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Nitrogenous Fertilizers – Boon or Bane?

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Review

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CONFLICTS OF INTEREST

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ABSTRACT

Agriculture is currently facing unprecedented challenges, *i.e.*, to provide food to the world population, and to maintain ecosystem services. Generally, overdoses of chemical fertilizers are applied by farmers in their agricultural fields to maximize crop productivity; however, approximately half of it is not taken up by the crops and gets lost in the environment due to leaching, runoff, emissions and volatilization which cause agronomical, economic, environmental concerns and health threats.

Growing human demand of food production has led to substantial increase in the quantity of nitrogen into the environmental reservoirs as nitrogenous fertilizers are the most excessively used chemicals by farmers. Overfertilization with nitrogen may have adverse impacts on ecosystem structure and function which include biodiversity loss, acidification of soil resulting in negative impact on plant health and productivity, and an increase in susceptibility of plants to secondary stresses. The nitrogen lost into the environment may lead to nitrate pollution of water courses and emissions of both ammonia and nitrous oxide to the atmosphere, which in turn may affect climate.

Despite the negative environmental and health impacts, it is difficult to reduce the application of nitrogenous fertilizers in view of the food security for growing global population. Therefore, there is a need to work out the strategies that may address the triple challenge of food security, environmental degradation and climate change. This paper aims at understanding the importance of nitrogen fertilization for meeting the global food demand as well as its adverse impact on environment, plant and human health.

Keywords: Climate, Environment, Food security, Human health, Nitrate, Nitrogenous fertilizers

INTRODUCTION

Nitrogen (N) is generally the most limiting nutrient in intensive crop production systems (Robertson and Vitousek, 2009). Although approximately 4×10^{21} grams of total amount of N is present in the atmosphere, soils, and waters of Earth (Mackenzie, 1998), more than 99% of this N is not available to more than 99% of living organisms due to its presence in molecular form, *i.e.* N_2. Therefore, its addition to agricultural cropping systems is an essential facet of modern crop management and one of the major reasons that crop production has been able to keep pace with human population growth. Nitrogen is added to the soil in the form of synthetic fertilizers by the farmers managing intensive cropping systems generally in the form of urea, as it is easy to transport, readily available, and relatively inexpensive.At present, 50% of the human population relies on nitrogenous fertilizers for food production, which cost agriculture more than US $ 50 billion per year.

As the effect of additional nitrogen on crop yield is usually substantial, application of inorganic nitrogen fertilizers has become an important tool in intensive agricultural systems in developing countries. However, only 50% or less of the applied nitrogen is used for producing the aboveground biomass of plants. The other 50% or more gets dissipated in the environment by volatilization, leaching, surface runoff and denitrification. This low recovery of nitrogen results in a number of negative environmental side effects. Despite these effects, there is no way of giving away nitrogen from the crop production scenario of the country (India), where grain production has risen from 80 million tonnes to 220 million tonnes due to application of nitrogen fertilizers (NAAS, 2005).

Therefore, agriculture is currently facing unprecedented challenges, *i.e.* to provide food to the world population, on one hand and to maintain ecosystem services, on the other. In view of the above, there is a need to explore the management practices that may maximize plant yield while minimizing the loss of nitrogen in the environment. The present paper aims at understanding the importance of nitrogen fertilization for meeting the global food demand as well as its adverse impact on environment, plant and human health.

Nitrogen and global food demand

The global population increased from 2.9 billion in 1958 to 6.7 billion in 2008 and the applications of synthetic N fertilizers increased from 10 Tg (1 Tg= 1 million tonnes) N/year in the late 1950s to 100 Tg N/year in 2008 (Robertson and Vitousek, 2009). Now (2018) the population has risen to 7.4 billion with paralleled increase of nitrogenous fertilizer usage. These synthetic N fertilizers have played a central role in the ability of intensive agriculture to increase the rateof food production more rapidly than that of human population growth.

The N fertilizer consumption has grown dramatically in Asia also, about 17-fold in the last 40 years (Dobermann and Cassman, 2004). In India, N-fertilizer use has been a success story for the Indian crop production from the beginning of the Green Revolution. The increase in N fertilizer use in the last three to four decades has resulted in unprecedented increase in agricultural production in the northwestern India leading to food security of the country. With 6 million tonnes N-fertilizer in 1989-90 to 10.4 million tonnes in 1998-99, every million tonne N–fertilizer used resulted in production of 10 million tonnes of cereals. Therefore, there is no way of excluding N from the crop production scenario of a country, where grain production which would have been 80 million tonnes without N-fertilization, now stands at 220 million tonnes with the use of N fertilizer.

Loss of nitrogen in the environment

About half of the nitrogenous fertilizer applied to agro-ecosystems is incorporated into crops that are harvested from fields and used for human food and livestock feed (Smil, 1999, 2001), the other half is lost into the environment through leaching to surface and groundwater, volatilization of ammonia (NH_3), denitrification to N_2, and fluxes of nitrogen oxides, *i.e.* N_2O and NOx to the atmosphere and, runoff and erosion.

The escape of N from agricultural soils leads to unintended adverse environmental impacts including groundwater contamination, eutrophication of freshwater and estuarine ecosystems, acidification of soil, tropospheric pollution due to emission of nitrogen oxides and ammonia gas, and accumulation of nitrous oxide. Nitrogen that escapes into the environment is reactive (Nr) and is present in the forms that are biologically active in soils and surface waters and/or chemically reactive in the atmosphere (Robertson and Vitousek, 2009). In the atmosphere, increased nitrogen concentration affects human and ecosystem health on a regional and global basis.

Leaching of N in the soil takes place in the form of nitrate (NO_3^-), the magnitude of which depends upon soil characteristics, management practices, agro-climatic conditions and the type and method of N use. Denitrification occurs when (NO_3^-)is present under anaerobic conditions in the soil, and it has been estimated by Aulakh et al. (2001) that 23–33% of the N applied through fertilizer is lost via denitrification during rice cultivation, which is the highest under alternate flooding and drying conditions. The major problems associated with denitrification process are that a considerable amount of nitric and nitrous oxides are emitted into the atmosphere. Nitric oxide leads to the formation of tropospheric ozone which is a major atmospheric pollutant that affects human health, agricultural crops, and natural ecosystems and nitrous oxide is approximately 300 times more potent than CO_2 in causing global warming (Abrol et al., 2012; Baggs et al., 2002)

Volatilization takes place when nitrogen fertilizer is applied to the moist soil where it rapidly hydrolyses under subtropical conditions. The factors affecting ammonia volatilization include pH, NH_4^+ content of soil and temperature of the floodwater, algal and aquatic weed growth, crop growth, and soil properties (Abrol et al., 2012). Once ammonia is emitted from agricultural systems, it may be transported and deposited in gaseous or dissolved forms to terrestrial and aquatic ecosystems causing eutrophication. Eutrophication further causes undesirable changes which are harmful for aquatic flora and fauna posing a major challenge to the viability of fisheries (Gordon et al., 2010).

Reactive N is also responsible for hypoxia, loss of biodiversity, and habitat degradation in coastal ecosystems and is considered the biggest pollution problem in coastal waters (*e.g*., Howarth et al., 2000, NRC, 2000, Rabalais, 2002). It further contributes to global climate change and stratospheric ozone depletion, both of which have impacts on human and ecosystem health (Cowling et al., 1998) and is responsible (together with sulphor (S)) for acidificaton and loss of biodiversity in lakes and streams in many regions of the world (Vitousek et al., 1997).

The role of deposition of N on ecosystem structure and function has recently been reviewed by Rehman and Kazi (2015). According to them, nitrogen deposition may lead to accumulation of ammonium ions that may have toxic effects on sensitive species inecosystems where nitrate is usually the dominant N form (Stevens et al., 2011).

Nitrogen and atmosphere

Use of nitrogenous fertilizers directly influences the amount of NH_4^+ or NO_3^-available in the soil as the higher the amount of N-NH_4^+ in the fertilizer, the greater will be the nitrification process (Mosier, 2001, Khalil et al., 2004); as a result, the loss of N_2O may also increase. Nitrous oxide,a potent greenhouse gas, is produced in the soil predominantly by the microbial processes of nitrification (ammonia oxidation) and denitrification (nitrate reduction; Robertson and Groffman, 2007) which affect both the climate system and stratospheric ozone (Wuebbles, 2009).

In addition to N_2O, agricultural systems emit reactive N gases, particularly NH_3 and oxides of N.Major atmospheric effects associated with increased NOx and NH_3 emissions include: (i) decrease in atmospheric visibility due to fine particulate matter, (ii) enhanced greenhouse potential of the atmosphere due to high ozone concentrations, (iii) serious impacts on human health (Pope et al., 1995), (iv) direct and indirect effects of aerosols on global climate change (Seinfeld and Pandis, 1998, Penner et al., 2001, Galloway et al., 2003), (v) decrease in productivity of crops, forests, and natural ecosystems and (vi) ecosystem acidification and eutrophication. NOx plays a role in tropospheric photochemistry; when NOx is elevated, the oxidation of atmospheric hydrocarbons and carbon monoxide lead to the production of ozone (O_3), but when NOx concentrations are low, O_3 is consumed (Chameides et al., 1992; Liang et al., 1998).

Management practices that may influence emissions of N_2O from agricultural soils include rate, type, timing and application method of nitrogen fertilizer, crop tillage, residue management, and irrigation (Parkin and Kaspar, 2006).

Nitrogen and water

The extensive use of fertilizers has been considered as the main nonpoint source of nitrate that leaches to groundwater and causes nitrate contamination (Chowdary et al., 2005; Hubbard and Sheridan, 1994; Postma et al., 1991). Nitrate is water-soluble and *a*negatively charged molecule with high mobility and potential for loss from the unsaturated zone of soil through leaching (Chowdary et al., 2005; DeSimone and Howes, 1998). Once N enters the groundwater, it may either get accumulated in the form of nitrate, lost from groundwater through denitrification to N_2, or may get distributed to other systems through hydrologic pathways (e.g., as NO_3^-) or atmospheric pathways (e.g., as N_2O or NO). Increased NO_3^-concentrations may lead to stream acidification, with resultant impacts on flora and fauna (Galloway et al., 2003). High nitrogen inputs may also lead to excessive algal growth, or eutrophication that may ultimately lead to creation of anoxic or hypoxic conditions in the water, thereby creating so-called "dead zones". (Galloway et al., 2003). It is due to the reason that high nutrient levels stimulate algal growth, and when algae sink into deeper water and die, their subsequent decomposition by bacteria consumes dissolved oxygen faster than it can be replenished from the surface, leading to the development of hypoxia and the reduction or elimination of deep water organisms that require oxygen (Rabalais et al., 2002). Reactive N pollution may also cause alterations of marine food webs leading to decreased fish production (NRC, 2000) and loss of biotic diversity in marine ecosystems (NRC, 1996 and 2000).

Nitrogen and soil

About 75% of the nitrogen created globally by humans is added to agro-ecosystems to sustain food production and the annual crop yield is determined primarily by the amount of nitrogen added to the soil.The compositional and functional changes induced by added N are not confined to plants only; changes in soil fungal communities also take place due to addition of reactive N. According to Rehman and Kazi (2015), nitrogen deposition leads to acidification of soil, cation depletion of the base and enhanced toxic metalsavailability (e.g., Al_3^+, Fe_3^+) that may adversely affect planthealth and productivity.

Nitrogen and plants

Crops respond markedly to applied nitrogenous fertilizers in growth, grain yield, and grain nitrogen production. A large number of crops, cereals in particular, that are grown for protein content and yield require large quantities of nitrogenous fertilizers to attain their maximal yields. However, although adding fertilizers generally results in enhanced yield, the efficiency of the uptake decreases with the increasing level of fertilization (Lawlor et al., 2001). Although plant breeders have concentrated in the past mainly on improving potential yield, increased emphasis is now being laid on aspects such as the nutritional value of foods (Ladha et al., 2005). For vegetable agriculture, nitrogenous fertilizers (mainly of nitrate variety) are used widely, which results in accumulation of nitrate in plants, if the rate of nitrate uptake exceeds the rate of its reduction to ammonium (Luo et al., 1993). When taken up in excess of immediate requirement, it is stored as free nitrate in the vacuole and can be remobilized subsequently when nitrogen supply is insufficient to meet the demand (van der Leij et al., 1998).It has been suggested by McCall and Willumsen (1998) that high rates of nitrate application lead to increase in plant nitrate content without any increase in the yield. Therefore, farmers who apply excessive fertilizers to ensure that nitrogen is not limiting for plant growth,may increase the nitrate content of crops to the levels potentially toxic to humans, without any increase in yield.

A study was conducted by the authors, in which it was found that providing plants with excess N fertilizer resulted in nitrate accumulation in plants that exceeded the Acceptable Daily Intake limit for a 60 kg person (if consumed @ 100 g/day) (Anjana et al., 2007a). It has been reported by Sareer et al. (2016) that *Andrographis paniculata*, a medicinal plant widely used as a component of herbal teas and medicinal infusions also contained nitrate levels beyond the safety limit. It may be due to the reason that there is an upper limit to resource utilization and consequently plant performance (Nejidat et al., 1997). Moreover, there is an upper limit to the levels of N-metabolizing enzymes that the plant can accommodate (Anjana, 2007d). Therefore, the plant continued nitrate uptake due to its abundant availability in the soil but was not able to assimilate it. As a result, accumulation of nitrate in the plant to unsafe limits occurred.

According to Phoenix et al. (2012), N deposition leads to an increase in the susceptibility of plants to secondary stresses, i.e. increased herbivory, reduced resistance to attack by pathogen or increase in susceptibility to drought or freezing damage.

Nitrogen and human health

The adverse impact of nitrogen on human health is mainly due to the ingestion of food and water containing high nitrate concentrations. Out of the total human nitrate intake, fruit and vegetables account for 70%, drinking water 21%, and meat and meat products 6% (Anjana et al., 2007b, 2009, Umar et al., 2013). The common nitrate-rich vegetables include lettuce, spinach, beetroot, celery, egg plant, beet, banana, strawberry, tomatoes and peas.Nitrate content has been reported also to be higher than ADI limit in Brassica genotypes (Mazhar et al., 2015).

It has been established by European Commission (EC)'s Scientific Committee for Food (SCF) that the Acceptable Daily Intake (ADI) of nitrate ion is 3.65 mg kg^{-1} body weight (which is equivalent to 219 mg day^{-1} for a person weighing 60 kg) (SCF, 1995), whereas the Joint Expert Committee of theFood and Agriculture (JECFA) Organisation of the United Nations/World Health Organisation (WHO) has established that the Acceptable Daily Intake of nitrate is 0-3.7 mg kg^{-1} body weight (Speijers, 1996). EC Regulation No. 1822/2005 was adopted by the European Commission on November 8, 2005and the harmonized maximum levels were set for nitrate in lettuce, spinach, baby foods and processed cereal-based foods.The limits varied depending on the season and higher nitrate levels were permitted in winter-grown vegetables. In a study conducted by the authors, nitrate content in the samples of spinach and chenopodium collected from the local markets of Delhi and nearby was found to be as high as 4451 and 4293 mg/kg fresh weight, respectively (Anjana et al., 2007a) which was far higher than the ADI limit.

The nitrate toxicity is considered to be due to the reduction of nitrate to nitrite and its further conversion to carcinogenic compounds*, i.e.* nitrosamines and nitrosamides through its reaction with amines and amides(Walker, 1990). Nitrite toxicity occurs due to the oxidation of ferrous ion (Fe^{2+}) in haemoglobin to ferric (Fe^{3+}) ion, thereby producing methaemoglobin. Its formation greatly reduces the oxygen-binding capacity of blood that results into impaired delivery of oxygen to human tissues (Knobeloch et al., 2000; Mensinga et al., 2003).Clinical findings vary with methaemoglobin concentrations and its percentage determines the clinical picture of oxygen deprivation with cyanosis, cardiac dysrhythmias and circulatory failure, and progressive central nervous system (CNS) effects ranging from mild dizziness and lethargy to coma and convulsions (Agency for Toxic Substances and Disease Registry, 2001). It was earlier believed that methaemoglobinemia occurs in infants only, however it has been reported by Gupta et al. (2000a) to occur in people of different age having high nitrate ingestion (infants and above-45 age groups being most susceptible). The acute toxicity symptoms occur in the form of cyanosis, severe gastroenteritis with abdominal pain, blood in the urine and faeces, dyspepsia, mental depression, headache and weakness (Gupta et al., 2008).

N-nitroso compounds have been associated with 15 different types of cancers, including tumours in the bladder(Michaud et al., 2004), stomach, brain, esophagus, bone and skin, kidney, liver, lung, oral (Badawi et al., 1998) and nasal cavities, colon, rectum or other gastrointestinal regions (Knekt et al., 1999; Turkdogan et al., 2003), pancreas, peripheral nervous system, thyroid, trachea, acute myelocytic leukaemia, and T and B cell lymphoma (Gupta el al., 2008).

Other health problems associated with nitrate toxicity include sclerosis (Giovannoni et al., 1997), vascular dementia of Biswanger type or multiple small infarct type (Tohgi et al., 1998), Alzheimer's disease, anencephaly (Croen et al., 2001), multiple spontaneous abortion or congenital defects (Fewtrell, 2004),non-Hodgkin's lymphoma (Michal, 1998) and cardiovascular disorders (Morton, 1971).

It has been reported by Gupta et al.(2008) that ingested nitrates converted to nitrite by microflora may also lead to increased free oxide radical formation that may predispose cells to irreversible damage and effects like cancer, increased infant mortality, abortions, birth defects, recurrent diarrhea in children up to 8 years of age and recurrent stomatitis. It has also been reported to affect human immune system (Ustyugova et al., 2002). Some other reported effects of nitrate toxicity include an early onset of hypertension, diabetes, hypothyroidismand adverse impact on cardiac muscles, alveoli of lungs and adrenal glands (Gupta, 2006).

Inhalation of NOx has also been reported to cause a large number of health and environmental impacts (Gupta et al., 2008). Low levels of nitrogen oxides in the air may cause irritation in the eyes, nose, throat and lungs, leading to cough and shortness of breath, tiredness and nausea. High levels of nitrogen oxides may causerapid burning, spasms and inflammatory swelling of tissues in the throat and upper respiratory tract. High exposures may also lead to pulmonary oedema, leading to hypoxemia and even death (Gupta el al., 2008). It may also cause unconsciousness, vomiting, mental confusion, congestion and inflammation of the respiratory tract, pulmonary oedema, genetic mutations, and may adversely affect development of the foetus and decrease fertility.

According to Galloway et al. (2003), increase in reactive nitrogen in the atmosphere leads to production of tropospheric ozone and aerosols that induce serious respiratory illness, cancer and cardiac disease in humans.

Recommended strategies

A number of strategies have been recommended by various scientists for minimizing the loss of nitrogen from the soil (Anjana et al., 2007c). The leaching loss of nitrate may be minimized by increasing the water use efficiency by crop plants, use of slow-release fertilizers and nitrification inhibitors. The volatilization loss may be minimized in the soil-water system by application of soluble salts of calcium, potassium and magnesium; use of urease and algal inhibitors; deep placement of N fertilizers; and use of modified forms of urea and slow-release fertilizers. Denitrification losses may be reduced by using nitrification inhibitors like iron pyrite, nitrapyrin, phenylacetylene, encapsulated calcium carbide, terrazole, etc. (Abrol et al., 2012).The use of slow releasing fertilizers has been suggested as an important strategy for reducing N_2O emissions induced by N-fertilizers (Signor and Cerri, 2013). Some common principles for fertilizer application include the '4Rs' approach of applying right source, at the right time,at the right rate and in the right place (Synder et al., 2014). It has also been suggested by Tan et al. (2009) that splitting the doses of N-fertilizers increases their efficiency and reduces losses by leaching and denitrification, implying benefits for reducing greenhouse gas emissions and ensuring natural resources preservation.

CONCLUSION

It may be concluded that excessive application of nitrogenous fertilizers has an adverse impact on plants, environment as well as human health. A number of strategies have been developed by the agronomists, physiologists as well as biotechnologists forachieving the ambitious target of high yield to meet future food demands while maintaining environmental quality; however there is a need to bridge the gap between the laboratory and the land for successful implementation of technologies and management practices at the farm level.

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