chemical amendment also represented an additional 5.60 grams of ammoniacal nitrogen and 0.96 grams of inorganic carbon per cubic meter of unprocessed slurry. The concentrated liquor was a good binding agent that provided the pellets with a compressive strength of 207.00 ± 26.36 N, which was above the threshold value for commercialization purposes (50 N). The advances in the development of the prototype enhanced the suitability of the technology for industrial scale applications but hindered the adoption of subsequent editions of this pedagogic tool.

KEYWORDS

ammonia, greenhouse gas emissions, mitigation technology, solid–liquid separation, modified static chamber method, circular economy, active teaching–learning method, curriculum content contextualization

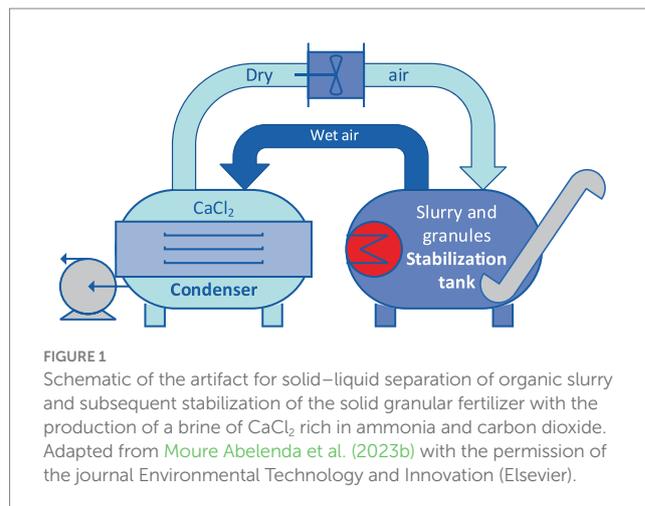
1 Introduction

Farming is responsible for 30% of global anthropogenic emissions (Lal, 2021). In the UK, the Clean Air Strategy (UK Government, 2019) is an essential element of the Agricultural Transition Plan, which has been established as roadmap for the period 2021 to 2024 (DEFRA, 2020, p. 55). These regulations include a slurry investment scheme, which grants funding for new slurry stores and equipment to protect the environment by covering slurry and digestate stores or using slurry

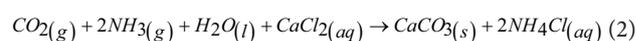
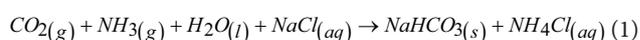
bags & using low emissions techniques for spreading slurries and digestate on land (for example, by injection, trailing shoe or trailing hose) (UK Government, 2019, p. 68). Many farms are opting for the CATNAP (Cheapest Available Technology Narrowly Avoiding Prosecution) approach that is not fully regulated (e.g., use of chemical amendments of slurry) and likely not very cost-effective (Lanigan et al., 2018; Buckley et al., 2020). This opens the possibility of developing and commercializing new technologies to enhance the rate of adoption by stakeholders (Hou et al., 2018). Some of these slurry additives claim to reduce gaseous emissions despite being cocktails of microbes that promote the fermentation of slurry (Kavanagh et al., 2021).

A modification of the static chamber method for measuring gaseous emissions from organic manures (Van der Stelt et al., 2007; Whelan et al., 2010) has been developed, taking into account all the possible synergies with the existing farm infrastructure, to minimize the cost of processing and land application of the slurry and keep the expenditure below £10/m³ (Moure Abelenda and Amaechi, 2022). The technology meets current regulations and corresponding subsidies available for farmers to seal their slurry stores (UK DEFRA, 2020) and process the manure in a closed environment which allows the saturation of the atmosphere, minimizes the emission of greenhouse gases, and maximizes the retention of nitrogen in the organic fertilizer. This technology combines the deliquescence property of the calcium chloride to enable the solid–liquid separation of slurry (Hjorth et al., 2009) and the formation of a chemical amendment (Husted et al., 1991; Vandr e and Clemens, 1996). The maximum performance of the prototype is attained by optimizing this physicochemical exothermic reaction that takes place in the tank of condensation and brine formation (Figure 1). To ensure the best contact of the anhydrous salt with the moisturized air coming from the stabilization tank, this deliquescent material will be suspended in a net/tray in the condensation tank. By increasing the power consumption of the heating circuit in the stabilization tank, tubular fan for greater turbulence and mass transfer in headspace, or even cooling in the condensation tank (APROVIS Energy Systems GmbH, 2023), it might be possible to attain the processing capacity specified in the guidelines published by the UK Government (2023) on eligibility of slurry processing items: *Screw press slurry separator, capable of processing a minimum of 10 m³/h, with a resulting solid fraction of 30% dry matter according to the model's theoretical capability. All other forms of slurry separation are not eligible under this item.* However, it is important to highlight that the design of the novel artifact considers the current logistics of managing organic manures with the aim of minimizing the power consumption, which for commercial solid–liquid separation equipment is often around 3.0 to 7.5 kW (CRI-MAN S.p.A, n.d.), while still allowing the complete dehydration of the 3% of the total organic slurries (with >95% moisture) produced in farms.

Additionally, unlike the use of hazardous chemicals to fix the NH₃ of manures, such as sulfuric acid (Ndegwa et al., 2009; Guštin and Marinšek-Logar, 2011; Liu et al., 2015; Costamagna et al., 2020), it is



possible to use a brine of sodium chloride, as in the Solvay process (Steinhauser, 2008). A similar strategy was already proposed by Fujioka and Ito (2020), but still the use of H₂SO₄ could not be avoided to recover NH₃. The novelty of the prototype of Moure Abelenda et al. (2023b) for manure treatment offers, thereby, safer and more convenient processing conditions. A preliminary investigation was conducted in the process simulation package Aspen Plus[®] v12 to evaluate the likelihood of absorption and trapping CO₂ and NH₃ in brines of NaCl and CaCl₂ (Equations 1, 2). For these simulations it was assumed that CO₂ and NH₃ were emitted at a rate of 132 mg/h and up to 5.1–510 mg/h, respectively, during the storage of manure at 25°C (Moure Abelenda, 2023a). The estimation of the most representative conditions to model the operation of the prototype (Figure 1) was based on the average content of CO₂ and NH₃ in the anaerobic digestate (~3 g/L CO₂ and ~2 g/L NH₃; Akhlar et al., 2017) and the operating capacity that was experimentally found: dehydrating 5 L anaerobic digestate liquor every 24 h. A simulation with the flash tank as calculation block, implemented ELECNRTL property method to model the liquid–gas mixture CO₂–NH₃–H₂O with the above composition (995 g H₂O, 3 g CO₂, and 2 g NH₃), resulted in no emission of volatile compounds (Moure Abelenda et al., 2023a). Therefore, the sensitivity analysis when using the anhydrous CaCl₂ deliquescent salt to trap CO₂ and NH₃, was applied to the minimum volatilization conditions, as it is widely reported that there are gaseous emissions from organic manures (Kavanagh et al., 2021; Lal, 2021). From the fertilization point of view, it was considered that the most valuable compound that needed to be recovered was NH₃. Importantly, it was found that the limiting factor to enable Equation (2) was the rate of volatilization of NH₃, that is why this parameter was studied in more detail than the rate of volatilization of CO₂ (Supplementary Figures 1–3). Similarly, the variability of the amount of CaCl₂ was also investigated and the results of the simulation showed that the first formation of NH₄Cl could be seen when the prototype operates with >5 kg CaCl₂ and volatilization rates >100 mg/h NH₃ (Supplementary Figure 3).



Abbreviations: ATR, Attenuated total reflectance; A-level, Advanced level; CATNAP, Cheapest technology narrowly avoiding prosecution.; COSHH, Control of Substances Hazardous to Health; CO₃²⁻-C, Inorganic carbon; Fiber, Solid phase obtained from the screw-press separation; FTIR, Fourier-transform infrared spectroscopy; Liquor, Liquid phase obtained from the screw-press separation; NH₄⁺-N, Ammoniacal nitrogen; PBL, Project-based learning; SWOT, Strengths, weaknesses, opportunities, and threats.

Depending on the extent of the deliquescence phenomenon, a liquid film over the solid CaCl_2 could be more relevant in the condensation tank (i.e., earlier in the 24-h operation) than the liquid brine (i.e., aqueous solution), as the latter prevailed at more advanced stages of the dehydration of the anaerobic digestate liquor. The supersaturated solution of 0.5 kg H_2O and 10 kg anhydrous salt was considered to account for any possible absorption in the liquid film that is generated during the deliquescence phenomenon (Supplementary Figure 1). Only in the case of using CaCl_2 as dehydrating agent in the prototype, the simulation predicted the absorption of CO_2 and NH_3 plus the formation of calcium carbonate (Supplementary Figure 2) and ammonium chloride (Supplementary Figure 3), as per the stoichiometry of Equation (2). On the other hand, the extents of formation of sodium bicarbonate, according to Equation (1), and even ammonium bicarbonate or ammonium carbamate as described in a previous investigation (Moure Abelenda et al., 2023a) were found to be negligible under the conditions that the prototype operates. The greater capacity of the CaCl_2 , compared to NaCl , to absorb the NH_3 can be seen by comparing the stoichiometries of Equations (1, 2). Another reason for the performance differences of the salts is more acid being required to neutralize the basicity of calcium oxide than that of sodium oxide; hence, the CaCl_2 “contains” more hydrochloric acid than the NaCl . The formation of precipitates was validated with the empirical data available in the literature for the different solid forms of $\text{CaCl}_2 \cdot x\text{H}_2\text{O}$ (x being equal to 0, 1, 2, 4, and 6; Supplementary Figure 4), CaCO_3 and calcium hydroxide (Supplementary Figure 5), and NaCl , NH_4Cl , and NaHCO_3 (Supplementary Figure 6).

It is necessary to experimentally validate the results of the simulation and confirm that the absorption of CO_2 and NH_3 in the forming brine of a deliquescent anhydrous salt is feasible. As described previously (Moure Abelenda et al., 2023b), since the functioning of the prototype relies on basic science (e.g., acid–base reactions, Ohm’s law, Watt’s law, etc.), its development could be also considered as part of a didactic proposal (i.e., project-based learning as active teaching–learning method) to address the educational needs of K-16 students (e.g., lack of contextualization of the contents of the curriculum, excess of propaedeutic approach, classroom not representing the most suitable learning environment, etc.). It is clear that the type of *egg drop* projects (Haupt, 2004), which are purely focused on scientific aspects of the design of the artifact, does not help students to understand their role in society and to acquire the skills to become active citizens promoting sustainable development. The present investigation describes the outcomes of a flexible model to support the knowledge transfer and the commercialization of this technology, where the artifact was developed to address the needs of the potential clients (i.e., stakeholders of the agroindustry). For the development of the prototype that addresses the current needs of agroindustry, the design relied on basic science because the emphasis was placed on searching for synergistic solutions that would demand the minimum consumption of energy and resources. Sufficient background was provided to secondary education students for them to play an active role in this research activity, which aimed to generate a significant contribution to manure processing technology. At the same time, the suitability of the pedagogic tool and didactic units that compose the different hands-on sessions of the project-based learning (PBL) were tested for addressing the educational needs of Advanced level (A-level) students in the UK. The preliminary SWOT (Strengths, Weakness,

Opportunities, and Threats) analysis of the didactic proposal estimates that the outreach event will constitute a transversal experience for A-level students (Moure Abelenda et al., 2023b).

2 Materials and methods

The didactic proposal (*Make it happen!*) of Moure Abelenda et al. (2023b) was adapted to fit the activities for a week of placements under the In2ScienceUK (2023a) program. A group of 3 students (17-year-old), selected following the criteria of In2ScienceUK (2023a), was hosted at the School of Engineering of Lancaster University for 5 days, and supported to advance the development of the prototype from its original incarnation (Figure 1). By accepting their place on the program, students confirmed that they have read, understood, and agree to abide by the code of conduct to In2ScienceUK (2023b), where is explicitly written: *Be fully engaged in all tasks and actively participate in discussions*. Additionally, the parents/guardians were asked for photo/video consent (or lack thereof) for the students, recordings consent (in case of online workshops and meetings involving students for safeguarding purposes), and travel consent for the students to be allowed to travel to and from their placements. This PBL activity (*Make it happen!*) provided them with experience of an entrepreneurial project beyond academic research. Table 1 details the items that were made available for students to replicate and improve the design of the artifact, with a total cost of approximately £700.

To evaluate the technical feasibility of the novel technology, it was necessary to collect empirical data that would provide insights several of parameters: rate of solid–liquid separation, power consumption, fixation of CO_2 and NH_3 during the stabilization process, and suitability of the isolated organic matter for granulation purposes. Among the whole chain of physicochemical effects on which the novel technology relies, the bottleneck of the process was considered to be the kinetics of the hydration of the calcium chloride. Therefore, the operating conditions of the artifact needed to be optimized for this slow stage, which indicated providing the condensation chamber with a sufficient amount of saturated vapor. Standard Operating Procedure, Risk Assessment, and form of COSHH (Control of Substances Hazardous to Health) were completed in line with the standard safety requirements, in addition to safeguarding of children (any person under the age of 18 years). As described in Table 2, the morning sessions ran from 10:00 am to 12:30 and the afternoon sessions went from 13:30 to 16:00.

The first morning session consisted of a presentation on the background of the project and students were able to visualize the traditional processing technological solutions (e.g., screw press, membrane treatment, etc.) available on the market to address the problem of handling organic slurry. An overview of the suitability of the operating conditions (e.g., processing capacity) and inconveniences (e.g., high power consumption and/or low efficiency solid–liquid separation) were described. On the first afternoon session, the students observed a functioning version of the prototype that they were tasked with replicating and improving (e.g., the addition of a heating circuit for the stabilization tank) with the materials that they were provided. The second day was devoted to assembling the pieces of the artifact that were already prepared in advance, due to the time constraint during the week of placements (e.g., 2 perforations of 150-mm diameter in each lid of the boxes to connect them with the

TABLE 1 List of components that were purchased to allow the 17-year-old students to replicate the artifact and propose improvements.

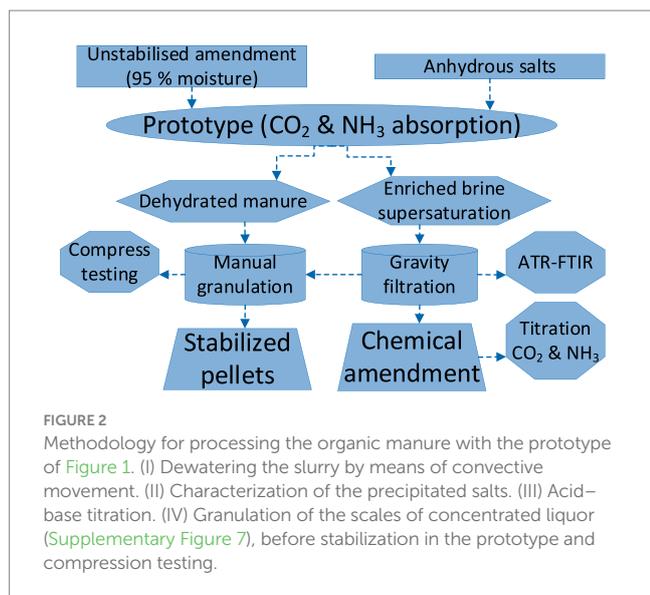
| Item | Number | Cots/(£) |
|--|--------|----------|
| 25-kg calcium chloride | 1 | 52.02 |
| 25-kg magnesium chloride | 1 | 34.62 |
| 25-kg calcium carbonate | 1 | 19.17 |
| 5-kg sodium chloride | 1 | 47.40 |
| 85-L polypropylene box | 4 | 123.00 |
| 10-m aluminum air duct | 1 | 30.59 |
| 102 × 320 cm ² fiberglass screen mesh for window | 1 | 9.90 |
| 10-m × 60-cm × 3-mm, double aluminum bubble thermal reflector panel | 1 | 44.99 |
| 100-m 12-K 33-ohm carbon fiber heating cable | 1 | 43.39 |
| 12-way 3-A electrical connectors | 10 | 13.18 |
| 12-way 5-A electrical connectors | 10 | 16.48 |
| 150-mm, 22-W, 240-V duct extractor fan | 2 | 102.34 |
| 20-W hot glue gun | 1 | 14.99 |
| 48-mm × 45-m aluminum foil tape (3-unit pack) | 1 | 17.95 |
| 20-AWG electrical wire kit | 1 | 14.87 |
| 5-A fused UK mains plug | 2 | 6.95 |
| Electrical junction watertight box of acrylonitrile-butadiene-styrene copolymer | 1 | 17.09 |
| 8-terminal bus bar terminal block (10-unit pack) | 3 | 40.47 |
| 5-m corrugated flexible tube for double insulation of electrical wire (15.8-mm outer diameter) | 1 | 9.99 |
| | Total | 659.39 |

TABLE 2 Details of the different sessions in which was divided the work for the In2ScienceUK placements at Lancaster University.

| July 2023 | Morning session (10:00–12:30) | Afternoon session (13:30–16:00) |
|----------------|---|---|
| Monday 24th | Informative presentation on the current situation of the agroindustry, particularly focused on the challenges and solutions of processing organic manures for mitigation of gaseous emissions and nutrient valorization. | Laboratory and workshop inductions, correct use of the personal protective equipment. Perforation of the propylene box to integrate the electric circuit with the carbon fiber heating cable around the manure stabilizing tank. |
| Tuesday 25th | Implement the parallel circuits of carbon fiber around the stabilization box, including a waterproof box for the connections in the busbars. Confirm that the heating circuit works for the desired power consumption. | Use the double aluminum bubble thermal reflector panel to insulate the stabilization tank. Continue assembling the artifact on the trolley to allow all parts remain connected while still enabling mobility of the artifact. Characterization of the rate of heating of the stabilization tank. |
| Wednesday 26th | Feed the prototype with the liquid fraction of the anaerobic digestate, which is known as liquor (WRAP, 2014), and test different types of dehydrating agents: CaCl ₂ , NaCl, and MgCl ₂ . Observation of the deliquescence phenomena and determination of the rate of brine formation. | Preparation of the questions for the primary market research to find out the suitability of the prepared prototype to address the potential customer' needs. Phone call to a supplier of the samples of the anaerobic digestate liquor. |
| Thursday 27th | Stop the operation of the prototype and sampling of the brine formed and the concentrated liquor. Manual granulation of the solid fraction of the anaerobic digestate, which is known as fibers (WRAP, 2014), using the concentrated liquor as binding agent. The performance of this material is compared to the quicklime self-hardening effect. | Operate the artifact with the granules of organic fertilizer in the stabilization tank to allow the maturation and self-hardening. Charge more anhydrous salt in the condensation tank. Vacuum filtration of the brine to remove suspended particles of calcium carbonate. |
| Friday 28th | Titration of the filtered brine and comparison with the titration of a saturated solution of the salt employed as dehydrating agent (e.g., 74.5 g CaCl ₂ /100 mL), to determine the absorption of CO ₂ and NH ₃ . Mixing the brine with acetone (i.e., antisolvent) and decrease the temperature to promote the supersaturation, precipitation, and isolation. | Isolate the precipitated salt by decantation and ATR-FTIR analysis to determine the composition and structure by comparing the spectrum to those of pure compounds: CaCl ₂ , CaCO ₃ , and NH ₄ Cl. Removal of the granules from the artifact and subsequent compression testing. |

aluminum tubes as described in Figure 1), and to adding new features. For example, the parallel heating circuits with the carbon fiber cable was entirely designed and implemented by the students during the

second day, to enhance the dewatering of the slurry in the stabilization tank while maintaining a moderate power consumption of approximately 80 W. During the morning of the third day, the

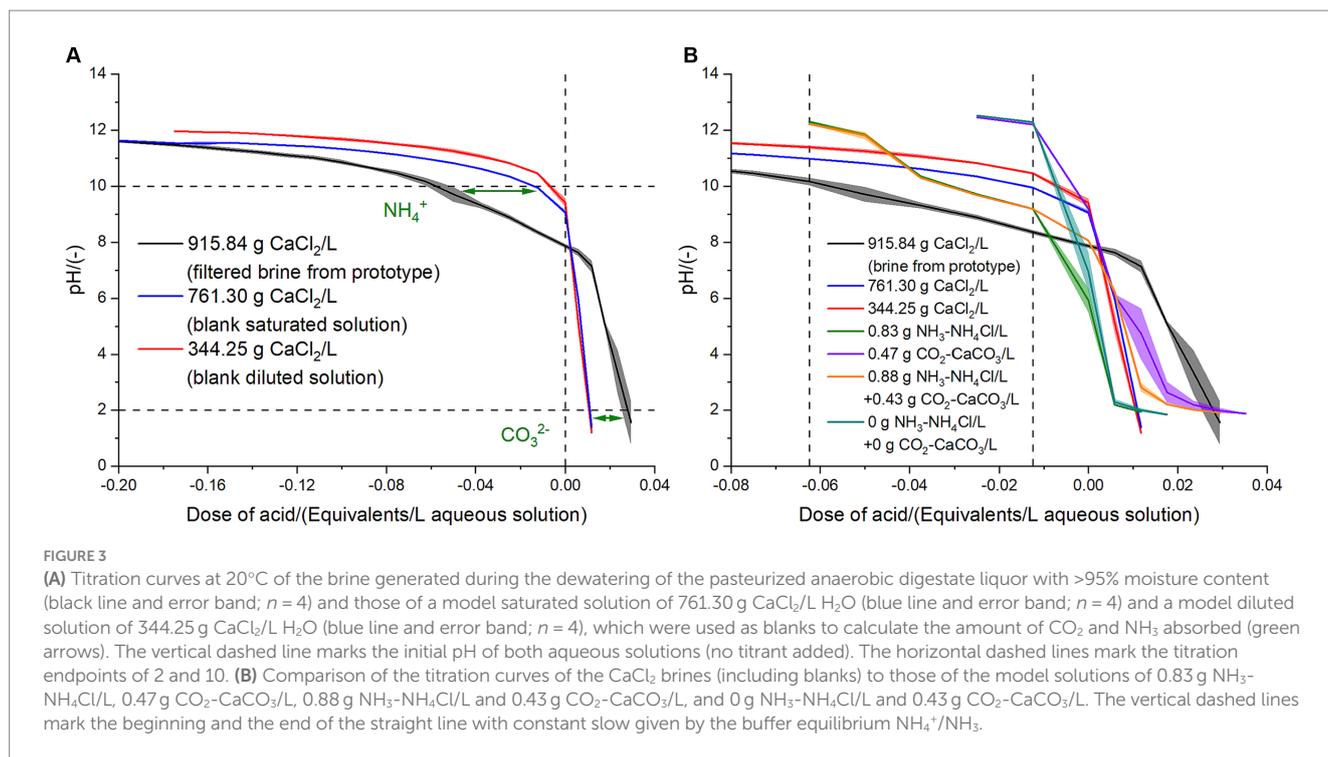


operation of the prototype was initiated (Figure 2) in the workshop of the School of Engineering, where 5 L of pasteurized anaerobic digestate liquor with >95% moisture content were charged in the stabilization tank and 2 kg of anhydrous salt were placed in the cradle of the tank of condensation. Figure 2 describes the methodology followed to operate the artifact and to analyze the products. The anhydrous salts of CaCl₂, MgCl₂, and NaCl were charged separately (i.e., in different experiments) in the condensation tank and the convective movement of the moisturized air coming from the stabilization tank with organic slurry was forced with an in-line tubular fan (Figure 1). The CO₂ and NH₃ released was absorbed in the forming brine as described by Equations (1), (2) and as the organic material was getting drier, the gaseous emissions increased.

Since each batch operation took 24 h to attain complete dewatering of the liquor placed in the stabilization tank, the afternoon session of the third day was spent preparing and organizing the questions for the stakeholders. The spirit of the primary market research was illustrated with a video (MScTE48, 2014) for better understanding of how to enquire about the suitability of the designed artifact to meet the demands of potential clients. The coordination and cooperative learning of the group members was meant to be promoted with the use of an adapted business model canvas template, which includes the Rumsfeld matrix to enable their metacognition and to improve the action lines that the groups of students would be drafting to address the problems of the potential clients (Moure Abelenda et al., 2023b). On the morning session of the next day, the operation of the prototype was stopped and the solid paste of dewatered liquor that remained in the stabilization tank was used as binding agent, to enable the granulation of the fibers of anaerobic digestate. The self-hardening effect of concentrated liquor was compared to that of quicklime, as the CaO was also used to enable the granulation of the solid fibers of the anaerobic digestate (Pesonen et al., 2016). The stabilization tank can also be used to enhance the maturation of pellets with quasi-spherical geometry, using different binding agents (e.g., lime, concentrated liquor, etc.). Before feeding the granules to the stabilization tank of the prototype, to allow sufficient maturation and solidification for the compression testing the following day, the brine generated in the previous run was sampled and fresh anhydrous salt was placed in the

shelf of the condensation tank. In the afternoon of the fourth day, the vacuum filtration of the brine was carried out in the lab to eliminate all the suspended particles of calcium carbonate, which otherwise would disturb the titration for determination of the NH₃ absorbed. The filter paper employed for this purpose was QL100 Fisherbrand, with a pore size of 8 μm. The presence of CO₂ and NH₃ in the brine was determined using the titration methodology described in a previous investigation (Moure Abelenda et al., 2023a), using HCl and sodium hydroxide to prepare the aqueous solutions of titrants and NH₄Cl and CaCO₃ to prepare the model titration curves. Based on preliminary investigations, the concentration of the titrant solutions were chosen as 0.06 mol HCl/L with a pH of 1.13 at 21.1°C and 0.12 mol NaOH/L with a pH of 13.19 at 20.9°C, to avoid excessive dilution of the titrate during the data collection.

On the morning session of the last day, saturated solutions of 344.25 ± 19.21 g CaCl₂/L (Supplementary Figure 4) were prepared and analyzed to have a blank titration curve, where no absorption of NH₃ or CO₂ can be accounted. The approximate concentration of the brine collected in the storage tank of the prototype (expressed in grams of CaCl₂ per liter of aqueous solution) was calculated by performing an extrapolation of the calibration curve elaborated with the density of pure water and that of a supersaturated solution of 761.30 g CaCl₂/L (20°C) (Haynes, 2010, pp. 8–122; Manivasakam, 2011, Table XVI; Solvay, 2023, p. 6). While preparing the aqueous solutions, students were encouraged to look at the temperature increase to appreciate the exothermic reaction of hydration of CaCl₂ and to optimize the deliquescence phenomenon by preventing the increase of the temperature of the condensation tank. Besides the titration of the brine, an attempt to isolate the NH₄Cl was done by promoting the supersaturation of the aqueous solution via addition of acetone as an antisolvent and cooling down. The precipitated salt was subsequently isolated, allowing the settling, decantation, and drying at room temperature in the fume hood. During the afternoon session, the attenuated total reflectance (ATR) Fourier-transform infrared spectroscopy (FTIR) analysis was performed for the precipitated salt and other chemicals of known composition: CaCl₂, NH₄Cl, and CaCO₃, to compare the spectra and elucidate the structure of the complex mineral matrix isolated from the brine. The equipment used for this purpose was the Agilent Technologies Cary 630 FTIR Spectrometer, with an ATR sampling module for reflection mode measurement. Intra-Laboratories Ltd. supplied various grades of chemicals including CaCl₂ (food/pharmaceutical grade), MgCl₂ (cosmetic grade), CaCO₃ (animal feed grade), and Fisher Scientific UK Ltd. supplied reagent grade HCl, NaOH, NaCl, and CaO. The mechanical compression testing of the pellets prepared using different binding agents was conducted with the Instron® 3,345 equipment, with a load cell capable of delivering up to 5 kN of compression force. Given the timeframe of the didactic activity, the granules with lime were prepared in advance (10 days before the preparation of the granules with the concentrated liquor), to allow the pellets to sufficiently self-harden before compression testing. Both the granules of lime and those of the concentrated liquor had a diameter of approximately 5 cm but the binder-to-fiber ratio was 5 times greater when using the concentrated liquor (2.07 ± 0.93), compared to that of lime (0.41 ± 0.20). Descriptive statistics (average values and standard deviations) were considered to identify whether the granule prepared with CaO had greater compressive strength than those prepared with CaCO₃.



Additionally, student experience was characterized by formative and summative assessments in the middle (day 3) and at the end (day 5) of the placements, following the advice provided by National Co-ordinating Centre for Public Engagement (2017). Both surveys, presented in the Supplementary material, were designed to give information on whether the didactic proposal was being applied successfully, to capture the main benefits for students and any aspects that needed to be further developed in future editions of the PBL activity (*Make it happen!*). Filling out the surveys was considered a metacognitive exercise for students that allowed them to evaluate their own performance during the learning process. The questionnaires gave them clues on what skills they were meant to be developing (entrepreneurial spirit, teamwork, environmental awareness, etc.) and how they could apply these when facing another real-world project (Moure Abelenda et al., 2023c).

3 Results

The 22-W duct fan (Table 1) that promotes the turbulence and gas exchange between the chambers (Figure 1) was complemented with 2 parallel heating circuits around the stabilization tank connected to power supplies of up to 3 A and 15 V, representing a total power consumption of around 100 W. The design of the heating circuits considered that the carbon fiber heating cable had a resistance of 13 Ω/m and the maximum heat dissipated could be attained when the current intensity is more relevant than the resistance. Therefore, the design of the parallel circuit relies on understanding the practical application of Ohm's law and Watt's law. The implementation of the heating circuit around the stabilization tank of the prototype enhanced the rate of dewatering of the organic slurry and the rate of brine formation in the condensation tank. The artifact was able to dehydrate 5 L of pasteurized anaerobic digestate liquor (> 95% moisture) within

a 24-h operation. The overall mass balance was the production of 8.5 kg of brine in the condensation chamber (Supplementary Figure 8) and 0.5 kg of solid with a moisture content below 50% remaining in the stabilization tank (Supplementary Figure 7). Most of the moisture of the fresh organic slurry was trapped in the condensation tank (Figure 1), along with some CO_2 and NH_3 . Based on the mass balance, the brine obtained should have a composition of 457.14 g CaCl_2/L (resulting from mixing 4 kg CaCl_2 and 4.5 kg H_2O) but the concentration measured gravimetrically and volumetrically in the filtrated brine was virtually 915.84 ± 9.57 g CaCl_2/L . This value of concentration was significantly higher than the saturation limit of 515.30 ± 200.02 g CaCl_2/L that is reported in literature (Haynes, 2010, pp. 8–122; Manivasakam, 2011, Table XVI; Solvay, 2023, p. 6), despite this solution has been filtered. Therefore, it was inferred that the aqueous solution should contain other compounds different from CaCl_2 , which also contribute to increase the density of this liquid.

Figure 3A shows the titration curves of filtered brine collected from the prototype, blank saturated solution (761.30 g CaCl_2/L), and blank diluted solution (344.25 g CaCl_2/L). The pH of the filtered brine resulting from the dewatering of the organic slurry and that of the saturated and diluted CaCl_2 solutions without the addition of any titration agent (i.e., acid dose of 0 Equivalents/L) were 7.86 ± 0.07 , 9.07 ± 0.07 , and 9.41 ± 0.15 , respectively (Figure 3). Since most of the CaCO_3 has been removed during the filtration stage, these differences in the pH were mainly given by the presence of NH_4Cl in the brine coming from the prototype and the different ionic strengths of the aqueous solutions of CaCl_2 . The salt NH_4Cl has acidic behavior, and the scale of pH shifts toward lower values, as the ionic strength increases (Kennedy, 1990; Samuelsen et al., 2019): blank diluted solution (9.31 M), blank saturated solution (20.58 M), and filtrated brine from the prototype (24.76 M). Under a sufficient flow of NH_3 or CO_2 , these gases can affect the chemistry of an aqueous solution in intimate contact, but when the flow rate is limited, the existing

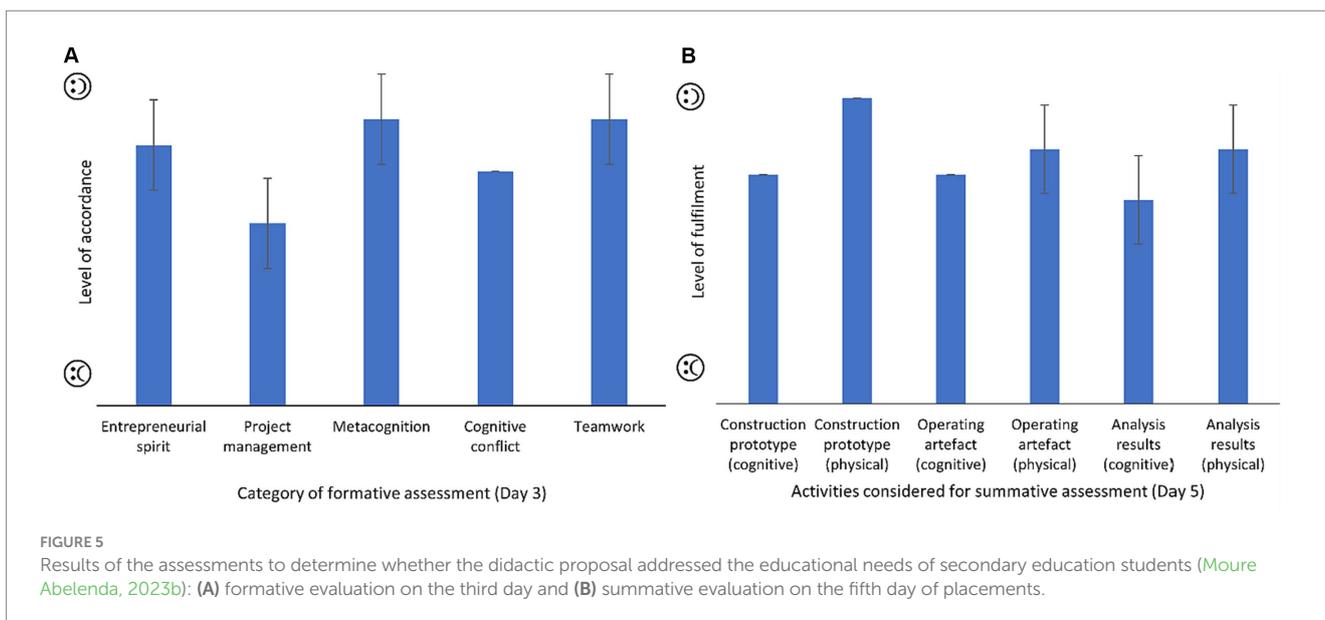
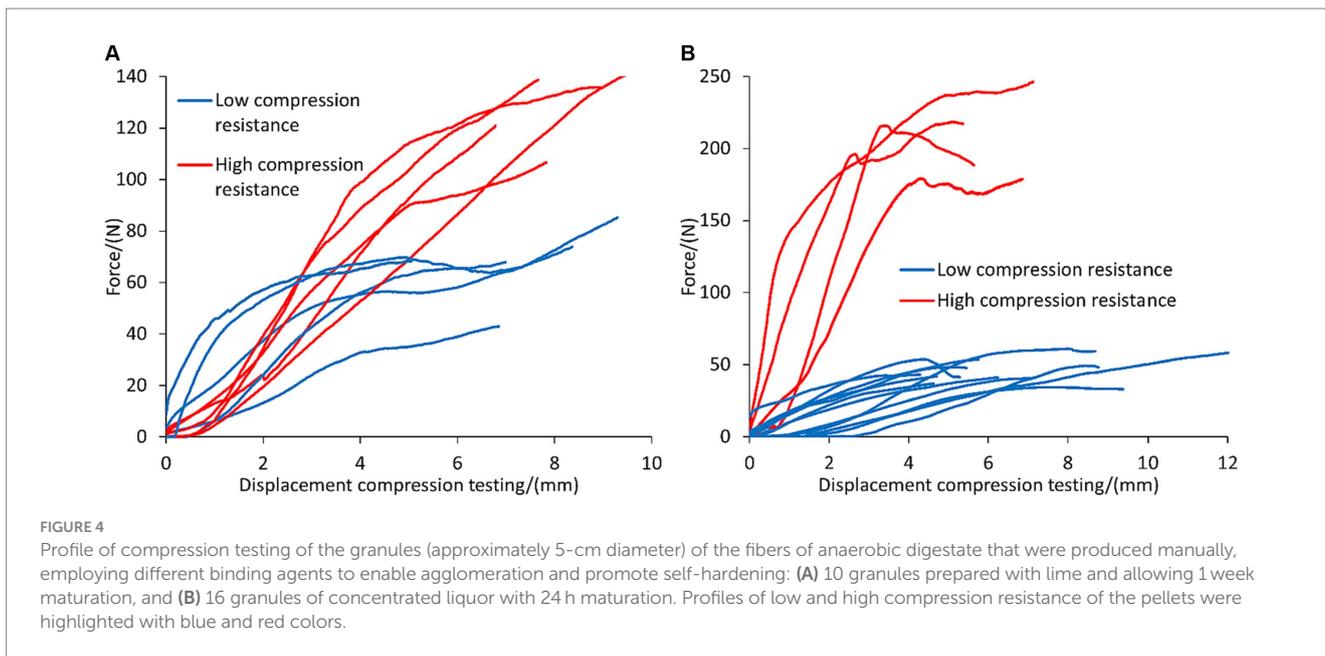
chemistry of the aqueous solution determines the form under which NH_3 and CO_2 are stored in the liquid phase. In this way, both inorganic compounds prevent the change of the pH of the aqueous solution and a flatter titration curve is indicative of a greater content of inorganic nitrogen and carbon in the brine, because it takes an increased amount of the titrant agent to modify the pH. In the conditions of the prototype, the most stable ionic compounds for allocating the gaseous stream of inorganic nitrogen and inorganic carbon were NH_4Cl and CaCO_3 . Both acidic and basic titrants were used to evaluate the buffer capacity of the aqueous solutions, as this is a proxy measurement of the content of NH_3 and CO_2 , corresponding to 0.85 and 0.44 g/L, respectively. The dose of titrant in the X axis of Figure 3 is expressed in terms of the equivalents of acid (HCl) and the negative values correspond to the addition of basic titrant (NaOH), since both compounds have the same valence. Previous investigations have shown that this is the most effective and reliable way of expressing the dose of titrants (Regueiro et al., 2016; Moure Abelenda et al., 2021b, 2022a,c). Model aqueous solutions of 0.83 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$, 0.47 g $\text{CO}_2\text{-CaCO}_3\text{/L}$, 0.88 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ and 0.43 g $\text{CO}_2\text{-CaCO}_3\text{/L}$, and 0 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ and 0.43 g $\text{CO}_2\text{-CaCO}_3\text{/L}$ were prepared, and the titration curves were compared to that of the brine recovered from the condensation tank of the artifact.

A conservative approach of comparing the titration curves of the filtrated brine to that of the saturated model solution indicated that approximately 2.5 times more equivalents of NH_3 were available in each liter of brine than the equivalents of CO_2 in the same volume (Figure 3A). This is in agreement with the fact that the CaCO_3 (Supplementary Figure 4) is less soluble than the NH_4Cl (Supplementary Figure 5), hence more amount of ammoniacal nitrogen ($\text{NH}_4^+\text{-N}$) remained in the aqueous solution after the filtration stage, compared to the amount of inorganic carbon ($\text{CO}_3^{2-}\text{-C}$). The 761.30 g $\text{CaCl}_2\text{/L}$ saturated solution was, therefore, regarded as a blank measurement for the content of NH_4Cl and CaCO_3 . The differences in the consumption of acidic and basic titrants by the filtered brine and the 761.30 g $\text{CaCl}_2\text{/L}$ solution were measured at the titration endpoints. According to Husted et al. (1991), at an ionic strength of 0.25 M, the mixed acidity constants (pKa values) for $\text{CO}_2/\text{HCO}_3^-$, $\text{HCO}_3^-/\text{CO}_3^{2-}$ and $\text{NH}_4^+/\text{NH}_3$ are 6.21, 9.90 and 9.46, respectively. However, it should be noted that the model solution of 1.08 g $\text{CaCO}_3\text{/L}$ (which can be expressed as 0.47 g $\text{CO}_2\text{-CaCO}_3\text{/L}$) did not show any buffer effect when alkalinizing above the initial pH of 9.19 ± 0.07 (Figure 3B), which implied that the CaCO_3 added to the distilled water immediately dissociated to enable the formation of the bicarbonate: $\text{CO}_3^{2-} + \text{H}_2\text{O} \rightarrow \text{HCO}_3^- + \text{OH}^-$. Thereby, the titration endpoints were the pHs at which there were the greatest difference in the titrant consumption by the filtered brine and the saturated solution, when depleting the acidity of NH_4^+ (pH above 10) and the alkalinity of CO_3^{2-} (pH below 2). These titration endpoints were also the end of the constant slope that define the rate of consumption of titrant under a particular buffer agent. In the case of pH above 10, both the filtered brine and the saturated solution ended at a similar pH of 11.61 ± 0.05 and 11.64 ± 0.01 , respectively. This could not be considered as titration endpoint because the consumption of the basic titrant is not entirely associated to the conversion of NH_4^+ to NH_3 . Since both aqueous solutions have similar ionic strength, above pH 10, the basic titrant is consumed by the ions Ca^{2+} (pKa of 11.6) to produce CaOH^+ . Therefore, since the beginning of the smoother variation of the slope, above pH 10, the consumption of alkali is not

considered as part of the NH_4^+ buffer effect. Figure 3B shows that the slope of the alkalinization curves (between -0.04 and -0.01 equivalents acid/L) of the solution 0.83 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ was the same as that of the titration curve of the filtered brine from the prototype but the intercept of the straight line of the model solution was higher due to its lower ionic strength. Also, there was a change in the titration curves of the solution and that of the brine from the prototype above a pH of 10. Finally, the profile of the solution 0.88 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ & 0.43 g $\text{CO}_2\text{-CaCO}_3\text{/L}$ follows a combination of the buffer trends of the solution 0.83 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ and the solution 0.47 g $\text{CO}_2\text{-CaCO}_3\text{/L}$. The non-buffer parts of the titration curves of these solutions match the profile of the blank (0 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ & 0 g $\text{CO}_2\text{-CaCO}_3\text{/L}$). The alkalinization of all model solutions (0.83 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$, 0.47 g $\text{CO}_2\text{-CaCO}_3\text{/L}$, 0.88 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ & 0.43 g $\text{CO}_2\text{-CaCO}_3\text{/L}$, and 0 g $\text{NH}_3\text{-NH}_4\text{Cl/L}$ & 0 g $\text{CO}_2\text{-CaCO}_3\text{/L}$) reaches pH above 12 due to the negligible content of Ca^{2+} . However, the purified water employed to prepare the model solutions contains some residual alkalinity, as can be seen in Figure 3B, and this resulted in the consumption of some 0.015 ± 0.004 Equivalents of acid/L of titrate to reach a pH below 2.

In order to attain the acid titration endpoint $\text{pH} < 2$ in a liter of brine from dewatering slurry, approximately 0.02 equivalents of acid were required more than when acidifying the fresh 761.30 g/L solution of CaCl_2 (Figure 3A). Since the valence of HCl (employed as acidic titrant) is half of that of CaCO_3 , the moles of monovalent acid titrant should be twice the moles of carbonate per liter of brine. On the other hand, the alkalinization of a liter of brine obtained from dewatering the anaerobic digestate liquor, required 0.05 equivalents of NaOH more than what was found necessary for the alkalinization of the fresh saturated 761.30 g $\text{CaCl}_2\text{/L}$ to reach the titration endpoint of 10. Since the valence of NH_4Cl is 1 and is the same as that of NaOH, the moles of ammonium per liter of brine were around 0.05. Based on this analysis, the contents of NH_3 and CO_2 in the brine generated in the artifact after 1 day of operation were 0.85 and 0.44 g/L, respectively. If all the volatilized NH_3 , CO_2 , and H_2O in the 24-h operation ended up in the brine, the rate of release of these compounds during the dewatering of the anaerobic digestate liquor was around 230 mg $\text{NH}_3\text{/h}$, 119 mg $\text{CO}_2\text{/h}$, and 200 g $\text{H}_2\text{O/h}$, which are comparable mass flow rates (i.e., in the same order of magnitude) to the values employed to run the initial simulations in Aspen Plus® v12 (Supplementary Figures 1–3). The artifact developed (Figure 1) is therefore a useful measurement tool of gaseous emissions from manure, avoiding the requirement for expensive analytical equipment since it can be easily coupled with a titration method.

The valorization of the dewatered liquor was investigated as binding agent to enable the granulation of the fibers (i.e., solid fraction) obtained from the screw press separator. The performance of the concentrated liquor as binding agent was compared against that of lime, which is often used as additive to promote the self-hardening of the granules upon sufficient maturation (Moure Abelenda and Amaechi, 2022). The results shown in Figure 4A indicate that 50% of the granules with lime showed high compression resistance: 111.84 ± 15.44 N of force and 6.09 ± 1.43 mm of size reduction before reaching mechanical failure. The other 50% of the lime granules showed a profile of low compression resistance: 50.20 ± 3.11 N of force and 10.32 ± 1.20 mm of oncoming platens of the testing machine, which account the deformation of the specimen. The reproducibility of the high compression strength granules prepared with the



concentrated liquor as binding agent was lower than that of lime because only 25% of the pellets supported 207.00 ± 26.36 N of force and 4.07 ± 1.33 mm of size reduction before fracturing. The 75% of the pellets of concentrated liquor fell in the range of 45.54 ± 8.22 N and 5.92 ± 1.98 mm (Figure 4B). It is important to highlight that the pellets of lime were subjected to 10 days of maturation time under the fume hood, while the pellets prepared with concentrated liquor only underwent drying in the stabilization tank of the artifact for 24 h. Another difference is that more binding agent was employed in the case of pellets prepared with concentrated liquor than in the preparation of the lime pellets. Generally, Figure 4 shows that the high-compression-resistance pellets of the concentrated liquor withstood greater compression forces than the pellets prepared with lime and the shape of the concentrated liquor pellets was also less affected.

The success rate of employing the prototype as a didactic tool for secondary education students was quantified in the middle of the engagement activity (formative assessment in day 3; Figure 5A) and at the end (summative assessment in day 5; Figure 5B). The students were happy with the freedom that they were given to develop their own initiative and entrepreneurial spirit. Due to the limited time to conduct the activity, most of the formalities (e.g., preparation of the risk assessment and COSHH form) were done before the arrival of the students, and they have highlighted that his part might be missing for developing their project management skills. In line with the freedom to use different materials, the students have highlighted that this didactic activity gave them the opportunity of making mistakes, rectifying, and reflecting on their own learning process to have a superior understanding of their capabilities (i.e., metacognition). However, it could be interesting to include specific tasks to force their

cognitive conflict. As indicated by [In2ScienceUK \(2023a\)](#), the preference of students is to work in small groups of 3 members that give them the chance of listening and being heard by others. In general, the physical activities proved more engaging than the cognitive work. Particularly, the students were observed to be very active and participative during the elaboration of the electric heating circuit. The complaint made by the students regarding the cognitive exercise of analyzing the results, was the difficulty of abstraction required for quantifying the content of NH_3 and CO_2 that ended up in the brine and provided buffer capacity ([Figure 3](#)). Thereby, more time should be devoted to the explanation of the titration method in the next edition of the didactic proposal because these concepts might fall outside of students' curriculum content. Overcoming intrinsic difficulties associated to the analytical method could be achieved, for example, by simplifying the units of the dose of titrants, since the students might find the use of the term "equivalents" ambiguous, when expressing the amount of acid or base.

4 Discussion

The comparison of the performance of the initial prototype (i.e., without the heating circuit and a total energy consumption of 22 W) allowed to characterize better the artifact developed by the students, where the heating was implemented. The relation between the power consumption of the artifact and rate of dehydration was not exactly direct: Doubling of power consumption increased the rate of dehydration of the slurry slightly less 2 times. Therefore, this needs to be taken into account when planning the next designs for expanding the processing capacity of the equipment to dehydrate larger quantities of organic slurry. Since the brine generated can be employed as chemical amendment (and additional source of $\text{NH}_4^+\text{-N}$) for the untreated slurry ([Husted et al., 1991](#); [Vandré and Clemens, 1996](#)) that does not pass through the artifact, it could be also considered that this system exceeds the expectations of slurry processing for its energy consumption. The brine produced in the condensation tank of the prototype had a composition of approximately 10 M CaCl_2 whereas typical concentrations employed for soil extraction are around 0.01 M CaCl_2 ([Houba et al., 2000](#)) and for chemical stabilization of raw slurry range from 0.025 M ([Vandré and Clemens, 1996](#)) to 0.08 M ([Husted et al., 1991](#)). Since the prototype is able to produce around 2 tonnes of brine per year, consuming 0.9 MWh at £80 and 1 t of CaCl_2 at £150, the total cost of adding the chemical amendment to 250 t of untreated slurry is £1/t, which is a competitive cost compared to other products available on the market. This way of preparing the chemical amendment by dehydrating 1% of the total organic slurry produced in the agribusiness is in line with the business model of the Bokashi composting method for the production of Effective Microorganisms (*Lactobacillus*), which can be applied to improve the management of the organic slurry upon suitable dilution ([Aryantha and Guest, 1999](#); [International Nature Farming Research Center \(INFRC\), 1999](#); [Bastami et al., 2016](#); [San Martin Ruiz et al., 2022](#)).

Attaining a concentration of 0.08 M CaCl_2 in the organic slurry should have the same impact on the pH as adding 0.16 equivalents of HCl per liter. It is noteworthy to mention that the acidic effect of the CaCl_2 can only be seen in suspension where most of the H^+ ions remain attached to solid particles. These protons are released upon a small addition of CaCl_2 that provides Ca^{2+} to replace some of them in

the surfaces of the suspended solids, hence the H^+ ions remain free in the bulk solution ([Department of Primary Industries and Regional Development. Government of Western Australia, 2018](#); [BACTO, 2021](#)). In fact, the material safety data sheet provided by the manufacturer of the solid flakes of CaCl_2 indicates that a solution of 100 g/L at 20°C should have pH between 9.0 and 10.5 ([Solvay, 2023](#)). The use of this material is sustainable because it is a byproduct of Solvay's Process for Soda-Ash production. According to the manufacturer, their product is free of materials that are harmful to the environment and contains a very low level of heavy metals and organic compounds. Total alkali chlorides (e.g., NaCl and KCl) are the main impurities of commercial calcium chloride. Since much more alkali than acid titrant was required to increase the pH of the aqueous solutions ([Figure 3](#)), above pH 10 almost flat titrations curves were found due to the progressive dilution effect, in addition to the content of Ca^{2+} in the titrate. Up to 8 mL of basic titration were added to 5 mL of brine to reach a pH close to 12, while it only took the addition of 3 mL (or less) of acid titrant to reach a pH below 2 in the titrate ([Figure 3](#)).

Unlike the NaCl, which showed very limited deliquescence, the MgCl_2 provided sufficient brine formation for capturing NH_3 and CO_2 , and the performance of this material should be compared to that of CaCl_2 . The treatment of the gases coming out of the stabilizing slurry can be improved by including a filter of activated carbon to trap the H_2S ([Yan et al., 2002](#); [Coppola and Papurello, 2018](#)). As with the static chamber method or any other procedure employing a sulfuric acid solution as a trap of NH_3 (including bubbling systems), calibration should be performed to determine the efficiency of absorbing gases in the device ([Ndegwa et al., 2009](#)) and the air quality that remains in the headspace of the artifact by the end of the operation. This could be done by using a model solution of NH_4Cl or NH_4OH of known composition from where emissions are promoted by increasing the pH or the temperature and following the increase of the concentration of NH_4^+ in the H_2SO_4 trap. This further characterization of the performance of the artifact can be implemented as part of additional didactic units, which allow the determination of the absorption efficiency and compare this to that of traditional static chamber or closed chamber methods. A benefit of this methodology, compared to the closed chamber, is that it allows quantification of the emissions of NH_3 and CO_2 with titrations of the brine because, unlike the pH of the H_2SO_4 solution, the pH of the brine does change considerably due to the absorption of NH_3 and CO_2 , which makes possible to avoid specialized analytical equipment (e.g., Autoanalyzer segmented flow colorimetry or Total Nitrogen machine). Interestingly, the absorption of NH_3 in H_2SO_4 solution implies, as in the brine of the anhydrous salt, a decrease in pH ([Moure Abelenda et al., 2021a](#)), due to the formation of the acidic salt $(\text{NH}_4)_2\text{SO}_4$, similarly to the developed artifact, which stores the NH_3 as NH_4Cl and decreases the pH. The range of pH of the CaCl_2 brine is more suitable to detect low amounts of NH_3 absorbed in the liquid, compared to the very low pH of the acid H_2SO_4 solutions. In a previous investigation, the initial pH of 10-mL solutions of H_2SO_4 (with concentrations ranging from 0.1 to 1 M) placed in the trap of the closed chamber method was 0.92 ± 0.005 . Due to the absorption of NH_3 released from the incubation of 3.22 ± 1.43 g of whole agrowaste anaerobic digestate (AWD) at pH 10.40 ± 0.46 for 60 h at 100 rpm at 20°C, the pH of the H_2SO_4 solutions decreased 0.25 ± 0.02 units ([Moure Abelenda et al., 2021a](#)). Assuming that all the NH_3 released ended in the H_2SO_4 trap, the rates of volatilization were:

20.15 ± 8.22 mg/h in an incubation with wood fly ash (WFA) for 60 h (Moure Abelenda et al., 2021a), 22.65 ± 6.08 mg/h in an incubation with WFA for 7 h, 2.03 ± 0.71 mg/h in a incubation of the AWD alone for 7 h at pH 8.32 ± 0.12 (Moure Abelenda et al., 2021c), and 3.65 ± 1.83 mg/h in an incubation of the AWD for 48 h at pH 7.55 ± 0.40 (Moure Abelenda et al., 2022b). All these values of NH₃ volatilization rate are lower than the value found for the artifact with the anhydrous salt (approximately 230 mg NH₃/h), although for a fair comparison is necessary to account the differences between the treatments, besides the dehydration effect, temperature, length of incubation, the type of organic material and any additive to tune its pH. However, it is still possible to infer the greater performance of the artifact in terms of capturing NH₃ than the classical closed chamber method. The present method with the formation of the brine might be also more convenient for isolating the ammonium as NH₄Cl rather than as (NH₄)₂SO₄, as the brine might prevent the absorption of impurities such as cyclohexene (Ukwuani and Tao, 2016).

Another inconvenience of the traditional static chamber method is that to measure the release of CO₂, it would be necessary to include another trap with a solution of NaOH. The information available in the literature regarding the NaOH trap, describes the decrease of the pH in the aqueous solution (Yoo et al., 2013; Kang et al., 2017; Krauß and Rzehak, 2017) as result of CO₂ absorption. The use of basic titrant is therefore required for quantification of NH₃ and CO₂ absorbed, and the differentiation of these compounds should be given by the type of trap that would be characterized. Figure 6 shows that the main compounds in the naturally precipitated salts from the brine and those promoted by means of adding an antisolvent (acetone) and cooling were CaCl₂ and CaCO₃. Generally, it is considered that the fingerprint region of the ATR-FTIR spectra goes from 1,000 to 2,000 cm⁻¹, with characteristic profile of the type of compound that allows the identification. The broad peak that can be seen for the precipitated salt and the CaCl₂, between the frequencies of 3,000 and 3,500 cm⁻¹, is associated with the O-H single bond stretch due to the presence of moisture in these hygroscopic samples. The N-H single bond stretch could be seen for the NH₄Cl between 2,750 and 3,250 cm⁻¹. The most relevant peak of the ATR-FTIR spectrum of the precipitated salt in relation to the

structure of the NH₄Cl was found at 1,380 cm⁻¹, and this bending vibration was marked with a vertical dashed line in Figure 6. This agrees with the results of the preliminary simulation (Supplementary Figure 1), in relation to the lower likelihood of the formation of NH₄Cl (Supplementary Figure 3), compared to that of the CaCO₃ (Supplementary Figure 2). Since the isolation of the NH₄Cl was found to be very complicated, the use of the filtered brine is more convenient as chemical amendment of untreated organic slurries, which also represent an additional supply of NH₄⁺-N. The results of the titration of the brine showed that 0.85 g NH₃ and 0.44 g CO₂ are trapped in each liter of brine and, since 8 L of filtered brine are meant to be applied to each tonne of untreated slurry, this represents a recirculation rate of 5.60 g NH₄⁺-N and 0.96 g CO₃²⁻-C per tonne of slurry. According to Lukehurst et al. (2010), the content of NH₄⁺-N in different types of organic slurry (i.e., dairy cow slurry, pig slurry, and anaerobic digestate) is 3 orders of magnitude greater than the supply derived from the CaCl₂ brine. Thereby, the addition of this chemical amendment for stabilization purposes should not prone NH₃ emissions that would be consequence of an excess of inorganic nitrogen in the slurry, but enrich the fertilization capacity of the organic slurry.

Another important outcome of the present investigation is to question the need for the solid-liquid separation via screw-press, if the granulation of the isolated solid fraction is implemented as part of the downstream processing. This is because very promising results were found for the use of the concentrated liquor as binding agent (Figure 4). The next step in the development of this processing route would be to determine whether drying the whole anaerobic digestate (which includes the liquor and the fibers) is sufficient to elaborate granules with the right mechanical properties or whether an addition of concentrated liquor is required to further increase the liquor-to-fibers ratio. While this interpretation is novel, the processing of the liquor alone to produce granular fertilizer has been already considered (Fivelman, 2013), hence the proposed strategy represents an enhancement of the valorization of the solid fraction that would come out of the screw-press. In a complex matrix with minerals, such as anaerobic digestate, there are many reactions that can be responsible of the self-hardening phenomena (Steenari and Lindqvist, 1997). The ratio of inorganic elements to organic matter is an important factor to optimize the mechanical properties of the pellets because the organic material acts as a sponge soaking the water that enables the reactions of self-hardening (Wróbel et al., 2016; Mudryk et al., 2018). Using lime as binding agent to benchmark the performance of the concentrated liquor is convenient since this material is employed to enhance the compressive strength of granules. Additionally, processing of whole digestate, fibers or liquor can be done by adding lime in the stabilization chamber to keep the pH above 12 for at least 2 h, to better control the biological activity in agreement with the regulations of the UK Government (2018). According to Pesonen et al. (2016), the main strength-providing reaction is the hydration of quicklime (CaO) to give slaked lime (Ca(OH)₂), while the subsequent carbonation gives limestone (CaCO₃) and provides further strength but this last reaction is very slow due to the limiting step of diffusion and absorption of CO₂ from the surrounding environment, depending on the conditions of storage and maturation of the pellets.

The recyclability of calcium is very high and these reactions can be easily reverted by incineration or calcination at sufficiently high temperatures (above 600°C) to enable the restoration of the oxide

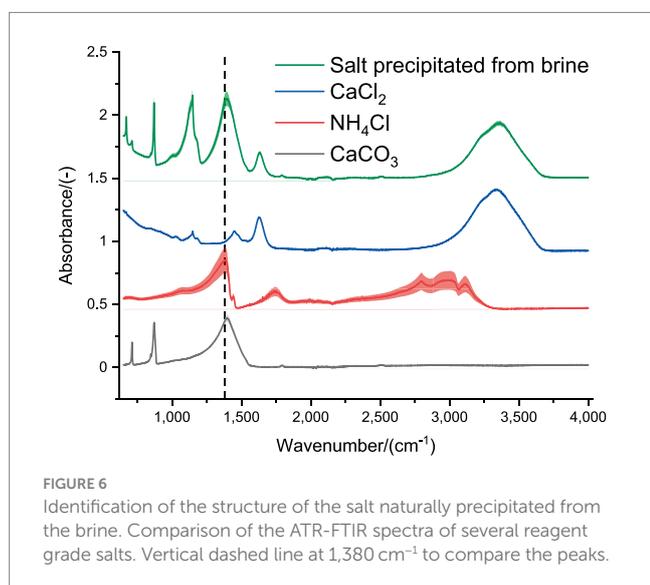


FIGURE 6 Identification of the structure of the salt naturally precipitated from the brine. Comparison of the ATR-FTIR spectra of several reagent grade salts. Vertical dashed line at 1,380 cm⁻¹ to compare the peaks.

form, due to the poor stability of the limestone and slaked lime that release CO₂ and H₂O (Sakthivel et al., 2012; Galan et al., 2013; Mor et al., 2016; Al-Mallahi et al., 2020). It is also important to highlight that the oxides are more alkaline than the hydroxides, and the latter compounds are also more alkaline than the carbonates. Thereby, aiming to increase the mechanical strength at shorter maturation times can harm the organic material by promoting hydrolysis, NH₃ volatilization, or even pH shock in soil and burning of crop tissues (Steenari and Lindqvist, 1997; Demeyer et al., 2001; Huotari et al., 2015; Pesonen et al., 2016; Belviso, 2018; Voshell et al., 2018; Bachmaier et al., 2021). For this reason, cured materials, which are less reactive, are often preferred for the formulation of granular fertilizers. As part of the present investigation, a granule was prepared with CaO as binding agent, and this specimen did not provide significantly different compressive strength to that of granules prepared directly with CaCO₃. This is likely because significant differences can only be seen at very short times of maturation for which the quicklime might be more suitable (e.g., 24 h), and these lime pellets were left drying in the fume hood for 10 days before the compression test. In any case, both the pellets of concentrated liquor and those of lime successfully achieved the minimum strength for granular fertilizer, which is around 50 N (Walker et al., 1997; Pesonen et al., 2016). Expressing the results of the compression test in N rather than in MPa is more convenient for granular fertilizers because the cross-sectional area does not remain constant in a sphere. In order to confirm the reproducibility of the mechanical properties found for the pellets prepared with the concentrated liquor, the procedure was repeated but using crystals of NH₄HCO₃ rather than the solid fiber, giving more homogenous granules, and subsequent allowing maturation for 4 weeks (Supplementary Figure 9). The results of the compression testing of these 2-cm diameter pellets of concentrated liquor and crystals of ammonium bicarbonate were ($n=8$) 198.57 ± 58.43 N and 0.94 ± 0.75 mm, which confirms the superior mechanical properties of the concentrated liquor as binding agent.

The organization of the activities was successful for the level of understanding of the A-level students. However, the briefing that was given to them at the beginning of the day was not as effective in generating an enthusiastic response as it was the opportunity of participating in the hands-on activities. For this reason, for the next edition of the didactic proposal, explanations will be spread throughout the day, just before and after carrying out the physical exercises. The team of students worked well with 3 members, but they could have taken more initiative in developing their intellectual property if they were competing against other groups. The students requested to expand the primary market research to have the chance of interviewing more potential clients, to hear the point of view of more stakeholders of agroindustry, and to further clarify the current situation. This pedagogic intervention was useful to develop the skills of students that were not initially planned, such as some aspects of their environmental competence (Al-Balushi and Al-Aamri, 2014). The students were reluctant to perform the manual granulation (Supplementary Figure 9), giving the opportunity for discussion about the composition of the soil, which is also composed by a large extent of stabilized organic matter, as they could observe in a visit that was made to the nearest field. Also, the technique of manual granulation was explained to them as the traditional preparation of seed balls, which was developed by Masanobu Fukuoka for no-till planting (Helliwell, 1980; Paudel and Belo, 2017; Hannur, 2019;

Tamilarasan et al., 2021; Parmar, 2022), and how this can be improved with the inoculation of microbial species (biofertilizers) during the granulation process (Jewiarz et al., 2018) to further enhance germination and sprouts. This conscientization process that every citizen should undergo, in terms of comprehending the role of organic matter and even some of the organic wastes that they generate throughout their daily life, is therefore ameliorated with this didactic activity, which is in line with other outreach events promoted by the British Society of Soil Science (2022), for example, *Dirty matters: The soil game*. The present didactic intervention could be improved by providing the students with a glossary in the first session, which would define all strange and ambiguous terms that are not part of the normal vocabulary (e.g., liquor, equivalents of acid, etc.). This would allow to minimize extrinsic difficulties of language, which are associated with the way in which the activities are presented to secondary education students. Nevertheless, what made this educational tool more effective in reaching the target audience was the observation of the physical phenomena of deliquescence of the anhydrous salts and the self-hardening of the pellets (Supplementary Figure 9). Intrinsic difficulties are inherent to the topic but could be solved with, for example, modeling with the kinetic molecular theory (Stern et al., 2008) the transfer of moisture from the stabilization tank to the condenser. In this way, students could have an interpretation of the important role of temperature and turbulence for the gas in the headspace to be in touch with solid and liquid phases of the 2 chambers of the artifact.

5 Conclusion

This investigation on the performance of the novel technology for processing organic slurry concluded that the operation capacity of the prototype was 5 L of liquor every 24 h or 2 t of slurry per year. Since approximately 2 t of CaCl₂ brine are produced per year, with a composition of around 10 M and the use of this fluid as chemical amendment requires 0.08 M CaCl₂ upon mixture with the slurry, a single prototype was deemed suitable for treating 250 t at a cost of £1/t of slurry. The results of the titration of the brine showed that 0.85 g NH₃ and 0.44 g CO₂ are trapped in each liter of filtered brine and, since 8 L of brine are meant to be applied to each tonne of untreated slurry, this represents a recirculation of additional 5.60 g N-NH₄⁺ and 0.96 g C-CO₂ per tonne of slurry.

This study questions whether the solid-liquid separation via screw press should be disregarded as best practice for handling organic slurry, if the subsequent processing of the fibers would be the granulation step. The use of the concentrated liquor as binding agent gave very promising results for the granulation of the fiber, since the liquor granules attained 207.00 ± 26.36 N, which was more than the lime granules (111.84 ± 15.44 N) and more than the threshold value that is generally required for commercialization of the pellets (50 N). A lower degree of deformation of the granules before fracture formation was also observed in the liquor granules (4.07 ± 1.33 mm), compared to the lime granules (6.09 ± 1.43 mm).

The flexible model for the commercialization of the environmental technology in the farming and educational sectors was considered suitable for this first edition of the PBL activity (*Make it happen!*). The advances in the development of the prototype and the expansion of the network of contacts enhanced

the adoption of the technology in industry but hindered the application of subsequent editions of this PBL activity on slurry management in secondary educational institutions. This is because the future activities planned for the different sessions are hard to be conceived as a way of contextualizing the syllabus, aiming to improve the very basic foundations of science and environmental awareness that are required to be an active member of society. For example, the students found difficult to understand the titrimetric method to determine the amount of NH_3 and CO_2 absorbed in the brine, hence establishing the calibration curve to determine the efficiency of the absorption process in the artifact and compare it with the traditional static chamber method needs to be carefully planned.

Data availability statement

The datasets generated for this study can be found in the ZENODO repository: <https://doi.org/10.5281/zenodo.8427906>, <https://doi.org/10.5281/zenodo.10535943>.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/ next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

AMA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JR: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2024.1321353/full#supplementary-material>

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