Nitrogen Use Efficiency: A Comprehensive Review on Cereals with its Scope of Improvement

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Abstract

The efficient management of Nitrogen (N) is a challenging issue, and a range of individual and collective solutions are utilized to control it. Sadly, as predicted by the researchers when creating nitrogen management tools and procedures, nitrogen use efficiency (NUE) has not improved to a level of just 33%. Several approaches, including soil testing, spectrum response, fertilizer distribution and timing, and vegetative indices (leaf area index, and NDVI) employing drones, portable sensors, and satellite imaging, were investigated about the user-friendliness and effectiveness of NUE. It was found that no single method could completely stop the nitrogen leak. Plant tissue testing was one of the procedures found unsuited to a particular crop's N absorption behavior. Precision agriculture tools like Green Seeke, Holland Crop Circles, drones,

and satellite imaging were more successful than more conventional methods like soil testing. These tools, however, are only useful when the crop is in bloom. For N management, only in-season N application methods are allowed. It is required to provide large nitrogen rates using an in-season approach and some nitrogen at planting using the results of soil tests because crops like maize and potatoes use 70% of the nitrogen applied within 25-30 days of sowing.

Introduction

Despite being one of the largest industries in the world, agriculture, particularly in India, has not met the enormous demand for food due to India's alarming population rise. Future generations are likely to experience excruciating pressure from global hunger as per capita consumption rises because of shrinking agricultural lands due to rapid urbanization, industrialization, eutrophication, and soil infertility brought due to excessive use of organic and inorganic fertilizers, etc. (1). To meet the global food demand of the growing population, synthetic fertilizers have been used dramatically in the farm from last 50 years for attaining higher production of agricultural products mainly cereals (2).

Cereals are the main sources of nutrients and energy in both developed and developing countries (used as staple foods in daily diets), contributing 30.4% of the total dietary energy supply with 64.1% manganese, 51% carbs, 48.5% dietary fiber, and 6-15% protein, etc., (3). However, a gap between yield potential and actual farm yield was produced by a reduction in agricultural area due to a reduction in arable land, a decline in groundwater level, increased crop intensity, and a bigger form of cash crops, which led to a low output of cereal crops globally (4). Among all the 17 essential elements, nitrogen has been considered the most essential nutrient for plant growth, especially for cereal crops, and is needed in the greatest amount to generate better-quality and more-abundant products (6). Factors like low plant population, excessive fertilizer addition, improper application methods, timing, etc., have led to high losses of nitrogen (up to 70% of the total nitrogen available), and are the cause of low cereal production (5). Thus, the excessive, imbalanced, or inefficient use of fertilizers, mostly nitrogenous, has become the most serious and uncontrollable problem which is now a major challenge for the world to be faced (1).

Urea and nitrate are two often utilized inorganic nitrogenous fertilizers that are commonly employed in cereal cultivation in regions like Asia and Latin America (Figure1.) (7). The manufacturing of nitrogenous fertilizers was made feasible by the Haber-Bosch process allowed for the provision of food for about half of the world's population (8). The plant absorbs it in the form of NH_4^+, NO_2^-, and $NO_3^-$where out of total nitrogen present in the soil these account for less than 5%, and uptake before flowering helps in the synthesis of amino acids which are further used for the synthesis of enzymes and proteins and thus, significantly involved in the building up photosynthetic machinery and different components of the plant (8,10). Further, it was reported that nearly 6% of the nitrogen in the cereal seeds was stored in the form of protein reserves (10). When nitrogen present in the form of nitrate is not absorbed by plants, it leaches out and increases the phytoavailability of the nitrogen, which causes eutrophication and acidification of the soil (11,19). It also takes other nutrients like magnesium (Mg) and calcium (Ca) with it. Eutrophication of freshwater and marine habitats are examples of how nitrogen leaching occurs when it is applied to soil at high rates for crop production (8). Even the maize yield was found to increase by 4% when the nitrogenous fertilizer application rate was increased by 30%, but nitrate leaching was seen to increase by 53%, while the yield was reported to decrease by 10% when the nitrogenous fertilizer application rate was reduced by 30%. However, the loss through leaching or runoff was found to be greatly reduced by 37% reported by Donner and Kucharik (9). The development of sustainable, productive agriculture and conserving the quality of the environment has become extremely difficult (8). Numerous efforts must be made to improve nitrogen use efficiency in cereals to reduce the worldwide environmental and ecological load of nitrogen since improved NUE in crop production or agricultural farming systems may boost yields as well as profitability with reduced environmental repercussions (12,13).

Discussion

Understanding of Nitrogen Use Efficiency (NUE) in cereals

The most important part of our staple food and human nutrition are cereals like rice, wheat, maize, millet, barley, and sorghum, but nitrogen is their essential structural component and is necessary for both good growth and high-quality yields (14). Due to its role in photosynthetic mechanism, growth-development process, and proteomic and phytohormonal alterations, it is regarded as one of the primary limiting nutrients (5). Being low availability of soil N content, nitrate (NO3-) is likely the major predominant source of N fertilizer. Except for rice, where ammonium ions are the main source of inorganic nitrogen, its available concentrations depend on pedoclimatic factors like temperature, pH, soil, etc. (10). So, it should be given to recommended amount otherwise limiting inorganic nitrogen can lead to reduced food production and consequently, hunger, while a surplus can harm the ecosystem by polluting the air and water (16). Figure.2 shows the world demand for total nitrogen from the year 2015 to 2019 and Figure.3 shows nitrogen usage across the world over the years.

Therefore, nitrogen use efficiency is the most significant factor in the uptake and utilization of nitrogen whose variation can be observed by N doses, methods of application, and some other agronomic factors, and can be defined as the percentage of nitrogenous fertilizer used by the different components of the crop from the total applied quantity of fertilizer (14). Agronomically, it is the output-input ratio including uptake, utilization, or photosynthetic efficiency of crops mostly cereals in the form of grain yield per unit nitrogen (7). It mainly consists of two processes: nitrogen uptake efficiency (NupE) and nitrogen utilization efficiency (NutE) where NupE is the nitrogen-removing ability of the plant from the soil in the form of ammonium and nitrate ions while NutE is the nitrogen-using ability of the plant to produce grain yield (8). These can be calculated as: (5)

$$\mathrm{NupE} = \mathrm{N\ contents\ in\ plant/total\ N\ applied}$$

$$\mathrm{NutE} = \text{Total yield / N contents in plant}$$

$$\text{And } \mathrm{NUE} = \mathrm{NupE} \times \mathrm{NutE}$$

Two important phases are involved in the uptake and utilization of nitrogen: the vegetative phase, in which young leaves and roots act as a sink, and the post-flowering phase, in which roots and shoots serve as sources. Both phases have subphases: reduction, assimilation, translocation, and remobilization (8,17). However, the cell membrane of the root is specialized to contain two main important systems i.e., a low-affinity transport system (LATS), to become active in the condition of high nitrate concentrations, and a high-affinity transport system (HATS), to become active in low nitrate concentration conditions (10).

The enzymes glutamine synthetase, glutamine oxoglutarate aminotransferase, nitrate reductase, nitrite reductase, and asparagine synthetase regulate the metabolism of nitrogen, which is a component of amino acids, nucleic acids, chlorophyll, phytohormones, and ATP (5). Nitrate is converted to nitrite in the plant cell's cytosol by nitrate reductase enzyme. Nitrite is subsequently transferred to the plastids and chloroplasts, where it is reduced to ammonium by the nitrite reductase enzyme (10). Moreover, glutamine synthase (GS) catalyzes the fixation of ammonium, which occurs mostly in cereal grains like wheat and rice. These findings suggest that grain dry matter, N consumption efficiency, and N harvest index are all improved by higher GS activity in plant leaves (10).

Now, the question arises why are NUEs so low in cereals? The low NUEs in cereals are generally because when N fertilizer (ammonium nitrate, ammonium sulfate, or urea) is applied to soil, fertilizer is subjected to N loss through different ways such as ammonium volatilization (after transformation of NH4+ to NH3), nitrous oxide emissions (due to nitrification and denitrification process), nitrate leaching (due to anionic nature, NO3- is highly mobile in soil), etc. (18). Maize crops have reported N losses of 52-73% and winter wheat losses of 21-41% of total N applied, respectively, in studies where surface runoff accounted for the loss of N fertilizer (19). In other words, even though improvements have been made in the areas of soil management, fertilization, irrigation techniques, and cultivars available, the NEU has been reported to be less than 50% when cereals are given a lot of N fertilizers to get the highest grain yields. This is because the remaining percentage of the fertilizer escapes to the environment through various mechanisms and functions (8). The remaining fertilizer that escaped is lost either by leaching through nitrogen solubility in water, immobilization, clay fixation, denitrification by anaerobic bacteria, or ammonia volatilization (13). To achieve maximum production of cereals, fertilizer is applied without properly incorporating the field surface, which results in surface runoff. The leaching of NO3 increases the loss of N by up to 40% and is proportional to factors including temperature, surface residue, and soil pH. (19). That’s why, even after a drastic increase in the usage of nitrogenous fertilizer, the world’s cereal production is very less as per the requirement as crops recover on an average of 33% of total applied N fertilizer only

(13). Thus, NUE should be enhanced as quickly as feasible for advantages to worldwide sustainable cereal production and the atmosphere (5).

Methods to Improve Cereals' Nitrogen Usage Efficiencies

- **Efficient Application Rate**

To fulfill the demand for food for large populations or high crop production, an excessive amount of synthetic nitrogenous fertilizer is being used on agricultural land by farmers which in turn created the problem of lodging due to shoot overgrowth and tender, spoilage of quality of grains, insect and pest infestations, and lastly low nitrogen use efficiency (5). Reducing the N fertilizer application dose rate to enhance NUE may cause late leaf senescence but in a report, it was found that late leaf senescence because of low N dose provides relatively higher photosynthetic capacity to plants which in result increase grain yield production (5). NUE in response to N fertilization rate particularly during crop rotation was observed to be 32-38% and 31-40% during the years 2011-2012 and 2012-2013 respectively (20). Hence, when the N fertilizer application rate is reduced by 20%, countries like Australia have observed minimal yield loss with the limitation that the plant density must be high (5).

- **Real-Time Foliar Application and Deep Placement of N Fertilizer**

According to reports, top dressing or deep placement of nitrogenous fertilizers applied seasonally to cereals is more effective at facilitating fertilizer uptake and utilization as compared to early or late application, where early application causes excess N and reduces NUE with inefficient grain yield, while late application increase grain protein content but certainly reduces NUE (19). The N loss encouraged by nitrification and denitrification in flooded rice-production systems can be reduced by deep placement of fertilizers as it prevents the conversion of NH4 to NO3 and it was found to reduce 65% N loss as well as a 50% increase in rice yield (18). When urea solution is applied at a rate of 11 to 56 kg/ha by the method of foliar application at the flowering stage, the grain protein of cereals is found to increase by 4.4%. The N recovery was found to be between 55 and 80% when supplied during the anthesis stage, but it was only 30 to 55% when N is supplied at the planting stage (19). In a study, 94% suppression of NH3 and N2O loss was reported in the deep placement method whereas its newly developed advanced technique i.e., "Closed-Slot Injection Method" has also been proven much effective in reducing NUE as it was seen to decrease NH3 emissions, like in the case of maize where 75% reduce in NH3 loss has been reported (18). In the case of barley, it was observed that the foliar application method had more efficiency as compared to the broadcasting method of fertilizer application because the grain protein content was found to be increased when 50 kg N/ha was applied in spray during the awn emergence stage (19).

- **Drip Fertigation**

For precise fertilizer and water delivery, drip fertigation is a good option. Recent years have seen a significant increase in the use of drip fertigation with mulching. It is well known that drip fertigation can increase crop production for each unit of nutrients and water used while also improving the efficiency of nutrients and water use. It benefits more from the soluble fertilizers that can be applied in a specific amount along with the healthy crop and potential yield due to continued fertigation in the root zone. Numerous studies have shown that fertigation can increase the effectiveness of fertilizer use by reducing application rates without reducing crop yield (5).

- **Cultivars with high harvest index and low forage yield**

The ability of a plant to transform fertilizer-acquired N into economic yield and the yield produced per unit of acquired N by the crop shoots depend on physiological efficiency and N utilization efficiency respectively while N allocation to yield concerning the whole plant N (21). In an early study, nitrogen use efficiency was found to be increased with comparatively low N loss in those varieties of cereal which have high harvest index as well as low forage yield, for instance, some varieties of wheat and rice are found to have high harvest index with low forage yield (19). Thus, the N harvest index can be very crucial in determining the amount of total N returned to the soil after harvesting in the form of plant N residue which serves as a source depending on the timing of N fertilizer application relative to crop N demand (21).

- **Enhanced Fertilizers**

When soil N content is the deficit, the crop parameters such as N content, biomass, and yield mainly depend upon applied fertilizers and are influenced by the factors such as agronomic efficiency (illustrates the improvement in productivity of a crop by supplied N), the recovery efficiency of fertilizer (addresses the apparent enhancement in crop N uptake in response to the N application), partial N balance (illustrates the ration of N removal to N use) and N balance intensity (describes the difference between N removed and used) (21). Therefore, the enhanced fertilizers should be used which include the fertilizer coated with low permeable materials attached to either urease or nitrification inhibitor such as phenyl-phospho-rodiamidate, 3,4-dimethyl pyrazole phosphate (DMPP), N-(n-butyl) thiophosphoric triamide (NBPT) and dicyandiamide (DCD) that regulates the process of urea hydrolysis and nitrification as a result of which there is reduce in N loss and increase in N uptake by crops especially cereals (18). DMPP and DCD with urea are found to be effective in reducing N2O emission while adding NBPT is found to reduce NH3 volatilization from agricultural soils (18).

- **Intercropping Method**

Intercropping is a sustainable approach used in countries like China, India, Southern Asia, Latin America, and Africa that incorporates the effective use of land and nutrients for high yield and productivity (22). Fertilization techniques have a significant impact on intercropped crops, which grow better with a variety of nitrogen supplies in interspecific rows as opposed to intraspecific ones. Applications that cross domains increase soil productivity, and resource use efficiency, and environmental factors like heat, light, and rainfall can be a constraint for cropping systems. Numerous earlier studies have shown that biological nitrogen fixation is negatively impacted by high N input. When nitrogen availability for mixtures of legumes and non-legumes is studied a high concentration of mineral nitrogen in the soil causes microbial nitrogen fixation, which reduces nitrogen availability for non-legume crops. Low nitrogen input, however, significantly increased fixation and encouraged the translocation of fixed nitrogen to non-legumes. (5). According to several studies, large N input negatively impacts biological nitrogen fixation. When nitrogen availability for legumes and nonlegumes mixture is evaluated, a high concentration of mineral nitrogen in the soil causes microbial nitrogen fixation, which reduces nitrogen availability for nonlegume crops. Low nitrogen supply, however, dramatically boosted fixation and encouraged the transfer of fixed N to nonlegume (5).

- **Shaping Microbial Activities Mechanism**

Arbuscular mycorrhizal fungi (AMF) and N-fixing microbial activities play a vital role in controlling N response to soil as these can improve N absorption efficiencies, soil N cycling, and NUE as well (21). Therefore, low soil N content conditions can be improved by associations of arbuscular mycorrhizal fungi through expanding the crop root surface area to approach more soil volume, accelerating nitrogen mineralization, and facilitating N uptake whereas in high N content soil having more efficient fungal partners with characteristics of proliferating and acquiring NH_4^+, AMF may be a very relevant factor (21). Another strategy might be N-fixing cereals plants such as rice, maize, wheat, and sorghum, which have been linked to a variety of fungi and bacteria, including N-fixing bacteria, which are diazotrophs found on plant roots and are effective in encouraging plant development by giving nitrogen to their host cereals crop (23). Nitrogen-fixing plants once used energy to secure their supply of nitrogen by biological nitrogen fixation and nodulation when there was insufficient nitrogen in the soil to meet plant needs (21). As a result, it has been discovered that using genetically engineered bacteria, such as ammonium excreting Azospirillum and mutants of Azospirillum, Kosakonia, Pseudomonas, and Azotobacter, may improve the N supply to wheat crops and promote plant growth, respectively (23).

- **Site-Specific N Fertilizer Management**

The response of a crop to added N depends on soil conditions as it takes into account the nutritional requirements of particular crops, the inherent capacity of the soil to supply N, calibrated N dosages, utilization of the maximum number of resources available to obtain N, and the best practices for N use (18). However, high grain yield has been achieved under high N fertilization by developing semi-dwarf varieties of cereals; however, even in this case, farmers frequently add excessive amounts of fertilizer and develop the problem of lodging and susceptibility to pests and diseases. This is because improper timing and excessive rates of N application have resulted in low nitrogen use and recovery efficiency. Hence, to improve the N usage efficiency of cereals, the site-specific N management (SSNM) approach was developed based on the crop N demand principle (24). It depends upon certain factors such as the yield potential of the crop, the amount of N required to fill the nutrient deficit gaps, plant nutrition, and N recovery calculations that significantly enhance the recycling of N in soil, minimize N loss in the form of NH_3 and N_2O mostly during growth stage (18). To determine the total N rate based on N supply capacity and attainable yield, SSNM involves four major and significant steps which are: - (a) based on 85% yield potential, set an achievable grain yield target, (b) based on without N fertilizer yield, estimate total N supply, (c) based on the difference between targetable yield and yield without N fertilizer, estimate N response, and (d) based on NUE and N response, estimate total N rate (24). The development of numerous additional strategies for variable-rate N management at the early growth and development stages of plants includes the real-time fluoro-sensing technique (emerging technology), where 15 kg N/ha has been reported to increase NUE without reducing wheat grain yield, and the proximal sensor-based technique, which reported an increase in maize yield with improvement in NUE (18). So, in comparison to farmers` N fertilizer practices, SSNM has been reported to reduce 32% N fertilizer as well as enhancement in grain yield of cereals especially rice by 5% (24). Therefore, site-specific N fertilizer application results in an increase in quality and quantity of yield as well as NUE with a positive impact on the economy and ecology (5).

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Figures

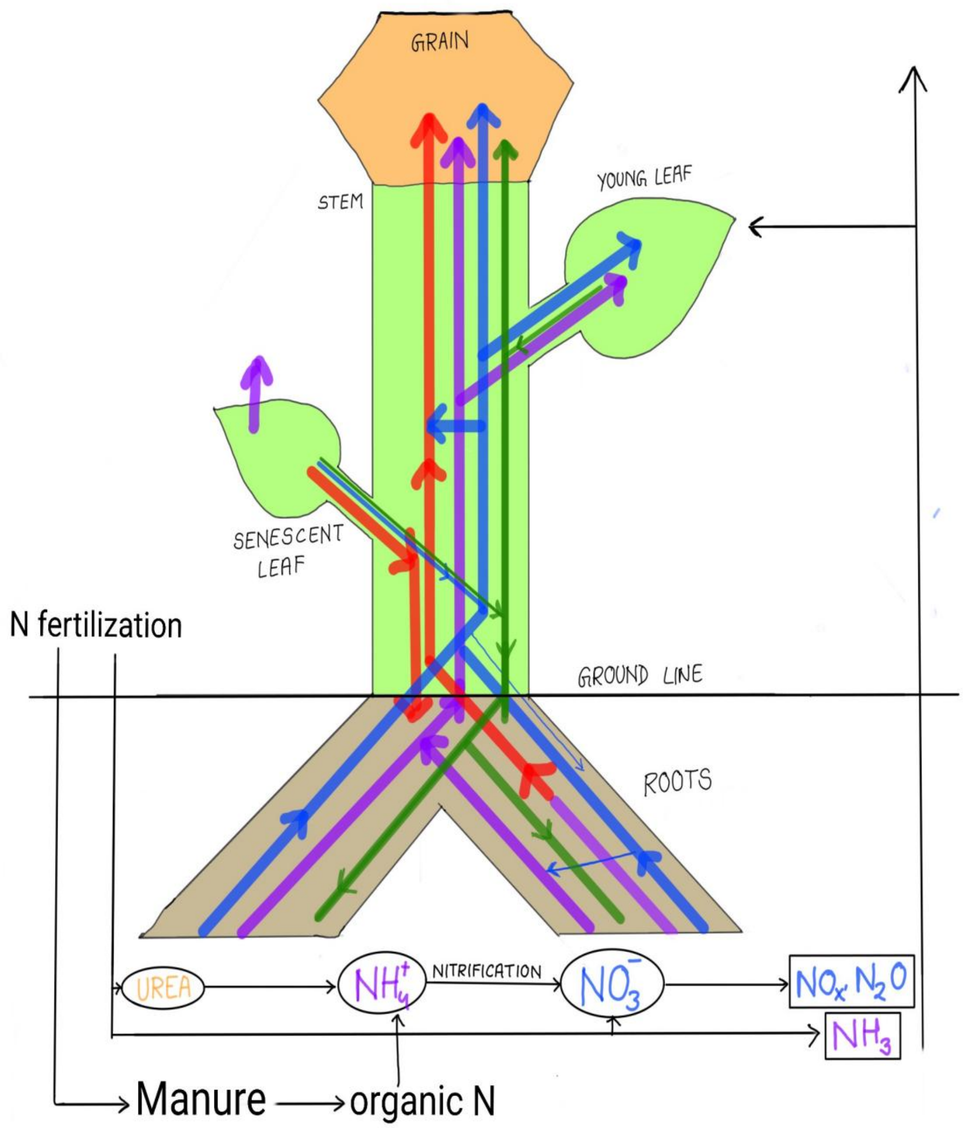

Figure 1. Diagrammatic representation showing the sources of fertilizer N to be absorbed by roots, primarily in the form of ammonium and nitrate, transportation within the plant. (Color coding: Purple-Ammonium transport, Blue-Nitrate transport, Red-Amino acid transport, Green- sugar transport, Black- N turnover in soil). (25)

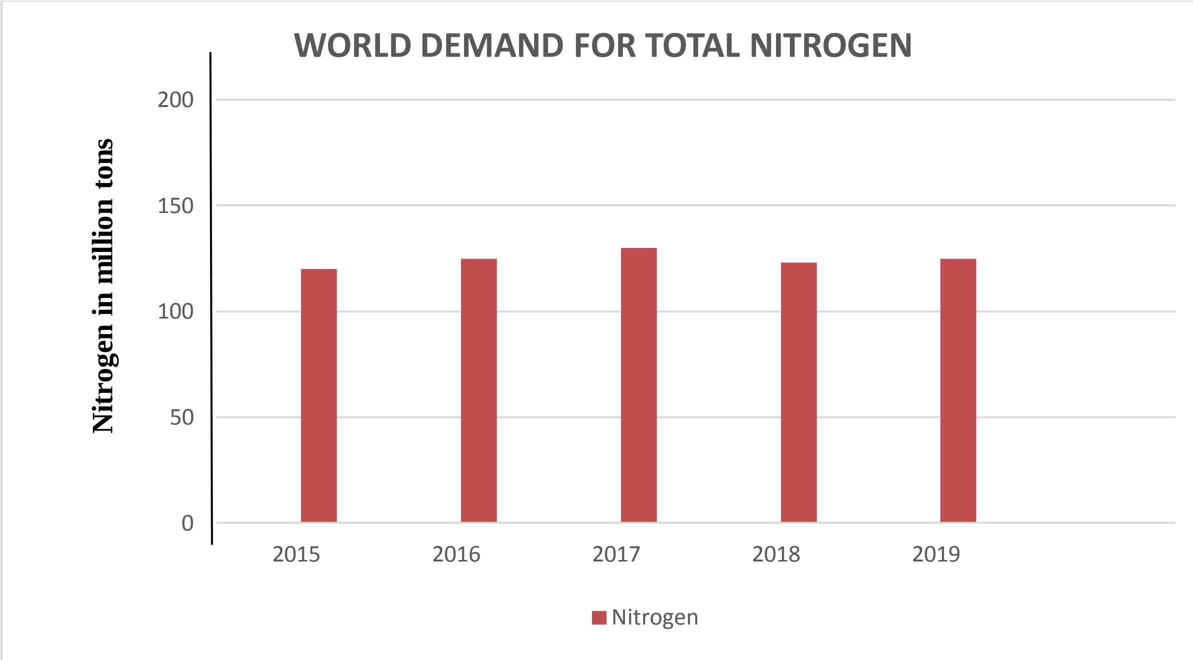

Figure 2. World demand for total nitrogen from the year 2015 to 2019

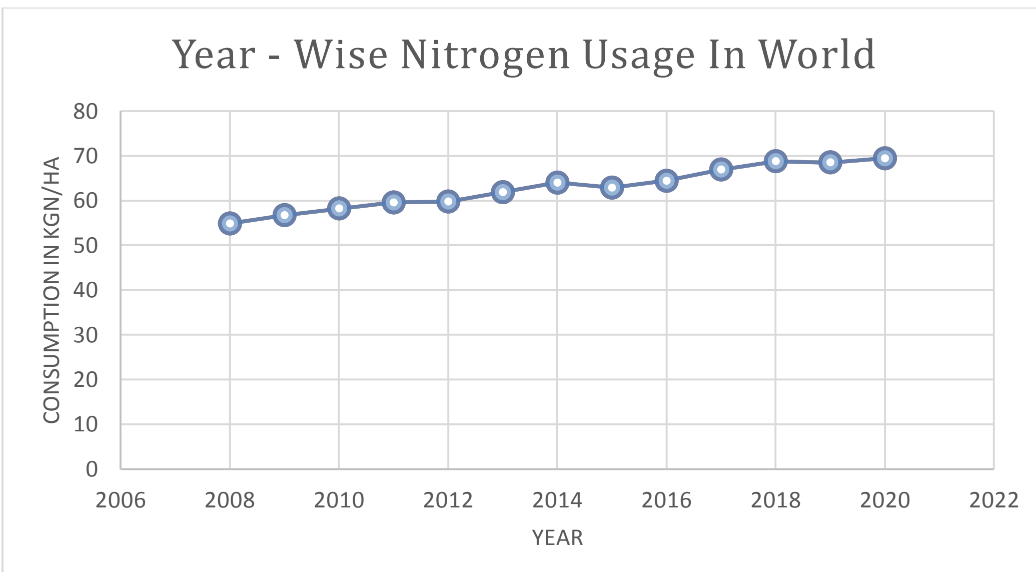

Figure 3. World nitrogen usage across the year (26)