REVIEW ARTICLE

Plants, Fertilizer Nitrogen, and Environment: An Overview

Rajendra Prasad, Yashbir Singh Shivay*, Sunil Mandi

DOI: 10.18811/ijpen.v6i02.01

Abstract

Fertilizer N has played a key role in increasing food production, especially of cereals and grasses in the world. However, fertilizer N has been also responsible for global warming, enhancing nitrate concentration in drinking water, and depleting the ozone layer. Crop plants also release ammonia, while trees absorb ammonia from the atmosphere. Agriculture soil can contribute 84% of global N_2O emission and it is now considered nitrogen next after CO_2 for global warming. In India, the average nitrogen use efficiency (NUE) is 33% which is far-reaching 50% acceptable and its consumption increased by 52 times from 1961 to 2018, but cereals production by 3.6 times. Therefore, approaches, such as, 4R, LCC, SPAD, Green Seeker, using control, and slow-release nitrogen fertilizers, using inhibitors along with SSNM may improve NUE in the developing world.

Keywords: Ammonia, Crop plants, Environment, Nitrogen, Trees.

International Journal of Plant and Environment (2020); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi-110012, India

***Corresponding author:** Dr. Yashbir Singh Shivay, Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi-110012, India; Mobile: +91-9868337578, 9650230379; Email: ysshivay@hotmail.com

How to cite this article: Prasad, R., Shivay, Y. S., and Mandi, S. (2020). Plants, fertilizer nitrogen, and environment: An overview. International Journal of Plant and Environment 6(2): 98-102.

Source of support: Nil

Conflict of interest: None

Submitted: 25/02/2020 **Accepted:** 25/04/2020 **Published:** 30/04/2020

Introduction

Plants are the main source of food, fodder, fiber, timber, etc. for humans and animals that need every day in the life. Plants require several nutrients from the atmosphere, water, and soils to complete their life cycle and for proper growth. However, in the agriculture field, we applied external sources of nutrients in the form of organic and inorganic fertilizers to harvest maximum productivity, as a consequence overdose of fertilizer application may cause environmental pollution and health hazards. Nitrogenous fertilizer application in the agriculture field is essential as most of the agriculture fields suffered from low nitrogen status. In field conditions, its recovery efficiency may vary from 21–63% (Doberman, 2005; Omara *et al.,* 2019) which varies from crops to crops and region to region. The remaining portion of nitrogen may be lost by leaching (Prakasa Rao & Prasad, 1980), volatilization (Sudhakara & Prasad, 1986), and run-off losses (Tian *et al*., 2007) that cause environmental pollution and health hazards of animal and human beings. Besides, nitrogen is also lost from plant parts mainly from senescing leaves. These losses are confirmed by Abrol (1986), Patron *et al*. (1988), Schjørring *et al*. (1989), Francis *et al*. (1993) and He *et al*. (2004). However, nitrogen losses from plants may or may not be controlled but leaching, volatilization, and run-off losses can be controlled by the application of advanced techniques and use of modern gadgets. There are many approaches which may improve nitrogen use efficiency, especially cereal-based cropping systems. In this review we have compiled an overview in relation to nitrogen with plants and human, nitrogen losses from the soil-plant system and also different aspects to improve nitrogen use efficiency.

Plants: The Main Source of Food in the World

The origin of life is a complicated issue and still remains a mystery; however, it is generally believed that life originated in water (Prasad, 2012) or aquatic medium as a unicellular organism. The evolution of chlorophyll molecule followed and the cells having it started photosynthesis and manufacture of food (sugar) from C in the air and H and O from water. The next step was fixing atmospheric N as in cyanobacteria (blue-green algae) and development of proteins. Since the development of DNA had taken place earlier, the cells could regenerate and life began. In this process, plants were the first, because they could manufacture their food, and thus, grow on their own. The unicellular organism that did not have chlorophyll, and therefore, could not manufacture food started consuming plants for their growth and so animal life originated. With the passage of time, chlorophyll-containing unicellular bodies developed into multicellular organisms or plants of various sizes and shapes, and the planet earth had a plant canopy. Non-chlorophyll unicellular organisms also developed into multicellular bodies, the animals, which still depended upon plants for food. As regards regeneration, DNA did the job of producing different but similar forms and sizes of animals, which all depended upon plants for food and do it even today. Man is also an animal and came in the scene in 200 KBP (thousand years before present including 2000 years A.D.). Humans are considered to have evolved in East Africa (Ackermann *et al*., 2015) and depended on animals for food, which they hunted and killed for meat. They had to shift from places to places in search of green pastures, where animals were to be found, searching for their own food (the green plants). Thus, the man was a hunter, to begin with, and gradually learned to raise the animals and herded them in flocks and pastoralism became his profession (Lewis, 1996; Prasad & Nene, 2016). Animals provided food and their skin provided for covering the bodies and making tents to save them from the bitter cold. Still, later he or probably the women left behind in camps, while men went or hunting played a key role in discovering fruits and seeds for eating (Lee & Heywood, 1999). They also observed the germination of seeds and the emergence of plants from them and man gradually turned from pastoral life to agriculture in the Fertile Crescent in the Middle East, according to western literature (Braidwood, 1960; Bender, 1975). Agriculture also developed in some Asian countries, such as, China (Liu *et al.*, 2013) at the same time. As of now, plants are the main source of food for humans and agriculture is the only way to grow food, both vegetarian and non-vegetarian, because even the animals and birds grow on plant food. While humans grow their food on farm fields as various food crops or in orchards as vegetables and fruit crops, the animals are raised on ranches.

Fertilizer N and Increase in Cereal Production

The world human population was only 1-billion in 1800 and grew to 2-billion in the next 130 years, i.e., in 1930. The next billion was added in 30 years, i.e., by 1974. Another billion was added only in 13 years, thus, requiring 1/10th of the period needed in its increase from the first one billion to two billion. In the 20th century itself, the world population increased from 1.65 to 6-billion. It is expected to increase by ~9.7 billion by 2050 (UN 2019). The earth's land area remaining the same, it puts great pressure on agriculturists to produce sufficient food for all. The only way has been to grow more plants using more nitrogen and other plant nutrients. Nitrogen has been the main source of raising vigorous crops, especially cereals. The first chemical N fertilizer was sodium nitrate, discovered in the early 19th century as natural deposits on the western shores of South America (Arias, 2003). Ammonia synthesis, the major source of chemical N fertilizer was made possible by German chemists Fred Haber and Carl Bausch in the 2nd decade of the 20th century (Appl, 1982). This was followed by the development of urea the most widely used fertilizer in India (Prasad, 1998). Erissman *et al.* (2008) observed that without the discovery of synthetic ammonia half of the world would have remained hungry. Heffer (2013) reported that of the total N consumed in the world, 55.2% was used in cereals (wheat 18.1%, rice 16.8%, maize 15.4%, and other coarse cereals 4.8%). In 1955, the world cereal (wheat, maize, and rice) production was only 446.8 Tg (million tonnes), which increased 4.5 times to 2,068 Tg in triennium (2005–2007), and is likely to increase to ~3,000 Tg in 2050 (Alexandratos & Bruinsma, 2012). By that time, the fertilizer use is predicted to increase to 225 to 250 Tg (Tillman *et al.*, 2011) from the present ~118 Tg. Connant *et al.* (2013) observed that from 1961 to 2007, there has been relatively more increase in fertilizer use (+134%) than in the yield of cereals (+120%), showing the need for efficient use of nitrogen and the same trend was observed in India (Fig. 1); where nitrogen fertilizers consumption increased by 52 times since 1961 to 2018, whereas, cereals production by 3.6 times (FAOSTAT, 2020; FAI, 2020). Nitrogen fertilizer application not only increases grain yield in cereals but also increases the protein content in grain. Protein is essential for animal and human growth. Institute of Medicine, USA, recommends 0.8-gram per kg body weight as the daily minimum protein requirement for a sedentary person, i.e., about 48 grams for a person having 60 kg weight. In India, protein deficiency in the diet of vegetarians is a serious problem. People in other south-east Asian countries acquire protein from semi-aquatic organisms, such as, frogs and even insects. Indians cannot think of consuming these sources of protein.

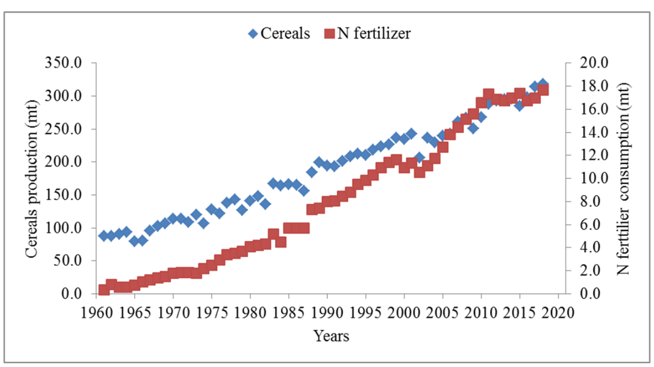

Fig. 1: Cereals production and nitrogen fertilizer consumption in India; adapted from FAOSTAT, 2020 for cereals (rice, wheat, maize, barley, sorghum, and millets) production data and N fertilizers consumption data from FAI Statistical Database, 2020

Fertilizer N Use Efficiency

NUE means different things to different agricultural professionals. Agronomists and agricultural economists use the term agronomic efficiency of N (AE_N) as kilograms of grain produced per kg of N applied to the field. This term is used for determining the optimum dose of nitrogen for raising a crop on a farm. Soil scientists and environmental scientists use the term crop recovery efficiency of N (CR_N), which denotes the percentage of applied N taken up by the crop. Plant physiologists use the term physiological efficiency of N (PE_N), which is kg grain per kg N absorbed by the crop. Moreover, EU Nitrogen Expert Panel (2015) recommended that NUE as a percentage (%) or mass fraction (kg/kg), while N input, N output in harvested produce, and N surplus in kg/ha/yr. Shivay *et al.* (2016) reported that when urea was applied to wheat at 130 kg N/ha, the CR_N was 31.6%. Doberman (2005) reported that on a global basis CR_N was 63% in maize, 54% in wheat, and only 44% in rice. However, when N application rates were higher as in China (180–220 kg/ha), CR_N even in research trials was 37.8% in wheat, 30.5% for maize, and only 20.8% in rice. In a recent study, Omara *et al.* (2019) reported that CR_N in cereals in 1999 was 39% for the world as a whole, 41% for the USA, 30% for China, and 21% in India. Voluminous data are available worldwide on this subject pointing to a similar situation and CR_N for rice is the lowest and this is a matter of concern in Asia because rice is the principal cereal of the region and staple food.

Soil scientists also conduct experiments with ^{15}N and determine the uptake of applied N by a crop. The term generally used for such values is TR_N (true recovery of applied N), because it does not take into account the native soil N. These values are generally lower than CR_N and in rice varies from 13.6 (Xin-hui *et al.*, 2006) to 31% (Bandyopadhyay & Sarkar, 2005), depending upon rate and method of N application. In a rice-wheat cropping system at New Delhi, CR_N was reported to be 31% (Goswami *et al.*, 1988).

What Happens to Applied N not Taken up by Crop Plants?

All fertilizer nitrogen is applied to soil, generally on the surface. Nitrogen is fairly soluble and that not taken up by crop is lost through run-off, ammonia volatilization, leaching, and denitrification that cause nitrogen pollution and water contamination (Fig. 2). Today, urea is the most widely used fertilizer in the world. Run-off losses of fertilizer occur on undulating or sloping land, especially if rainfall occurs soon after fertilizer application. In the Taihu lake region of China, the annual loss of N through runoff and leaching was 13.7 to 48.1 kg/ha from the rice-wheat cropping system (Tian *et al.*, 2007). Urea applied on moist soil surface gets hydrolyzed to ammonia, which is lost by volatilization (Sudhakara & Prasad, 1986). Pathak *et al.* (2006) from a simulation study reported that ammonia volatilization losses in a rice-wheat rotation could vary from 13 to 62 kg N/ha, with an average value of 30 kg N/ha.

Ammonium formed on hydrolysis of urea is oxidized by soil bacteria (*Nitrosomonas* sp.) are to nitrite and then by *Nitrobacter* sp. to nitrate. Nitrates so formed are leached down (Prakasa Rao & Prasad, 1980) and are responsible for increasing its concentration in drinking waters (Prasad, 2000), which is harmful to humans and responsible for causing blue baby syndrome (Knobeloch *et al.*, 2000). Bharadwaj *et al.* (2012) reported that 28% of shallow well waters of Ludhiana district contained 11 to 25 mg NO_3^- N/L, which is higher than the safe limit of 10 mg NO_3^- N/L recommended by Environmental Protection Agency (EPA) of USA and WHO. The situation is alarming in vegetable growing northern China, where very high doses of N (500–1,000 kg/ha) are applied and Zhang *et al.* (1996) reported that in most samples from this area nitrate in drinking water was above 70 mg N/L, much above the EPA safe limit. Under anaerobic water conditions as obtained in rice paddies, nitrate is reduced to N_2O (nitrous oxide) by denitrification caused by several species of bacteria, fungi, and other micro-organisms (Coyne, 2016). Aulakh *et al.* (2001) reported that 22 to 23% of N applied to rice may be lost by denitrification. Pathak *et al.* (2004) reported that in rice-wheat rotation, 10 to 15 kg N/ha was lost by denitrification in rice and 5 to 10 kg N/ha in wheat. Agricultural soils are believed to contribute about 84% of global N_2O emission (Smith *et al.*, 2007).

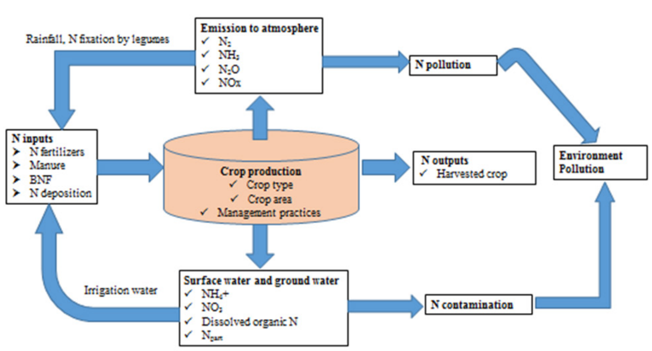

Fig. 2: Concept of the N cycle and nitrogen input-output mass balance in crop production systems; Adapted and modified from the EU Nitrogen Expert Panel, 2015; NUE—An Indicator for the Utilization of Nitrogen in Agriculture and Food Systems; Wageningen University, Alterra, Wageningen, The Netherlands; www.eunep.com

The N_2O produced by denitrification has about 300 times global warming potential (Prasad & Shivay, 2019) as compared to CO_2 and is also responsible for reducing ozone layer in the atmosphere (Portman *et al.*, 2012). Losses of applied N are most under alternate flooding and drying conditions. A laboratory study at New Delhi showed that ~95% of applied N was lost after three cycles of wetting and drying (Prasad & Rajale, 1972).

Enhanced Efficiency Fertilizers

The traditional agronomic techniques to increase the nitrogen use efficiency (NUE) include time and method of N application (Prasad *et al.*, 1970). Since most of the nitrogen losses are due to easy solubility of N fertilizers, efforts were made to develop slow-release fertilizers by coating urea with insoluble materials, such as, sulfur as in sulfur coated urea (SCU) or by developing less soluble urea compounds, such as, isobutylidenediurea (IBDU) (Prasad *et al.*, 1971). Another approach has been to develop chemicals with nitrification inhibiting capacity, such as, nitrapyrin or N-Serve (Goring, 1962). Blending urea with nitrification inhibitors is reported to reduce N losses and increase rice yields (Lakhdive & Prasad 1970; Prasad *et al.*, 1971). The use of these enhanced efficiency fertilizers reduces N losses from soil to a large degree. Neem coating of urea as in neem coated urea (NCU) also partially inhibits nitrification (Reddy & Prasad, 1975). NCU has a great role in improving the environment (Prasad & Prasad, 2018). In India, NCU was developed (Prasad *et al.*, 1994), which has been quite successful and all urea manufactured in India is now neem coated (Kumar, 2015). Moreover, EU Nitrogen Expert panel, in 2015, proposed four main directions to optimize NUE, i.e., by, 1) intensification, 2) extensification strategies, 3) increasing efficiency, and 4) avoiding soil degradation.

Plant and Environment

Plants absorb CO_2 and release O_2 in the atmosphere, so much necessary for animal and human life on the planet earth (Vasanthaiah, 2012). A mature leafy tree produces as much oxygen in a season as 10 people inhale in a year. That is why there is so much effort for afforestation (Patra, 2014). Even indoor plants release oxygen (TOI, 2017). Little is known about N losses from plants. Nitrogen being a constituent of proteins is the key nutrient in plant growth. When N is in short supply, it moves from senescing (old) leaves to growing young leaves (Thimann, 1980), which turn yellow. Mobilization of N involves the breakdown of leaf proteins and in the process, ammonia is evolved. The concentration of ammonia in sub-cells of stomata is much higher than in the outer atmosphere and ammonia moves out by concentration gradient (Wu *et al.*, 2009). Ammonia concentration in the atmosphere is generally 1 to 5 parts per billion but could be higher in agricultural regions, where heavy doses of N are applied. In China, abundant concentrations of NH_3 [1 to 23.9 μg m^{-3}] were spotted in typical agricultural regions, especially in the North China Plain (NCP) (Wang *et al.*, 2018). Ammonia so released is oxidized to nitrate and finds its way to the soil by rainwater, where it is either leached or denitrified. Nitrogen losses from field crop plants (annuals) are most during anthesis and maturity (Wetselaar & Farquhar, 1980). However, field crops (annuals) release ammonia in the atmosphere. Patron *et al.* (1988) reported that ammonia loss was 0.36-gram NH_3^- N/ha/day from senescing leaves with a leaf area index of 5. Losses of N from different crops reported are winter wheat 5.9 to 80 (Daigger *et al*., 1976; Harper *et al*., 1987; Abrol 1986), maize 4.5 to 81 (Francis *et al*., 1993), and rice 7.3 to 59.8 kg/ha (Hayashi *et al*., 2009; He *et al*., 2014). A ^{15}N study on barley using fertilizer N doses varying from 30 to 150 kg/ha showed that about 45% of applied fertilizer N was lost from plants (Schjørring *et al*., 1989). Farquhar *et al.* (1983) reviewing results from a number of agricultural plant species observed that N losses from plants could reach up to 75 kg N/ha (Farquhar *et al*., 1983; Behera *et al*., 2013). Thus, crop plants release a lot of nitrogen in the atmosphere. Most N-balance sheets for the soil-plant system (Allison, 1955; Pillai *et al*., 2007) have skipped the loss of N from plants and have mainly concentrated on N losses from soil. Plants are also involved in ammonia emission indirectly as forage and grains fed to cattle, which release a lot of ammonia in urine and dung (Hristov *et al*., 2011). This also brings out that fertilizer nitrogen, which has saved humanity from hunger could also pollute the environment to a degree that may hurt humanity beyond repair. In the crop production system, nitrogen has losses in many ways. Therefore, input-output mass balance and its life cycle are very complicated, part of the input is harvested as crop and the remaining portion is dissipated into the atmosphere and contaminated to surface and groundwater (Fig. 2). It is noteworthy that agricultural crop plants form an important link in the possible pollution of the environment by fertilizer nitrogen, which has to be more carefully managed.

As a contrast, trees absorb ammonia from the atmosphere (Boaretto *et al*., 2013) and are used for mediating a high concentration of ammonia in the atmosphere (UK Centre for Ecology and Hydrology, 2018). This makes agroforestry quite interesting from nitrogen point of view; however, this aspect has not received much attention in India.

Conclusion

Plants thus, serve as a source, as well as, sink for ammonia and are an important component in adding to/preventing environmental pollution due to fertilizer nitrogen. Coordinated studies by plant and soil scientists and agronomists are required to reduce the menace of environmental problems created by fertilizer nitrogen.

References

Abrol, Y.P., Kaim, M.S. and Nair, T.V.R. 1986. Nitrogen distribution and its loss in wheat. In: Lanthers, H., Neetesan, J.J. and Sultan, S. (Eds.), Fundamental, Ecological and Agricultural Aspects of Nitrogen Metabolism in Higher Plants, Martinus Nijoff, Dordrecht, Netherlands, pp. 389.

Ackermann, A.R., Mackay, A. and Michael, L. 2015. The hybrid origin of modern humans. *Evolutionary Biology* **43**(1):1-11.

Allison, F.E. 1955. The enigma of soil nitrogen balance sheets. *Advances in Agronomy* **7**:213-259.

Alexandratos, N. and Bruinsma, C.J. 2012. *World Agriculture Towards 2030/2050.* International Atomic Energy Commission, Vienna, pp. 3-22.

Appl, M. 1982. The Haber-Bosch Process and the Development of Chemical Engineering. In: Furter, W.F. (Ed), A Century of Chemical Engineering, Plenum Press, New York, pp. 29-54.

Arias, J. 2003. On the Origin of Saltpeter, Northern Chile Coast. International Union for Quaternary Research, 24 July 2003 *(*Wikipedia).

Aulakh, M.S., Khera, T.S., Doran, J.W. and Bronson, K.F. 2001. Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and green manuring. *Biology and Fertility of Soils* **34**(6):375-389.

Bandyopadhyay, K.K. and Sarkar, M.C. 2005. Nitrogen use efficiency. ^{15}N balance and nitrogen losses in an inceptisols. *Communications in Soil Science and Plant Analysis* **36**:1661-1670.

Behera, S.N., Sharma, M., Aneja, V.P. and Balasubramanian, R. 2013. Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environmental Science and Pollution Research* **20**:8092-8131.

Bender, 1975. Farming in Pre-History. *From Hunter-gatherer to Food Production*. Billing and Sons, London, U.K.

Bharadwaj, A., Garg, S., Sondhi, S.K. and Taneja, S.K. 2012. Nitrate accumulation of shallow aquifer ground water in the central districts of Punjab, India. *Journal of Environmental Science and Engineering* **54**(1):90-97.

Boaretto, R.M, Mattos Jr. D., Quaggio, J.A., Cantarella and Trivelin, P.C.O. 2013. Absorption of $^{15}NH_3$ volatilized from urea by *Citrus* trees. *Plant and Soil* **365**(1-2):283-290.

Braidwood, R.I. 1960. The agricultural revolution. *Scientific American* **203**(30):130-162.

Connant, R.T., Berdanier, A.B. and Grace, R.R. 2013. Patterns and trends in nitrogen use and nitrogen recovery efficiency in world agriculture. *Global Biogeochemical Cycles* **27**:558-566.

Coyne, M.S. 2016. Denitrification in soil. In: Lal, R. and Stewart, B.A. (Eds.), *Soil Nitrogen Uses and Environmental Impacts*, CRC Press, Boca Raton, FL, USA, pp. 95-140.

Daigger, L.A., Sender, D.H. and Petersom, G.A. 1976. Nitrogen content of winter wheat during growth and maturation. *Agronomy Journal* **68**:815-818.

Doberman, A.R. 2005. *Nitrogen Use Efficiency-state of Art*. Agronomy and Horticulture Faculty Publications, paper 316, University of Nebraska, Lincoln, USA.

Erissman, J.W., Sutton, M.A., Galloway, J., Kilmont, Z. and Winiwarter, W. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* **1:**636-639.

EU Nitrogen Expert Panel, 2015. Nitrogen Use Efficiency (NUE)—An Indicator for the Utilization of Nitrogen in Agriculture and Food Systems. Wageningen University, Alterra, Wageningen, The Netherlands. http://www.eunep.com/.

FAI Statistical Database, 2020. The fertilizer Association of India, New Delhi, India. available at https://www.faidelhi.org/general/con-npk.pdf.

FAOSTAT, 2020. Food and Agriculture Data. Food and Agriculture Organization of the United Nations, Rome. Available at: http://www.fao.org/faostat/en/#home.

Farquhar, G.D., W*et al*aar, R. and Weir, B. 1983. Gaseous Loss of Nitrogen from Plant-Soil Systems. In: Freney, J.R. and Simpson, J.R. (Eds.), *Gaseous loss of nitrogen from plant-soil system*, Springer, **9**:159-180.

Francis, D.D., Scheppers, J.S. and Vigil, M.F. 1993. Post-anthesis nitrogen losses from corn. *Agronomy Journal* **104**(5):1201-1207.

Goring, C.A.I. 1962. Control of nitrification of ammonium fertilizers and urea by 2-chloro-6-trichloromethyl pyridine. *Soil Science* **93**:431-439.

Goswami, N.N., Prasad, R. Sarkar, M.C. and Singh, S. 1988. Studies on the effect of green manuring in nitrogen economy in a rice-wheat rotation using a ^{15}N technique. *Journal of Agricultural Science* **111**(3):413-417.

Harper, L.A., Sharpe, R.R., Langdale G.W. and Giddens, J.E. 1987. Nitrogen cycling in wheat crop, soil, plant and aerial transport. *Agronomy Journal* **79**:965-973.

Hayashi, K. Nishimura, S. and Yagi, K. 2009. Ammonia volatilization from a paddy field following application of urea: rice plants an absorber and an emitter for atmospheric ammonia. *Science of the Total Environment* **390**(2):485-494.

He, Y.S., Yang, J., Xu, J., Wang, Y. and Peng, S. 2014. Ammonia volatilization losses from paddy fields under controlled irrigation with different drainage treatments. *The Scientific World Journal* Article ID417605, pp. 1-7.

Heffer, P. 2013. *Assessment of Fertilizer use by Crops at the Global Level 2001-2011*. International Fertilizer Industry Association, Paris.

Hristov, A.N., Hanigan, M., Cole, A., Todd, R., McAllister, T.A., Ndegwa, P. and Rotz, A. 2011. Review: Ammonia emissions from dairy farms and beef feedlots. *Canadian Journal of Animal Science* **91**:1-35.

Knobeloch, L., Saha, B., Hogan, A., Pestle, J. and Anderson, H. 2000. Blue babies and nitrate contaminated well waters. *Environmental Health Perspectives* **108**(7):675-678.

Kumar, A. 2015. Government allows fertilizer firms 100% production of neem coated urea. The Economic Times, January, 2015.

Lakhdive, B.A. and Prasad, R. 1970. Yield of a tall and dwarf indica rice as affected by fertilizer nitrogen, with and without nitrification inhibitors. *Journal of Agricultural Science, Cambridge* **75**:375-379.

Lewis, I.M. 1996. *A Pastoral Democracy*, LIT Verlag, Munster, Germany.

Lee, R.B. and Heywood, D.R. 1999. Cambridge Encyclopedia of Hunters and Gatherers. Cambridge University Press, USA.

Liu, L., Bestel, S., Shi, J., Song, Y. and Chen, X. 2013. Paleolithic human exploitation of plant foods during the last glacial maximum in North China. *Proceedings of the National Academy of Sciences, USA* **110**(14):5380-5385.

Omara, L., Aula, L., Oyebiji, F. and Raun, W.R. 2019. World cereal nitrogen use efficiency trends-review and current knowledge. *Agrosystems, Geoscience and Environment* **2**(1):1-8.

Pathak, H., Li, C., Wasserman, R. and Ladha, J.K. 2006. Simulation of nitrogen balance in the rice-wheat cropping systems for the Indo-Gangetic plains. *Soil Science Society of America Journal* **70**:1612-1522.

Pathak, H., Tismina, J., Humphry, E. and Goodwin, D. 2004. Simulation of rice crop performance and water and nitrogen dynamics and methane emission in northwest India using CERES rice model. *Technical Report, CSIRO Land and Water* **23**(4):111.

Patra, H. 2014. Importance of afforestation in India. *Indian Geography*, February 16, 2014.

Patron, W.I., Morgan, J.A., Attenhoffer, J.M. and Harper, L.A. 1988. Ammonia volatilization from spring wheat plant. *Agronomy Journal* **80**:410-425.

Pillai, P.S., Issac, S.R. and Geetalakshmi, V.L. 2007. Balance sheet of soil nitrogen in rice (*Oryza sativa*) based cropping systems. *Indian Journal of Agronomy* **52**(1):16-22.

Portman, R.W., Daniel, J.S. and Ravishankara, A.R. 2012. Stratospheric ozone depletion due to nitrous oxide: Influences of other gases. *Philosophical Transactions of the Royal Society B* **367**:1256-1264.

Prakasa Rao, E.V.S.P. and Prasad, R. 1980. Nitrogen leaching losses from conventional and new nitrogenous fertilizers in lowland rice culture. *Plant and Soil* **57**:383-392.

Prasad, R. 1998. Fertilizer urea, food security, health and the environment. *Current Science* **75**(7):677-683.

Prasad, R. 2000. Nitrate pollution of groundwater. In: Srivastava, P. (Ed.), Environmental pollution and its management, A.P.H. Publication Co., New Delhi, pp. 120-127.

Prasad, R. 2012. The planet earth, life, and agriculture—Science, mythology and history. *Asian Agri-History* **16**(20):111-122.

Prasad, R. and Nene, Y.L. 2016. Asia's contribution to the evolution of agriculture: Creativity, history and mythology. *Asian Agri-History* **20**(4):233-250.

Prasad, R. and Prasad, S. 2018. Neem and environment. *International Journal of Plant and Environment* **4**(1):1-9.

Prasad, R. and Rajale, G.B. 1972. The influence of nitrification inhibitors and slow-release nitrogen materials on transformation of fertilizer nitrogen in soils of fluctuating moisture content. *Soil Biology and Biochemistry* **4**:451-457.

Prasad, R., Rajale, G.B. and Lakhdive, B.A. 1970. Effect of time and method of application of urea and its treatment with nitrification inhibitors on the yield and nitrogen uptake by irrigated upland rice. *Indian Journal of Agricultural Sciences* **40**:1118-1127.

Prasad, R., Rajale, G.B. and Lakhdive, B.A. 1971. Nitrification retarders and slow release nitrogen fertilizer. *Advances in Agronomy* **23**:337-338.

Prasad, R. and Shivay, Y.S. 2019. Fertilizer nitrogen and global warming. *Indian Journal of Agricultural Sciences* **89**(9):1401-1406.

Prasad, R., Singh, S., Saxena, S.S. and Devakumar, C. 1994. Coating prilled urea with neem (*Azadirachta indica*, Juss). *Naturwissenschaften* **86**:538-539.

Reddy, R.N.S. and Prasad, R. 1975. Studies on the mineralization of urea, coated urea and nitrification inhibitor treated urea in soil. *Journal of Soil Science* **26**:304-312.

Shivay, Y.S., Prasad, R., Pooniya, V., Pal, M. and Bansal, R. 2016. Sulphur coated urea as a source of sulphur and an enhanced efficiency of nitrogen fertilizer for spring wheat. *Cereal Research Communications* **44**(3):513-523.

Schjørring, J.K., Nielsen, N.E., Jensen, H.E. and Gottschau, A. 1989. Nitrogen losses from field-grown spring barley plants as affected by rate of nitrogen application. *Plant and Soil* **116**(2):167-175.

Smith, C.J., Nedwell, D.B., Dong, L.F. and Osborn, A.M. 2007. Diversity and abundance of nitrate reductase genes (narG and napA), nitrite reductase genes (nirS and nrfA), and their transcripts in estuarine sediments. *Applied and Environmental Microbiology* **73**(11):3612-3622.

Sudhakara, K. and Prasad, R. 1986. Ammonia volatilization losses from prilled urea, urea supergranules (USG) and coated USG in rice fields. *Plant and Soil* **94**:293-298.

Tian, Y.H., Bin, Y.B., Yin, S.X. and Zhu, Z.L. 2007. Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake Region, China. *Pedosphere* **17**(4):445-456.

Thimann, K.V. 1980. The senescence of leaves. In: Thimann, K.V. (Ed.), *Senescence of Plants,* CRC Press, Boca Raton, FL., USA.

Tillman, D., Blazer, C., Hill, J. and Befort, B.L. 2011. Global food demand and sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *USA* **108**(50):240-264.

TOI 2017. 5 plants that release oxygen at night! *Times of India,* Aug 8, 2017.

UK Centre for Ecology and Hydrology, 2018. Trees can help mediating ammonia in the atmosphere (*by internet*).

UN 2019. *World population, 2019 Review*. UN Population Division, Vienna.

Wang, S., Nan, J., Shi, Ch., Fu, Q., Gao, S., Wang, D., Cui, H., Saiz-Lopez, A. and Zhou, B. 2018. Atmospheric ammonia and its impacts on regional air quality over the megacity of Shanghai, China. *Environmental Science and Technology* **5**:15482.

Vasanthaiah, H. 2012. *Plants and Environment,* Florida Agricultural and Mechanical University, Tallahassee, FL, USA.

Wetselaar, R. and Farquhar, G.D. 1980. Nitrogen losses from top of plants. *Advances in Agronomy* **33**:263-302.

Wu, Y., Walker, J., Schwede, D., Peters-Lidard, C., Robin Dennis, R. and Robarge, W. 2009. A new model of bi-directional ammonia exchange between the atmosphere and biosphere: Ammonia stomatal compensation point**.** *Agricultural and Forest Meteorology* **49**(2):263-280.

Xin-hui, F.S., Ying-Sheng, L. and De-Xi, Y. 2006. Ammonia volatilization ^{15}N losses from urea applied to rice in a paddy soil. *Journal of Environmental Science* **16**(2):299-303.

Zhang, W., Tian, Z., Zhang, N. and Li, Z. 1996. Nitrate pollution of groundwater in northern China. *Agriculture, Ecosystems and Environment* **59**: 223-231.