



Localized Delivery of Liquid Fertilizer in Coarse-Textured Soils Using Foam as Carrier

Mohammad Javad Shojaei¹ · Dani Or^{2,3} · Nima Shokri⁴ 

Received: 19 October 2021 / Accepted: 10 June 2022 / Published online: 30 June 2022
© The Author(s) 2022

Abstract

Agrochemicals and fertilizers are central to modern agriculture and are credited with the large increase of crop yield as a part of the Green Revolution of the 1960's. Timely and targeted fertilizer application to crop root zones enhances effectiveness and reduces unintended release to the environment. This is particularly important for highly mobile liquid fertilizers (e.g., nitrate) that can be mobilized with infiltrating water to bypass root-bearing soil volumes. We report a novel liquid fertilizer delivery method using foam as carrier. The high degree of control and mechanical stability of liquid fertilizer foam (defined dispersed gas bubbles in a continuous liquid phase) injection into coarse soils (most susceptible to preferential flows) is proposed a novel delivery method to targeted root zone volumes at concentrations and geometry that promote uptake and reduces losses. This note and preliminary communication meant to serve a proof of concept report comparing foam and conventional liquid fertilizer applications. The results indicate that foam-delivery reduced fertilizer leaching thus improving its retention in soil for similar flow conditions of liquid delivery. Theoretical estimates suggest that the effects of fertilizer retention could be enhanced in more localized (3-D) injection of foam fertilizers and other agrochemicals thus enhancing agronomic efficiency and reducing environmental risk of contamination.

1 Introduction

Agricultural activity is one of the largest sources of water pollution (Mateo-Sagasta, Zadeh et al. 2018). The global growth of crop production heavily depends on the intensive use of chemical fertilizers, such that fertilizer consumption has increased tenfold worldwide since the 1960s (Mateo-Sagasta, Zadeh et al. 2018). This intense level of fertilizer application leads to fertilizer leaching, which is one of the main sources of

✉ Nima Shokri
nima.shokri@tuhh.de

¹ School of Biological and Behavioural Sciences, Queen Mary University of London, London, UK

² Division of Hydrologic Sciences, Desert Research Institute, Reno, NV, USA

³ Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland

⁴ Institute of Geo-Hydroinformatics, Hamburg University of Technology, Am Schwarzenberg-Campus 3 (E), 21073 Hamburg, Germany

groundwater pollution. Annually, the costs of agricultural pollution surpass billions of dollars. For example, a national investigation in the USA found that agricultural nitrogen pollution has an annual cost in the range of US\$59–US\$340 billion (Mateo-Sagasta, Zadeh et al. 2018). This cost is in the range of €35–€230 billion per year in the European Union (Mateo-Sagasta, Zadeh et al. 2018). These figures illustrate the importance of devising innovative and more effective approaches for fertilizer application.

Following surface application of fertilizers, their downward transport with percolating water is essential for their introduction to root zones. However, transported too rapidly to larger depths below the reach of roots reduces their efficiency and may pose various environmental hazards (Kronvang et al. 1999, Hanna, White et al. 2001, Lehmann and Schroth 2003, Maharjan and Venterea 2014). Agricultural fertilizer leaching is known to pollute groundwater, reduce soil productivity, damages aquatic ecosystems, and indirectly impact human health. The World Health Organization (WHO) considers rising nitrate concentrations in water resources a threat in many European countries. For example, in the UK, an average annual increase of 0.7 mg/l has been observed, with concentrations nearly doubling over the past 20 years in some regions. High levels of nitrate in drinking water can disrupt the blood's ability to carry oxygen and cause methemoglobinemia (Johnson 2019). Recent findings have shown potential relationship between a high level of nitrate/nitrite in the body to other health effects such as increased heart rate, nausea, headaches, and abdominal cramps (WHO). Eutrophication caused by the accumulation of nutrients in water can also change the aquatic ecosystem (Ngatia, Grace III et al. 2019). Enriched nutrients in surface water bodies are potential for algae blooms (Pedersen and Borum 1996) that adversely affect aquatic life and water quality (Roy, Finck et al. 2006).

A variety of agronomic practices have been developed to enhance the efficiency of fertilizer application and reduce leaching to the environment. These include amounts and timing of fertilizer application (management) and delivery methods in liquid or solid forms close to crop row or direct injection to the crop root zone (Goh, Härdter et al. 2003, Lehmann and Schroth 2003; Kramer et al. 2006). Here, we propose a novel method for improving the efficiency of liquid fertilizer delivery to crops using foam as a carrier through utilization of its unique characteristics and hydrodynamic stability (Fig. 1).

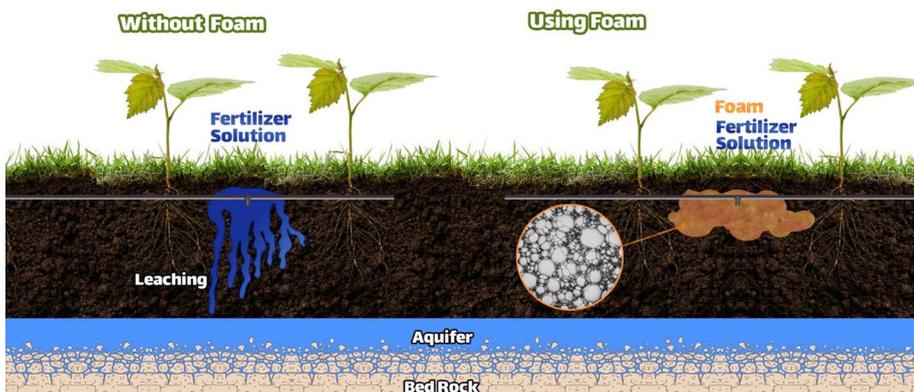


Fig. 1 Foam as a potential vehicle for fertilizer delivery in soil to reduce leaching rate

Foam is defined as dispersed gas bubbles within a continuous liquid phase. Foam exhibits an apparent viscosity of a few orders of magnitude higher than its constituent gas and liquid in porous media, leading to well-defined displacement fronts and low mobility (Shojaei et al. 2018a, b; Shojaei et al. 2018a, b). The low density of foam reduced susceptibility for gravity-induced mobilization and leaching and ensures large volumes for interactions with roots and soil surfaces (Shen et al. 2011). Shen et al. (Shen et al. 2011) have used foam as a carrier to deliver nanoparticles for vadose zone remediation. They observed the fractions of nanoparticles in the soil column were much higher when the particle-laden foam was injected through the columns compared to direct injection of the water suspensions (Shen et al. 2011). Maire et al. (Maire et al. 2019) investigated the targeted delivery of hydrogen for aquifers' bioremediation using foam. They injected H₂ either alone, or as foam, in a 2D saturated cell packed with glass beads. Their results showed that foam retained greater volumes of H₂ gas (3.5 times higher than traditional biosparging). The retained foamed-gas persistently lowered relative permeability of water by 1.7 to 5 times, reducing contaminant diffusion to groundwater (Maire et al. 2019). Other studies have shown the potential of foam for targeted delivery in porous media and improve sweep efficiency by reducing downward flow of the solution (Hirasaki, Hughes et al. 2005, Zhong et al. 2011, Ding et al. 2013, Davarzani, Colombano et al. 2015, Maire et al. 2015, Portois et al. 2018a, b). Foam has also been used for delivering other agrochemicals such as pesticide (Tiernan and Woogerd 1994; Howe 2004), herbicide (Monaghan and Line 1998; Lampe 2016), and also for drug delivery (Purdon et al. 2003; Tamarkin et al. 2006; Shinde et al. 2013).

The use of foamed liquid fertilizer makes use of readily available liquid fertilizer delivered to targeted soil volumes without reliance on infiltrating water for transport to the roots. Although foam bubbles are thermodynamically unstable, they remain stable for months or years (Shojaei, Méheust et al. 2021). For example, foam has been proposed for CO₂ sequestration efforts that require stability of the gas bubbles over extended periods (how long?) [30]. Stable foam offers control over fertilizer placement, while offering prescribed local concentrations (favoring root uptake of nitrate). Moreover, its application is agrotechnically feasible using methods similar to anhydrous ammonia injection into soil (without the risk of direct volatilization, adsorption, and transformations (Sommer 1997, Sommer and Jacobsen 1999)).

Agronomic and environmental considerations and technological advances make the use of foam as a potential carrier for fertilizer (and other agrochemicals) feasible and promising. Foam generation requires the use of gas injection into aqueous for emulsification (Shojaei, de Castro et al. 2019) using advanced surfactants to improve adsorption efficiency (Li 2003; Bansiwala et al. 2006; Huang et al. 2019). To evaluate the potential efficacy of foam as a carrier for targeted fertilizer delivery in soil, we performed two sets of experiments, applying commercially available fertilizers to the soil column with foam and without foam.

2 Materials and Methods

Leaching experiments (Maguire and Sims 2002; Kalbe et al. 2014) were conducted in soil columns made of acrylic cylinders of 30 cm height and 4 cm diameter. Similar leaching experiments in soil columns have been performed and reported in the literature (Misra et al. 1974; Wehrhan et al. 2007; Ding et al. 2010; Meza et al. 2010, Zaheer, Wen et al. 2017). Bottom of the column was covered with a stainless steel mesh with

40- μm opening size to prevent soil loss. Levington John Innes soil (Evergreen Garden Care (UK) Limited) which is a commercial soil was used in the leaching experiments. Before the experiments, soil was sieved through a 710 μm mesh. The elemental composition of the study soil is presented in.

OMEX 30 N, which contains 50% urea-N, 25% ammonium-N and 25% nitrate-N was used as fertilizer and WATER MAX was used as a surfactant agent both provided by OMEX Company in the UK. The volume concentration of surfactant in the solution was chosen 10%. Foam was generated by injecting compressed air and OMEX 30 N/WATER MAX solution simultaneously into a foam generator fitted with a sintered disk (Scientific Glass, UK). The gas flow rate was controlled using a mass flow controller (Bronkhorst, UK) connected to a computer. The digital mass flow controller was operated through a computer to inject gas at a constant rate of 10 ml/min, using FlowDDE and FlowView (Bronkhorst, UK) as the interface and the operating platform, respectively. The surfactant solution was injected using a syringe pump (Harvard Apparatus, USA) at varying flow rates to achieve the required foam quality. The quality of foam in all the experiments was fixed to 80%. Foam quality is the ratio of gas volume to foam volume (gas + liquid).

The schematic of the experimental setup is depicted in Fig. 2a.

Studies show leaching could happen in both dry and wet soil, but it is higher in the later one (Sommer and Christensen 1992). We performed the leaching experiments in six columns filled with wet soil. Hence, in terms of the experiments, two pore volumes of deionized water were added to each column each day for three days and then left for another three days for water drainage. Then, 20 ml of fertilizer and surfactant were added to three columns directly as a liquid solution and into three other columns as foam each day for five days. At the end of the experiments, 50 ml of deionized water was added to each column each day for another three days. All the leachate samples were collected from the outlet and at the bottom of the columns every 24 h. Figure 2b shows a flowchart demonstrating the steps taken to conduct the leaching experiments.

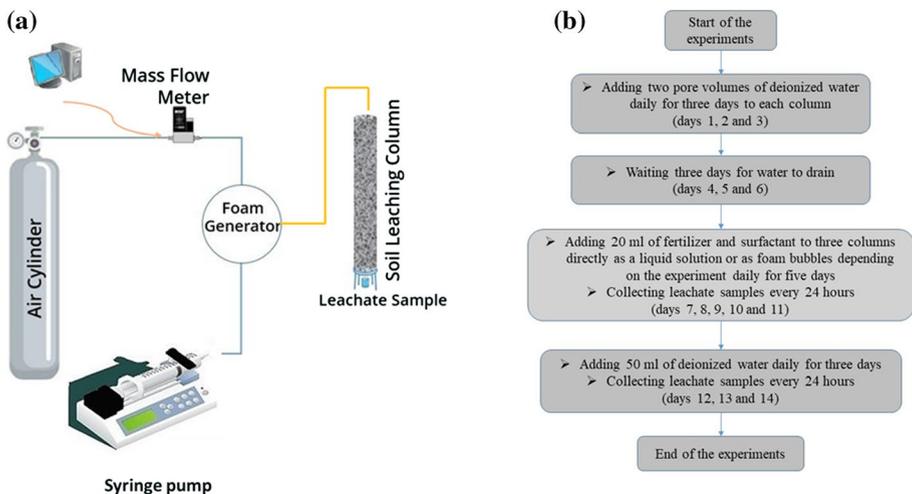


Fig. 2 **a** Schematic design of the experimental setup used in this study to evaluate foam performance as a carrier for fertilizer delivery in soil. **b** The experimental procedure followed to conduct the leaching experiments

Autoanalyzer, ICP, and electric conductivity tests were performed on the leaching samples. For electric conductivity test, as the concentration of the solution was above the detection level of the kit, 5 ml of the leachate was diluted with 20 ml of water (reverse osmosis water). Then, the electric conductivity meter was dipped into the solution, the probe was rinsed with reverse osmosis water after each sample and the reading in mS was recorded.

3 Results and Discussion

Figure 3 shows the elemental composition of the leaching samples measured by AutoAnalyzer.

Figure 3 shows the breakthrough of fertilizer in the soil column occurred one day earlier when applied using foam. This is due to foam having a larger volume than the solution itself which reaches the outlet earlier. However, the subsequent leaching solutions had fewer fertilizer components when applied using foam suggesting a higher fertilizer retention in soil. The transport of the fertilizer in soil is influenced by the gravity and preferential flow paths. Foam bubbles have a lower density that makes them less susceptible to gravity and hence leaching. Also, foam bubbles have less downward mobility that reduce the chance of preferential flow paths in the soil column and provides better uniformity of contact between the fertilizer and soil and a higher adsorption rate.

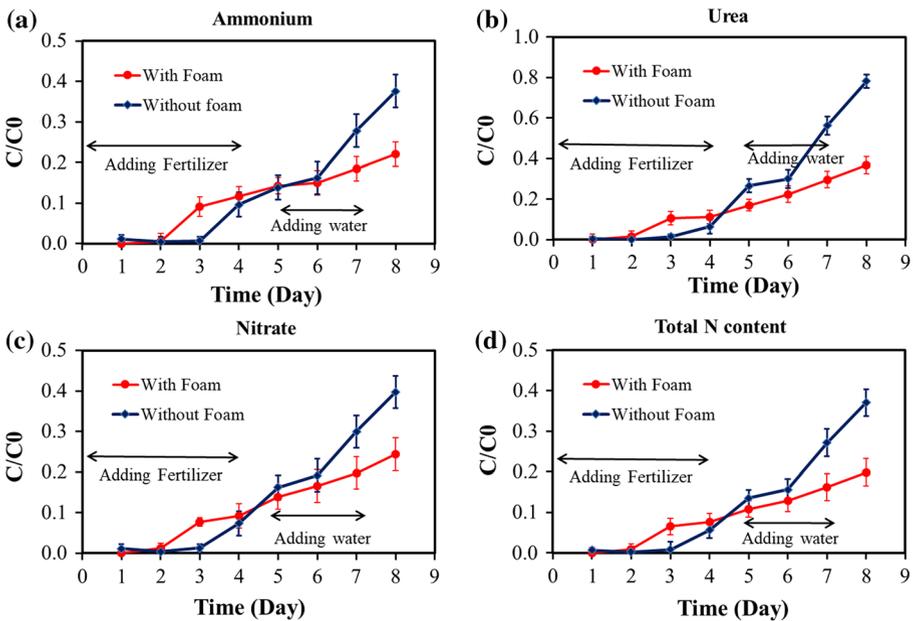


Fig. 3 a–d show the variation of the concentration (C) of Ammonium, Urea, Nitrate and total N content with respect to the initial concentration (C₀) over time, respectively. Total N content is the summation of Ammonium, Urea, and Nitrate. These results were obtained using Autoanalyzer and ICP tests. The initial fertilizer solution contained 8.8, 8.3, 8.7, and 35.8 w % of Ammonium, Urea, Nitrate and total N content, respectively

In our investigations, we considered the application of liquid fertilizer which is influenced by the occurrence of preferential liquid pathways limiting its efficiency (Jiao et al. 2004; Grant et al. 2019). Gravity-driven fertilizer dropout is ubiquitous in coarse-textured soil, and also fertilizer can quickly reach to the shallow water tables (Bonczek and McNeal 1996). As foam has a lower density and higher viscosity, it can control the transport of fertilizer in soil and reduce the leaching rate. Investigation of foam flow in porous media for other applications showed foam has an excellent ability to reduce the mobility of fluid at high permeability pathways specially in coarse-textured soil (Needham 1968; Islam and Ali 1988; Portois et al. 2018a, b). Therefore, the proposed delivery method would be most suitable for coarse-textured soils and shallow water tables where leaching is critical (Table 1).

Foam injection and flow in soil are common in remediation practices [42]. The same approach could be potentially used to inject and deliver fertilizer based in foam to the root zone in soil. Moreover, subsurface drip irrigations are becoming more popular in the agricultural industry due to their high water application efficiency. Those tools and facilities could be used to deliver fertilizer based in foam to the root zone effectively. Also, fertilizer based in foam might be injected to the root zone at a given depth using a perforated rod (He et al. 2018) or from the surface by disk permeameter (Perroux and White 1988).

4 Summary and Conclusions

Fertilizer leaching is caused by gravity fingering associated with the density contrast between the soluble fertilizer and the air in the pore space (Gächter et al. 1998; Kalkhajeh et al. 2021). Heterogeneity in the soil aggravates this effect by channeling the applied fertilizer through the medium to large pores within the soil matrix (meso and macro-pores), and leaving the root zone behind (Addiscott and Bland 1988). In high rainfall areas, fertilizers can also easily be leached into the groundwater and washed into waterways via surface runoff (Grant et al. 2019). The intensive fertilizer application leads to nutrient leaching, resulting in underground water pollution, damage to aquatic ecosystems, and environment. Nitrate concentrations in groundwater from fertilizers have steadily increased in many European countries in the last few decades and have doubled over the past 20 years in several places. In the UK, the range of nitrate concentration is between 2 mg/l and greater than 50 mg/l with an average annual increase of 0.7 mg/l in some areas. This compares to the World Health Organization (WHO) recommended a maximum of 10 mg/l nitrate concentration in drinking water. Studies have shown strong associations between a high level of nitrate/nitrite in the body and adverse health effects.

Fertilizer leaching in soil is common in certain climates and soil types leading to reduced fertilizer efficiency and poses contamination risk to ground and surface water resources. Fertilizer leaching rates are dependent on a number of factors including the structure and properties of soil and fertilizer mobility and other properties. In agriculture, certain methods have been devised to control fertilizer mobility in soil. This technical note

Table 1 Elemental composition and concentrations in the study soil obtained by Inductively Coupled Plasma (ICP) test in mg/l

P	K	Mg	B	Na	S	Ca	Cu	Fe	Mn	Mo	Zn
58	426	521	6.4	82	176	3267	4.5	273.8	11.37	0.16	4.96

and preliminary communication meant to serve as a proof of concept study offering a novel approach to control fertilizer delivery. Within this context, we investigated foam's potential as a carrier for fertilizer delivery to manage and decrease the leaching rate. We observed reduced leaching of nutrients when the fertilizer was applied to the soil column using foam. This study could pave the road for designing new fertilizer based in foam with a high retention capacity to address the leaching issue in soil especially in coarse-textured areas in the world such as coastal regions which suffer from high leaching rates (Sexton, Moncrief et al. 1996, Nyamangara et al. 2003). Different methods can be followed to apply this new novel method on a large scale. Different methods can be followed to apply this novel method on a large scale. Foam injection is common in soil remediation practices (Wang and Mulligan 2004). The same approach could be used to inject and deliver foam-based fertilizer to the root zone in soil. Subsurface drip irrigation systems that are widely used, for instance, for growing maize, due to their high water delivery efficiency, could also be used for foam injection into the root zones in soil (Camp 1998).

Acknowledgements We would like to acknowledge David Booty and Andy Eccles from Omex Agricultural Holdings Limited Company for providing us with OMEX 30N, and WATER MAX used in this study and performing Autoanalyzer & ICP tests on the leaching samples. The leaching experiments were conducted at The University of Manchester.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflicts of interests The authors have no relevant financial or non-financial interests to disclose.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Addiscott, T., Bland, G.: Nitrate leaching models and soil heterogeneity. *Nitrogen Eff. Agric. Soils*: 394–408 (1988)
- Bansiwala, A.K., Rayalu, S.S., Labhasetwar, N.K., Juwarkar, A.A., Devotta, S.: Surfactant-modified zeolite as a slow release fertilizer for phosphorus. *J. Agric. Food Chem.* **54**(13), 4773–4779 (2006)
- Bonczek, J., McNeal, B.: Specific-gravity effects on fertilizer leaching from surface sources to shallow water tables. *Soil Sci. Soc. Am. J.* **60**(4), 978–985 (1996)
- Camp, C.: Subsurface drip irrigation: A review. *Trans. ASAE* **41**(5), 1353 (1998)
- Davarzani, H., Colombano, S., Fatin-Rouge, N., Joubert, A., Cazaux, D.: Modeling of the foam injection in porous media: application to treatment of the polluted soils. 7th International Conference on Porous Media & Annual Meeting (2015)
- Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M., Zhong, Z.-K.: Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water Air Soil Pollut.* **213**(1), 47–55 (2010)
- Ding, Y., Liu, B., Shen, X., Zhong, L., Li, X.: Foam-assisted delivery of nanoscale zero valent iron in porous media. *J. Environ. Eng.* **139**(9), 1206–1212 (2013)

- Gächter, R., Ngatiah, J.M., Stamm, C.: Transport of phosphate from soil to surface waters by preferential flow. *Environ. Sci. Technol.* **32**(13), 1865–1869 (1998)
- Goh, K.-J., Hårdter, R., Fairhurst, T.: Fertilizing for maximum return. *Oil Palm: Management for large and sustainable yields: 279–306* (2003)
- Grant, K.N., Macrae, M.L., Rezanezhad, F., Lam, W.V.: Nutrient leaching in soil affected by fertilizer application and frozen ground. *Vadose Zone J.* **18**(1), 1–13 (2019)
- Hanna, H. M., White, M. L., Baker, J. L.: Improving the uniformity of anhydrous ammonia application (2001)
- He, S., Yu, X., Banerjee, A., Puppala, A.J.: Expansive soil treatment with liquid ionic soil stabilizer. *Transp. Res. Rec.* **2672**(52), 185–194 (2018)
- Hirasaki, G. J., Hughes, J. B., Miller, C. A.: Foam delivery of hydrogen for enhanced aquifer contacting and anaerobic bioremediation of chlorinated solvents. *Rice Univ Houston Tx* (2005)
- Howe, M. F.: Foam generator, foamable pesticide, and method, Google Patents (2004)
- Huang, Z., Cheng, C., Liu, Z., Feng, B., Hu, Y., Luo, W., He, G., Yu, X., Fu, W.: Highly efficient potassium fertilizer production by using a gemini surfactant. *Green Chem.* **21**(6), 1406–1411 (2019)
- Islam, M. R., Ali, S. M.: Numerical simulation of foam flow in porous media. In *Annual Technical Meeting. OnePetro* (1988)
- Jiao, Y., Hendershot, W.H., Whalen, J.K.: Agricultural practices influence dissolved nutrients leaching through intact soil cores. *Soil Sci. Soc. Am. J.* **68**(6), 2058–2068 (2004)
- Johnson, S.F.: Methemoglobinemia: Infants at risk. *Curr. Probl. Pediatr. Adolesc. Health Care* **49**(3), 57–67 (2019)
- Kalbe, U., Bandow, N., Bredow, A., Mathies, H., Piechotta, C.: Column leaching tests on soils containing less investigated organic pollutants. *J. Geochem. Explor.* **147**, 291–297 (2014)
- Kalkhajah, Y.K., Huang, B., Hu, W.: The relation of preferential flow pathways to phosphorus leaching from typical plastic shed vegetable production soils of China. *Agr. Ecosyst. Environ.* **307**, 107218 (2021)
- Kramer, S.B., Reganold, J.P., Glover, J.D., Bohannan, B.J., Mooney, H.A.: Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils. *Proc. Natl. Acad. Sci.* **103**(12), 4522–4527 (2006)
- Kronvang, B., Hoffmann, C.C., Svendsen, L.M., Windolf, J., Jensen, J.P., Dørgé, J.: Retention of nutrients in river basins. *Aquat. Ecol.* **33**(1), 29–40 (1999)
- Lampe, J. K.: Dispenser for Dispensing Foam such as Foam Herbicides, Google Patents (2016)
- Lehmann, J., Schroth, G.: Nutrient leaching. *Trees, Crops and Soil Fertility*, CABI Publishing, Wallingford: 151–166 (2003)
- Li, Z.: Use of surfactant-modified zeolite as fertilizer carriers to control nitrate release. *Microporous Mesoporous Mater.* **61**(1–3), 181–188 (2003)
- Maguire, R.O., Sims, J.T.: Soil testing to predict phosphorus leaching. *J. Environ. Qual.* **31**(5), 1601–1609 (2002)
- Maharjan, B., Venterea, R.T.: Anhydrous ammonia injection depth does not affect nitrous oxide emissions in a silt loam over two growing seasons. *J. Environ. Qual.* **43**(5), 1527–1535 (2014)
- Maire, J., Coyer, A., Fatin-Rouge, N.: Surfactant foam technology for in situ removal of heavy chlorinated compounds-DNAPLs. *J. Hazard. Mater.* **299**, 630–638 (2015)
- Maire, J., Davarzani, H., Colombano, S., Fatin-Rouge, N.: Targeted delivery of hydrogen for the bioremediation of aquifers contaminated by dissolved chlorinated compounds. *Environ. Pollut.* **249**, 443–452 (2019)
- Mateo-Sagasta, J., Zadeh, S. M., Turrall, H.: More people, more food, worse water?: a global review of water pollution from agriculture (2018)
- Meza, S.L., Kalbe, U., Berger, W., Simon, F.-G.: Effect of contact time on the release of contaminants from granular waste materials during column leaching experiments. *Waste Manage.* **30**(4), 565–571 (2010)
- Misra, C., Nielsen, D., Biggar, J.: Nitrogen Transformations in Soil During Leaching: III. Nitrate Reduction in Soil Columns. *Soil Sci. Soc. Am. J.* **38**(2), 300–304 (1974)
- Monaghan, J. D., Line, K.: Apparatus for generating and dispersing foam herbicide within a sewer, Google Patents (1998)
- Needham, R. B.: Plugging high permeability earth strata, Google Patents (1968)
- Ngatia, L., Grace III, J. M., Moriasi, D., Taylor, R.: Nitrogen and phosphorus eutrophication in marine ecosystems. *Monitoring of Marine Pollution: 1–17* (2019)
- Nitrate and nitrite in drinking-water Background document for development of WHO Guidelines for Drinking-water Quality
- Nyamangara, J., Bergström, L., Piha, M., Giller, K.: Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. *J. Environ. Qual.* **32**(2), 599–606 (2003)

- Pedersen, M.F., Borum, J.: Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae. *Mar. Ecol. Prog. Ser.* **142**, 261–272 (1996)
- Perroux, K., White, I.: Designs for disc permeameters. *Soil Sci. Soc. Am. J.* **52**(5), 1205–1215 (1988)
- Portois, C., Boeije, C.S., Bertin, H.J., Atteia, O.: Foam for environmental remediation: generation and blocking effect. *Transp. Porous Media* **124**(3), 787–801 (2018a)
- Portois, C., Essouayed, E., Annable, M.D., Guiserix, N., Joubert, A., Atteia, O.: Field demonstration of foam injection to confine a chlorinated solvent source zone. *J. Contam. Hydrol.* **214**, 16–23 (2018b)
- Purdon, C.H., Haigh, J.M., Surber, C., Smith, E.W.: Foam drug delivery in dermatology. *Am. J. Drug Deliv.* **1**(1), 71–75 (2003)
- Roy, R.N., Finck, A., Blair, G., Tandon, H.: Plant nutrition for food security A guide for integrated nutrient management. *FAO Fertil. Plant Nutr. Bull.* **16**, 368 (2006)
- Sexton, B., Moncrief, J., Rosen, C., Gupta, S., Cheng, H.: Optimizing nitrogen and irrigation inputs for corn based on nitrate leaching and yield on a coarse-textured soil, Wiley Online Library (1996)
- Shen, X., Zhao, L., Ding, Y., Liu, B., Zeng, H., Zhong, L., Li, X.: Foam, a promising vehicle to deliver nanoparticles for vadose zone remediation. *J. Hazard. Mater.* **186**(2–3), 1773–1780 (2011)
- Shinde, N.G., Aloorkar, N.H., Bangar, B.N., Deshmukh, S.M., Shirke, M.V., Kale, B.B.: Pharmaceutical foam drug delivery system: General Considerations. *Indo Am. J. Pharm. Res* **3**, 1322–1327 (2013)
- Shojaei, M.J., Osei-Bonsu, K., Grassia, P., Shokri, N.: Foam flow investigation in 3D-printed porous media: fingering and gravitational effects. *Ind. Eng. Chem. Res.* **57**(21), 7275–7281 (2018a)
- Shojaei, M.J., Osei-Bonsu, K., Richman, S., Grassia, P., Shokri, N.: *Ind. Eng. Chem. Res.* **58**(2), 1068–1074 (2018b)
- Shojaei, M.J., de Castro, A.R., Méheust, Y., Shokri, N.: Dynamics of foam flow in a rock fracture: Effects of aperture variation on apparent shear viscosity and bubble morphology. *J. Colloid Interface Sci.* **552**, 464–475 (2019)
- Shojaei, M. J., Méheust, Y., Osman, A., Grassia, P., Shokri, N.: Combined effects of nanoparticles and surfactants upon foam stability. *Chem. Eng. Sci.* 116601 (2021)
- Sommer, S.: Ammonia volatilization from farm tanks containing anaerobically digested animal slurry. *Atmos. Environ.* **31**(6), 863–868 (1997)
- Sommer, S., Christensen, B.: Ammonia volatilization after injection of anhydrous ammonia into arable soils of different moisture levels. *Plant Soil* **142**(1), 143–146 (1992)
- Sommer, S., Jacobsen, O.: Infiltration of slurry liquid and volatilization of ammonia from surface applied pig slurry as affected by soil water content. *J. Agric. Sci.* **132**(3), 297–303 (1999)
- Tamarkin, D., Friedman, D., Shemer, A.: Emollient foam in topical drug delivery. *Expert Opin. Drug Deliv.* **3**(6), 799–807 (2006)
- Tiernan, B. H., Woogerd, S. M.: Method for controlling pests by a pesticidal foam, Google Patents (1994)
- Wang, S., Mulligan, C.N.: An evaluation of surfactant foam technology in remediation of contaminated soil. *Chemosphere* **57**(9), 1079–1089 (2004)
- Wehrhan, A., Kasteel, R., Simunek, J., Groeneweg, J., Vereecken, H.: Transport of sulfadiazine in soil columns—experiments and modelling approaches. *J. Contam. Hydrol.* **89**(1–2), 107–135 (2007)
- WHO "Nitrate and nitrite in drinking-water " WHO/SDE/WSH/07.01/16/Rev/1.
- Zaheer, M., Wen, Z., Zhan, H., Chen, X., Jin, M.: An experimental study on solute transport in one-dimensional clay soil columns. *Geofluids* (2017)
- Zhong, L., Szecsody, J., Oostrom, M., Truex, M., Shen, X., Li, X.: Enhanced remedial amendment delivery to subsurface using shear thinning fluid and aqueous foam. *J. Hazard. Mater.* **191**(1–3), 249–257 (2011)