Challenges and Potential Solutions to Improve Fertilizer Use Efficiency and Reduce Agricultural GHG Emissions

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Introduction

The Canadian government in April 2021 announced C$200 million for 2021-23 to launch immediate, on-farm climate action under the Agricultural Climate Solutions program to target, among other things, projects accelerating greenhouse gas (GHG) emission reductions by improving nitrogen management. Recent work offers some insights into early priorities for those resources.

Nitrogen (N) availability is the primary limiting nutrient to sustain crop yield and quality after carbon, hydrogen and oxygen. It plays a fundamental role in the biochemical and physiological functions of the plant.[1,2] Consequently, nitrogen fertilizer application has become an indispensable and unavoidable part of crop production systems, helping to provide adequate food and nutritional security for the world's growing population. During recent decades, a tremendous amount of N fertilizers has been applied to agricultural lands to promote crop production worldwide. Globally, the amount of nitrogen use increased by more than 80% over the period 1980 to 2018 (FAO, 2021). This increase is expected to continue as a result of the growing demand for food, feed, and fibre (Tian et al., 2020).

Despite its many benefits, N utilization comes at an environmental cost. The loss of N from agriculture has resulted in a major deleterious environmental impact, including an increase in nitrous oxide (N_2O) – a GHG and important catalyst of stratospheric ozone depletion – soil acidification and fertility deficiency, as large-scale, long-term fertilizer use significantly alters soil nutrient balance. Moreover, N utilization can result in off-site pollution of the air, groundwater and waterways (Kumar, 2001; Yang, 2006).[3] Over the past 150 years, increasing N_2O emissions have contributed to stratospheric ozone depletion at 2 percent per decade. While little of the nitrogen applied is converted to N_2O emission (typically, 0.5% to 3% of nitrogen added to soil is released as N_2O emission), this emission generally represents a large percentage of the total GHG emissions in the crops sector, since N_2O has 310 times the global warming potential of CO_2 (IPCC, 2007; Bouwman et al., 2002).

[1] Among the different types of N fertilizer, anhydrous ammonia contains the highest concentration of N (N>80%) (Kaag and Krishnamurthy, 2010).
[2] Compared to other fertilizers such as phosphorus and potassium, nitrogen is widely used in the Canadian Prairies as it is considered the most important nutrient to improve a plant's biochemical and physiological functions, proper plant growth and development and improvement in yield quantity and quality. Therefore, Due to its importance, this study focuses only on the use of fertilizer nitrogen.
[3] To mitigate the environment consequences of fertilizers, energy efficient innovations and less CO_2 emitting methods to manufacture fertilizers are needed.

On the Canadian Prairies, N_2O emissions from fertilizer application increased by more than 100% between 1985 and 2016 – in Alberta, N_2O emissions increase by 61%, in Saskatchewan nearly threefold, and in Manitoba by 71% (Awada et al., 2020; 2019).[4] This increase was driven by intensified crop production by means of increased crop rotation and reduced summerfallow, which required the greater use of fertilizer. In Alberta, the amount of nitrogen used increased by 91% over the period of 1985 to 2016, while crop production increased by 117% over the same period. In Saskatchewan, the use of fertilizer increased 98%, while crop production increased by 61% over the same period. In Manitoba, fertilizer use increased 77% and crop production increased by 26% (Statistics Canada Fertilizer Shipments, CANSIM 001-0068; Statistics Canada CANSIM 001-0017 (1985–2016)).

It has been widely reported that fertilizer nutrient use efficiency (NUE) by crops is low, ranging between 25% and 50% depending on the crop, environmental conditions, and management practices (Hofmann et al., 2020; Herrera et al., 2016). The NUE is the product of two main components: nutrient uptake efficiency and utilization efficiency. The nutrient uptake efficiency is the ability of plants to take up nutrient from the soil, while nutrient utilization efficiency describes the capability of plants to assimilate and remobilize nutrient within the plant (Anas et al., 2020). Excessive and inefficient use of N fertilizer causes a significant amount of the applied N to be lost to the environment via nitrification, denitrification, leaching, and volatilization (Chien et al., 2016; Bowman et al., 2008).

From the economic perspective, improving NUE would enhance farm profitability as N fertilization is a major cost in crop production. Globally, a 1% increase in crop NUE could save about $1.1 billion annually in fertilizer cost (Li et al., 2020; Kant et al., 2011). In Canada, expenditures for fertilizers in 2019 were equal to $5.7 billion, representing the largest operational cost factor (9.5%). Fertilizer expenses increased in Canada by more than 150% over the period 2000 to 2019 (Statistics Canada, 2019).

Potential solutions to improve nutrient use efficiency and reduce agricultural emissions

With the Canadian government draft regulation of Mach 2021 to establish a domestic market for trading carbon credits, farm adoption of practices and technologies that improve NUE and reduce fertilizer emissions creates opportunities for farmers to earn additional revenues.

Optimizing NUE requires the development and adoption of technologies and agronomic practices that improve fertilizer efficiency and reduce environmental consequences. Controlled-release and slow N release fertilizers (e.g., urease inhibitors, urea-triazone) have been commercially used in some countries and are identified as promising tools to increase the recovery of applied N fertilizer, while mitigating the negative impacts of N_2O (Upadhyay, 2012; Bedmar et al., 2005; Shaviv, 2000). However, due to the high costs of these fertilizer formulations, their application is mainly limited to high value crops (Chien et al., 2009).

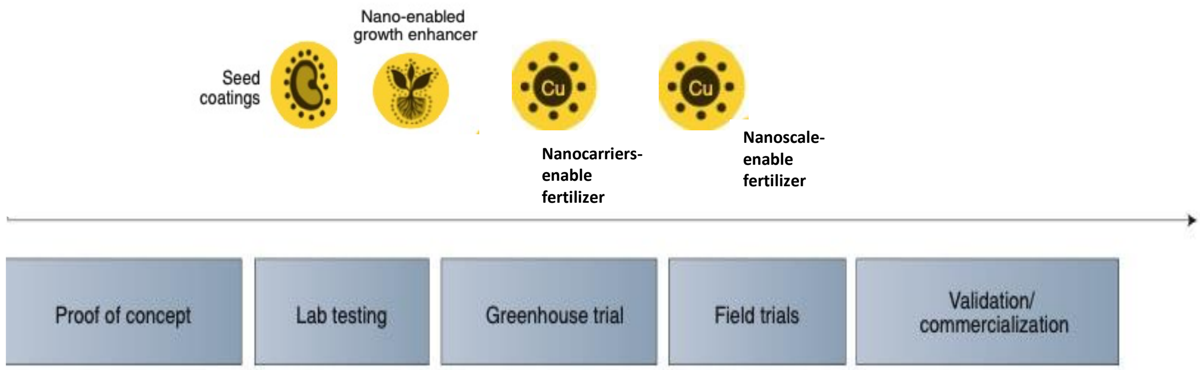
Methods of applying N fertilizers, such as the 4R nutrient management principles (right source, right rate, right timing, and right placement), represent the best management principles to achieve high NUE (IPNI, 2021). The N source and timing of application determine which method is more suitable for applying fertilizers (details reviews about N source, rate, placement and timing are presented in Boswell et al. (1985) and Peterson and Fryre

[4] Here, we focus on N_2O emissions calculation. Other forms of emissions from fertilizer nitrogen may also be released into the environment, (e.g., NH_4, NH3, and NO3), referred to as indirect N_2O emissions, that can be transferred into N_2O in downwind or downstream ecosystems (IPCC, 2007). These emissions have been well documented, albeit the quantity of N lost through these mechanisms remains difficult to measure (Davidson et al. 2012).

(1989)). A precise synchronization of N availability with N demand – timing N application to match the maximum uptake of N by crops – is critical to improving N uptake and reducing N losses (Walters and Malzer, 1990).

The development of nanotechnologies offers potential solutions for increasing NUE. Laboratory studies of these versatile technologies are signaling that a number of new technologies could provide sustainable solutions to plant growth and protection, including nanofertilizers, macro- and micronutrients and pesticides, genetic engineering of plants with enhanced photosynthetic capacity, and sensors for plant monitoring (Hofmann et al., 2020). Hofmann et al. (2020) ranked four different nanotechnologies based on their technological readiness level (TRL), going from most to least ready for widespread adoption (Figure 1).

Figure 1. Technology readiness level (TRL) for nano-enabled technologies to improve nutrient use efficiency (NUE)



Source: Hofmann et al. (2020)

First, nanoscale-enabled fertilizers (e.g. micronutrient form of fertilizer) have been well documented to deliver direct nutrients to crops (kah et al., 2019). Nanoscale fertilizers can also have indirect effects by enhancing macronutrient uptake (Pradhan, 2014). Nanoscale fertilizers for improving NUE and crop productivity have been tested at the laboratory, greenhouses and in fields. Thus, it has a higher TRL.

Second, nanocarrier-enabled fertilizers use nanomaterials as carriers and targeted applications of nutrients, the slow-release mechanisms for micronutrients delivery to improve NUE. Nanomaterials as carriers offer slow fertilizer release to reduce losses in runoff and infiltration. Cai (2015) indicated that, compared to conventional fertilizer, a large-scale field trial using this fertilizer improved NUE by 20%. However, while promising, most of the nanotechnologies for micronutrient delivery have been tested only in the laboratory and some in greenhouses.

Third, nano-enabled growth enhancers (e.g., coating nanomaterials with guiding biomolecules) offer the potential to increase nutrient uptake efficiency and enables targeting to plant cell compartments and organelles (e.g., chloroplasts and mitochondria). These enhance plant protection and nitrogen delivery efficiency to crop while reducing emissions of ammonia and N2O (Miernicki et al., 2019). Formulations that promote leaf adhesion and precision spraying could improve the efficiency of foliar delivery and retention. Although, nanomaterials related to crop growth have demonstrated significant results in the laboratory, these technologies have not yet been tested in the field as the cost of most nanomaterials for crop growth are too high to be viable in the field.

Fourth, nano-enabled seed coatings facilitate seed germination and increase pathogen resistance by using nutrients such as amino acids. This suggest that nano-enabled seed coatings with nutrients could be a promising technology to improve NUE (Herrera et al., 2016). Although promising, little information and few scientific studies are available on the beneficial effects of seed coating. Recent innovations (e.g., electrospun seed coatings, coatings of biosynthesized silver nanoparticles for germination enhancement) show promising results, but their applications to improve NUE have been tested only in the laboratory. Therefore, the TRL for nano-enabled seed coating is low due the lack of comprehensive studies that show the efficacy of this technology in greenhouses and fields.

Conclusion

The current efficiency of nitrogen (N) fertilizers is low, ranging from 25% to 50%. The loss of N from agriculture has resulted in a major deleterious environmental impact. The development and adoption of technologies and agronomic practices that improve fertilizer efficiency and reduce its environmental consequences are needed.

The use of controlled-slow-release N fertilizers and the application of the 4R nutrient management principles are considered the best current techniques to increase nutrient use efficiency (NUE). Among potential new technologies we identified nano-enabled growth enhancer, nanofertilizer, and nano-enabled seed coating. Laboratory studies of nanotechnologies indicate tremendous promise to improve NUE and to make the crop sector more sustainable, efficient and resilient. However, efficient delivery at field scale is considered a barrier for the implementation of nano-enabled technologies in agriculture. The successful development, commercialization and adoption of nanotechnologies at the farm level is needed to achieve their results. Moving from laboratory to the field scale requires the involvement of the industry.

Not all the barriers are technical. From a social perspective, the success or failure of nano-enabled technologies in agriculture will be intimately linked to public perception and acceptance. Uncertainty about the potential health and safety hazards of nanomaterials on human and the environment could limit their public acceptance and, consequently, application in the field. The potential for toxicity of various types of nanomaterials and the health and safety are subject of ongoing research. Moreover, given that the regulatory communities across different jurisdictions have not arrived at a consensus on the definition of nanomaterials, it is expected that nanotechnologies will come under regulatory scrutiny in which the risks of these technologies will be questioned.

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