REVIEW

Split application of liquid urea as a tool to nitrogen loss minimization and NUE improvement of corn – A review

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ABSTRACT

Nitrogen loss minimization is the main challenge to sustainable crop production and reducing environmental and economic losses. There is a new approach to urea application in liquid form (LU) so that the NH_4^+ can be evenly distributed throughout the soil profile, soil particles adsorb it and reduce the local substrate concentration inhibiting further transformation. Liquid urea has been hydrolyzed even prior to soil application, whereas the urea in granulated urea (GU) must be hydrolyzed after application before it can be transformed to NH_4^+. Increased urea application frequency with lower doses can lower the NH_4^+ concentration in soil compared to a single application. These mechanisms reduce the N loss potential and increase the N crop uptake potential of applied N by conforming to the proper synchronization between N availability and crop N demand as well as reduce N loss potential as NH_3 volatilization, NO_3^- leaching and N_2O emission. The inconsistent results and clarifications from various studies highlight the importance and benefits of relating the effect of LU application on N loss minimization, N availability and corn (*Zea mays* L.) yield. This review summarizes the potential ways of N losses and their management and provides the scientific reference to achieve sustainable corn yield and reduce N losses.

Key words: Corn, liquid urea, NH_3 volatilization, NO_3^- leaching, N_2O emission, split application, *Zea mays*.

INTRODUCTION

Corn (*Zea mays* L.) is one of the most important and extensively cultivated cereal crops all over the globe. It is used as food, animal feed and manufacturing goods such as milk to toothpaste, shoe polish, ethanol in the first world, provides food, feed and dietary safety in the third world's nations of Africa, Asia and Latin America (Ranum et al., 2014; USA.gov, 2019). It is grown on about 160 million hectares of land, 11% area of the entire world's cropland (Linquist et al., 2012), and above 73% of the corn cultivated area is located in developing countries. It is expected that the demand for corn for food and feed will be rising, governed by higher population growth and commercial advancement (Shiferaw et al., 2011).

The agricultural system is the primary source of greenhouse gas (GHG) emission, and more than half of applied N to the soil as granulated urea (GU) is lost through gaseous and leaching loss resulting in low N use efficiency (NUE) (Sutton et al., 2011; Khan et al., 2014). The surface application of urea is the principal anthropogenic cause of gaseous emissions. Faulty application method, excessive use, uneven distribution, seasonal variation, climatic interference, and edaphic factors promote loss of applied urea which causes low NUE and increases the cost of crop production and disruption of the natural ecosystem.

The gaseous and leaching loss of N mainly depends on the rate of urea hydrolysis, N mineralization and density of urea in soil. Soil moisture content is one of the influential factors that starts the urea hydrolysis process (Abera et al., 2012) and maintained soil total N content. It affected N mineralization and losses (Fu et al., 2019). Faster hydrolysis promotes higher urea mineralization, and higher soil water content increases the hydrolysis as well as the mineralization of urea. On the other hand, fast urea hydrolysis reduced gaseous N losses as it diffused the applied urea and NH_4^+ in the deeper soil layer (Kissel, 1988). The NH_3 volatilization, N_2O emission and leaching of N increased with the increased rate of urea applications (Zhang et al., 2015; Ma et al., 2019; Degaspari et al., 2020). However, N losses can be minimized if urea hydrolysis is fast so that the ammonium cations (NH_4^+) are more uniformly distributed throughout the soil profile. Researchers have projected several methods to reduce N losses and improve the efficiency of urea application. There is no single method that can effectively restrict NO_3 leaching, N_2O and NH_3 losses from applied urea except by reducing the application rate. The process of urea hydrolysis started earlier in the liquid urea (LU) application because the urea had already been hydrolyzed even before it was applied to the soil. At the same time, the GU needed time to absorb water before it can be hydrolyzed. Therefore, earlier urea hydrolysis may promote faster N mineralization. Application of LU could be distributed throughout the soil column, ensuring lower N concentrations in the soils.

Ammonia (NH_3) volatilization loss

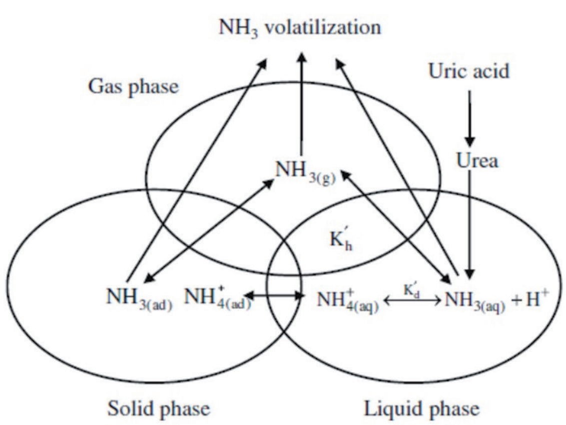
Nitrogen loss as NH_3 volatilization is the most problematic as NH_3 is a corrosive GHG that causes environmental degradation. This loss becomes more alarming when urea is broadcasted (Mira et al., 2017). These losses in farming areas range as high as 64% of applied N, depending on the variations of sources, rates, places, and times of N fertilizers applied (Pan et al., 2016). The NH_3 volatilization loss reduces NUE, hence, increases crop production costs (Recio et al., 2018). The agricultural sector emits the highest (98%) NH_3 volatilization, and 35% is estimated from N fertilization (Fontelle et al., 2014). In addition, more than 50% of applied urea is lost through NH_3 volatilization (Majaron et al., 2020). Urea, ammonium sulphate, ammonium nitrate, and urea ammonium nitrate (UAN) are N fertilizers that are all vulnerable to NH_3 volatilization (Dari et al., 2019).

As a gas, NH_3 is likely to be volatilized to the atmosphere when present in the soil, water or manure and shows a significant affinity to water. The basic determinants of volatilization rate are NH_3 reactions in water. The process of NH_3 volatilization (Simpson, 1981; Vlek et al., 1981) is as follows:

$$\uparrow \text{to atmosphere}$$
$$NH_4^+ \text{ (absorbed)} \leftrightarrows NH_4^+ \text{ (in solution)} \leftrightarrows NH_3 \text{ (in solution)} \leftrightarrows NH_3 \text{ (gas in solution)}$$

The ammonia volatilization rate can be regulated by the withdrawal rate and dispersion of NH_3 into the air and by concentration alteration of NH_4^+ or NH_3 in soil solution (Figure 1). The partial pressure difference of NH_3 between the liquid phase and the surrounding atmosphere is the driving force of NH_3 volatilization (Freney et al., 1983).

Figure 1. Mechanisms of ammonia volatilization from applied urea in soil (Liang et al., 2014).



The immediate contact of urea granule to the soil particles increases the adsorption of NH_4^+ to the soil colloids, which effectively reduces the NH_4^+ conversion to volatile NH_3 of applied N in the presence of sufficient moisture (Silva et al., 1995). Likewise, Cabezas et al. (1997) stated that a suitable amount of moisture in the field affects the ammonia volatilization loss from surface-applied urea by diluting the hydroxyl ions concentration, which accounts for the conversion of NH_4^+ to volatile NH_3^+. Therefore, ammonia volatilization decreases when soil provides optimum moisture for urea hydrolysis and disperse inside the soil profile for the adsorption by the particles.

The amount of NH_3 losses is also affected by the soil pH, buffer capacity, cation exchange capacity (CEC), organic matter (OM), N source and rate, fertilization time, and placement of urea (Randall and Sawer, 2008; Rimski-Korsakov et al., 2012). A higher rate of urea application increases the NH_3 volatilization loss (Ma et al., 2019). Periodic differences in soil wetness, heat, and precipitation sharply also influence NH_3 volatilization loss. Initial soil wetness resulted in the maximum NH_3 volatilization. The seasonal variation in the field significantly affects NH_3 volatilization loss because soil moisture, temperature, and rainfall are different from season to season.

Urea concentration and pH significantly stimulate NH_3 volatilization. During hydrolysis of the surface applied urea, the local soil pH increases depending on the urea concentration. This will increase the soil pH and promotes higher NH_3 volatilization. Urea in a solution form (e.g., LU) may decrease the local urea density as it defuses quickly into the soil column. This process prevents the unexpected rise in soil pH. Besides, it decreases the local NH_3 concentration because of the higher adsorption by the soil particles.

Nitrous oxide (N_2O) emission loss

Agricultural soil is a prime source of N_2O emission that is active in lowering the NUE of applied urea (Zhang et al., 2019; Yao et al., 2020), the most injurious greenhouse gas (IPCC, 2014). Microbial nitrification and denitrification processes in general soils contribute to about 70% of the world's N_2O emissions (Syakila and Kroeze, 2011; Braker and Conrad, 2011). The nitrification rates are greatly affected by the physical, chemical, and biological properties of soil, such as nutrient status, pH, and moisture content. The highest rate of nitrification occurs at around field capacity moisture content. In wetter or very dry soils than field capacity moisture content, the rate of nitrification is slower. In addition, nitrification rates are greatly variable depending on the density and diversity of nitrifying soil microbes and substrate concentration, and the presence of oxygen (Parkin, 1993; Stark and Firestone, 1996). Light textured soils promote higher nitrification due to their higher aeration potential than heavy-textured soils. The lower substrate concentration decreases the rate of nitrification. Therefore, fast urea hydrolysis disperses the NH_4^+ ions inside the soil profile, decreasing the local NH_4^+ concentration, hence, lower nitrification. Furthermore, synchronized urea application to plant N uptake potential can reduce the substrate concentration in soil.

The denitrification is a major contributor to overall N_2O emissions from applied urea while soil having relatively higher moisture content and low (5.0 to 7.5) soil pH (Clark et al., 2012; Goulding, 2016). Regular and heavy year-round precipitation and relatively high temperatures may influence numerous biochemical processes to discharge atmospheric N_2O during N conversions (Khalil et al., 2001). The N losses increase with the increase of precipitation frequency and/or intensity along with N application rates under tropical conditions (Owino and Sigunga, 2012).

Nitrogen leaching loss

Nitrogen leaching is the most crucial N loss pathway and an estimated about 19% of applied N leaches out from agricultural systems globally, contaminating groundwater and eutrophication of surface water creating lots of economic loss and health hazards (Zhu et al., 2009; Sutton et al., 2011; Zhou and Butterbach-Bahl, 2014). Nitrogen leaching loss decreases crop growth, development, and NUE. Leaching is more problematic in light-textured upland soil (Puga et al., 2020). The amount of nitrate leached from a soil system depends on the nitrate concentration in the soil solution along with rainfall pattern, irrigation mechanism and soil texture, while the nitrate concentration in the soil solution depends on the rates of N application, nitrification, denitrification, plant uptake, etc. (Cameron et al., 2013). Nitrate ions are unlike to be adsorbed by the soil particles, and leaching down occurs by the combination of three principal processes convection, dispersion, and diffusion. Normally the nitrate drains out through either mass flow of water (convection), dispersion inside the soil particles, or the substrate movement from high concentration to low concentrate water (diffusion). In most agricultural systems, all the three mechanisms are active collectively though one of the processes is more dominant (McLenaghen et al., 1996; Cameron et al., 2013).

Nitrate (NO_3^-) is transformed from ammonium (NH_4^+) through nitrification catalyzed by ammonia-oxidizing bacteria. The rate of NO_3^- formation depends on the various soil factors, such as soil pH, moisture content and fertility status, and the maximum rate of nitrification at the field capacity moisture content (Haynes et al., 1986). The favorable conditions for nitrification increase NO_3^- leaching while plant uptake and denitrification decrease NO_3^- concentration in the soil solution, thus reducing the risk of NO_3^- leaching. The clayey soil with higher CEC adsorbs more NH_4^+ ions on its surfaces; therefore, they have lower NH_4^+ concentrations in the soil solution. The LU application reduces the NH_4^+ concentration in the soil by dispersing the NH_4^+ into the soil profile and decreasing the NH_4^+ concentration in the soil (Motasim et al., 2021b). In addition, the increase in urea application frequency with lower doses lowers the NH_4^+ concentration in soil compared to a single application. These mechanisms reduce the rate of nitrification and ensure less NO_3^- concentration in soil solution, therefore, decreasing the potential of NO_3^- leaching.

Nitrogen leaching decreases the NUE of applied N fertilizer significantly (Puga et al., 2020). Nitrogen leaching was higher in light-textured upland soil than in relatively heavier soils (Gioacchini et al., 2002; Motasim et al., 2021b), and the higher application rate of urea increased higher N leaching loss (Ma et al., 2019). On the other hand, the slower transformation of NH_4^+-N and faster hydrolysis of applied urea decreased the leaching loss of N (Zuki, 2020). When applied at the right time and placed at a proper position, N leaching from soil decreased, and the NUE was increased (Nasielski et al., 2020).

Nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) is the portion of applied urea that the plant consumes for growth and development. It is the ultimate output of plant N absorption and assimilation efficiency of absorbed N. Agronomic operations, the use of controlled released or enhanced efficiency fertilizers, incorporation or impregnation of urea fertilizer to various organic or inorganic materials can significantly increase NUE and yield of corn (Latifah et al., 2017; Martins et al., 2017; Zhang et al., 2017; Kubota et al., 2018). The conventional tillage in the rain-fed condition also increased corn yield and NUE (Pareja-Sánchez et al., 2019) while urea top dressing decreased corn grain yield by 6.8%-9.8%, NUE by 13.2%-14.3% with annual net loss increased by 15.4%-21.8% compared to coated urea at the similar rates of N application (Zheng et al., 2017). In addition, the N uptake in grain increases with the increase of N application frequency compared to a single or double application, while total N uptake and biomass production also increase significantly (Lü et al., 2012).

In the case of late-sown corn, a high plant population density effectively increased the accumulative N uptake (Maltese et al., 2019), and late harvest of the crop increased yield and improved NUE in corn. The delayed harvest promoted N accumulation and physiological NUE; thus, grain productivity increased by promoting N accumulation after tasseling and N movement to grain (Liu et al., 2019). In addition, the interaction between plant density and N availability has been found effective on the growth and development of the corn plant. Higher plant density under low-N conditions significantly increased the grain yield of corn (Adu et al., 2018). Timing and placement of urea fertilizer significantly reduce N losses, increase NUE and grain yield of corn which also depends on the mean emission factor of total N. There is a correlation between the total N input and cumulative emissions and emission factors. Increasing N input increases the risk potential of N losses. Moreover, surplus N application increases the risk of N emission to the atmosphere (Martins et al., 2017; Cardenas et al., 2019). Best management practices that synchronize optimum irrigation, sufficient N availability, and effective N uptake can maximize the NUE of crops. The combination of proper irrigation methods and split N fertilizers application can significantly improve the NUE of a crop (Chilundo et al., 2016). In addition, the application of N fertilizers by mixing to the irrigation system promotes continuous N supply to the crop and reduces the risk of N losses as emission or leaching.

The placement of N fertilizers also increases NUE by reducing N losses. In the surface application, a high level of applied N is immobilized by other than the crop or increases N losses with increasing soil pH, temperature, and surface stover. Application of N fertilizers in-band or side-dress, soil mixing or injecting into the soil have been proved to be the most efficient in improving N availability than surface broadcasting (Ullah et al., 2019). Deep placement of N fertilizers increases N recovery efficiency by 55% and decreases 91% ammonia volatilization loss than surface broadcast application (Yao et al., 2018). It increases the N availability within the rhizosphere, increases N uptake, corn yields and ultimately NUE (Paustian et al., 2004). In addition, while UAN was applied 2-3 cm deep, it resulted in higher growth and development in crop production. Moreover, deep placement of LU increases the 20% yield compared to broadcast granular urea (Holloway et al., 2001; Ii et al., 2017), whereas Watkins (2013) have not found any advantages on the surface and subsurface application of UAN.

Factors influencing NUE

Nitrogen use efficiency (NUE) is a very dynamic and complex perception affected by various factors. The genetic characteristics of crops mainly affect the NUE of urea as the high-yielding modern crop verities utilized applied urea more efficiently (Muchow, 1998; Tolessa et al., 2007). The environmental parameters influence the growth and development of crops as well as the N demand for crops and N availability in the soil. The crop N demand with uptake capacity and N availability with loss minimization are the major issues of NUE (Yadav et al., 2017). In contrast, N availability and losses are greatly affected by various environmental and physicochemical properties of soil. Fertilizer application method, timing, and placement influence the NUE of the crop, while the application of modified urea (e.g., controlled released fertilizers, slow-release fertilizer, coated urea, etc.) fertilizers minimizes losses. In addition, the use of UAN or LU, sub-surface urea application, mechanical application, and splits application of urea effectively increase the NUE of crops (Holloway et al., 2001; Lü et al., 2012; Singh et al., 2013; Steusloff et al., 2019).

Best management practice (BMP) is a technique that synchronizes optimum irrigation, sufficient N availability, and efficient N uptake to increase NUE. Effective irrigation management and splits urea application can boost NUE (Cassman et al., 2002; Chilundo et al., 2018; Ullah et al., 2019).

The influential factors of NUE may be classified into three major groups:

Nitrogen demand of the crop: NUE is crucially affected by the N demand of a crop. Nitrogen demand depends on various environmental parameters such as the surrounding temperature, solar hour, amount and distribution of rainfall, and relative humidity. These parameters influence the growth and development and the N demand (Hutchinson et al., 2002; Yadav et al., 2017). The interactions of these parameters mainly control the crop performance and the agro-climate of a region. Besides, seasonal variation with fluctuation in climatic parameters also interferes with N demand (Mosier et al., 2002).

The high-yielding modern corn varieties can increase the NUE while growing under sufficient N available conditions in the well-fertilized field. But if they grow under low fertilized fields, NUE will remarkably decrease. The low N demand genotype has low NUE, even if it grows in a high N available field. Optimum and stable NUE is expected from genetically N efficient crop varieties only (Tolessa et al., 2007). Biotic and abiotic stresses crucially affect the NUE as they will negatively influence plant growth and development. The biotic stresses, such as pests and abiotic stresses, such as drought conditions, salinity, extreme temperature, harmfully affect crop growth and development and lower the NUE (Gong et al., 2014).

Nitrogen supply to crop: Nitrogen supply to crop is a continuous process through decomposition of OM and mineralization of applied N fertilizers. Consistent and sufficient N supply from OM decomposition is comparatively less because of the slower mineralization rate. In contrast, fertilizer contributes a larger N supply due to its quick availability through a higher mineralization rate.

The rate of N mineralization is significantly promoted by various soil factors (soil moisture content, temperature, pH, texture, aeration, microbiological activity) and environmental factors (precipitation, sunshine hour, air velocity, topography, vegetation) For example, low soil moisture content and temperature reduce the rate of N mineralization (Giller et al., 2004; Yadav et al., 2017). Suitable soil and environmental conditions increase the rate of mineralization and N availability to the plant. Nitrogen use efficiency declines if N is oversupplied or when the plant suffers from severe moisture deficiency (Muchow, 1998). Efficient N management is possible only when the N is applied according to the demand of the plant, specifically, by supplying N based on the crop growth stages.

Nitrogen loss minimization: Nitrogen loss decreases the N availability, and the plant suffers nutrient stress which severely decreases the NUE. Moreover, different types of nutrient losses from the soil crop system lower the NUE of a crop. Suitable environmental conditions will reduce stress in plants and increase crop N demand. Nevertheless, N demand cannot be fulfilled if N loss is huge, creating lower N recovery of applied N fertilizer (Yadav et al., 2017). Gaseous loss, runoff and leaching loss of N from the rhizosphere reduce the NUE of a cultivation system (Mosier et al., 2002). Urea top dressing promotes the high N loss, and about 10%-80% N loss from urea remains unexplained (Torello et al., 1983). The leaching loss of NO_3^- and volatilization loss of NH_3 are the leading N loss mechanisms estimated as 78% and 93% of the yearly loss from applied urea, respectively (Zhou et al., 2016). In addition, about 0.1% to 2.0% urea is lost from the systems as N_2O gas depending on the soil-environmental conditions (de Klein et al., 2001).

Nitrogen loss management is the most effective way to increase crop uptake and increase the NUE. Researchers have developed some user-friendly, cost-efficient, stable and eco-friendly technologies that can effectively reduce N loss and ultimately increase the NUE of the crop. Physical, mechanical or chemical methods, such as coated and slow/controlled release urea, using liquefied urea (UAN, LU), subsurface or root zone application, mechanical application, and splits application are the commonly used technologies to minimize N loss. A combination of two or more techniques may be required to increase the NUE of the crop efficiently.

Efficacy of LU fertilizer

The liquid form of N has several benefits and has started to be recognized all over the world. The use of liquid fertilizers in the USA fertilizer market is rising compared to granular fertilizer, and the use of liquid fertilizer has been advised for beneficial corn production (Leikam, 2010). The use of LU and split application was recorded beneficial to GU application in grain corn production (Motasim et al., 2022). The application of liquid N fertilizer in wheat increases its production and has higher NUE (Holloway, 1996). The benefits of LU application are discussed below.

Effects of LU on reduction of N losses

Liquid urea application to soil significantly reduces the risk of N losses, increases plant N utilization, and keeps the environment sound. Liquid N fertilizer (e.g., UAN) significantly reduces cumulative NH_3 volatilization and N_2O emission more than granular urea (GU) (Wang et al., 2020). Nitrogen loss in the form of NH_3 from the top-dressed GU was higher (25% of used N) than from two LU (UAN and Nitamin) (18% of used N) in experimental plot and laboratory incubations. In addition, both LU recorded about 70% uptake efficiency of ammonium nitrate (Vaio, 2006). Besides, surface and deep placement of liquid N (e.g., UAN) significantly minimized the leaching loss of N in corn cultivation in poorly drained claypan soils (Steusloff et al., 2019). The LU application also reduced the gaseous loss from applied urea (Motasim et al., 2021a).

Applications of liquid fertilizers can decrease the emission of soil greenhouse gases (e.g., N_2O), producing higher yields than granular fertilizers. Researchers found that applications of liquid N fertilizer significantly lowered total N_2O emission with the emission factors ranging from 0.0%-0.1%, but it was 0.6%-11.0% in solid fertilizers (Toonsiri et al., 2016).

Effects of LU on growth and development of plant

The liquid source of N fertilizers significantly affects the growth and development of the plant as it reduces N losses and increases N availability to the plant. The urea ammonium nitrate (UAN), a liquid fertilizer, can significantly increase plant height, root length, root surface area and root tips of wheat. The application of UAN at 2-3 cm depth below the seed has resulted in maximum performance of seedlings growth and development (Blackshaw et al., 2002; Silva et al., 2017; Sundaram et al., 2017). However, other researchers did not find any benefits of the sub-surface application of UAN over broadcast surface application (Shapiro et al., 2016). The application of LU in the split resulted in higher corn yield and NUE than the GU application (Motasim et al., 2022).

A significant impact of LU application on growth and development in cereal production has been recorded as it resulted in higher grain yield and maximum protein content in grain (Walsh and Christiaens, 2016). Holloway (1996) found that the application of liquid N fertilizer increased wheat production significantly.

Effects of LU on NUE

Liquid urea has been suggested as the best N fertilizer source for cereal (e.g., corn, spring wheat) cropping systems. The LU was a better and more efficient N source than GU, while no performance difference among liquid N fertilizers (UAN and High NRG-N, a commercial liquid N fertilizer) on the uptake, NUE, grain yield and grain protein content were observed (Walsh and Christiaens, 2016). Liquid N fertilizer increases NUE and results in 19% higher NUE than GU in winter wheat. It is also more economical, cost-beneficial and has positive effects on the gradual N uptake by the plant in maintaining equilibrium into the soil-crop nutrient mechanism than typical granular fertilizer (Holloway et al., 2001; McLaughlin et al., 2011). It is recommendable during tropical or temperate growing seasons for quicker recovery of N demand. In addition, it is less corrosive, a lesser risk of leaf burn than other liquid N fertilizers like UAN (Wesley et al., 1998). The combined application of liquid N fertilizers with irrigation water or agrochemicals (e.g., herbicides or pesticides) is more money, time, and labor efficient than a separate application. Liquid fertilizers are easily transported, preserved and can be precisely calibrated during use for effective plant growth and development (Boyer et al., 2010; Johnson et al., 2013). Liquid urea and its dilutions are suitable for deep placement by mechanical means (Sundaram et al., 2017). The application of LU resulted in higher corn yield and NUE compared to the GU at the same rate of application (Motasim et al., 2022).

Liquid N fertilizer (e.g., UAN, ammonium nitrate) application decreased gaseous loss (NH_3 and N_2O), increased NUE compared to GU (Vaio, 2006; Jones et al., 2013; Cowan et al., 2019). Urea ammonium nitrate (13.0 kg N_2O ha^{-1}) significantly reduced N_2O emission than GU (21.4 kg N_2O ha^{-1}) application and increased corn yield by 9.1% (Ren et al., 2021). Liquid urea is a hydrolyzed form of urea that distributes quickly throughout the soil profile and no longer stays on the soil surface. It has a lower risk of loss and has a higher mineralization potential than the GU. It ensures faster N availability to plants and reduces further transformation (nitrification and denitrification) (Motasim et al., 2021b) and losses (e.g., leaching loss) (Motasim et al., 2021b). Moreover, the frequency of LU application can improve crop production as well as increase NUE (Motasim et al., 2022).

Timing and splits of N applications

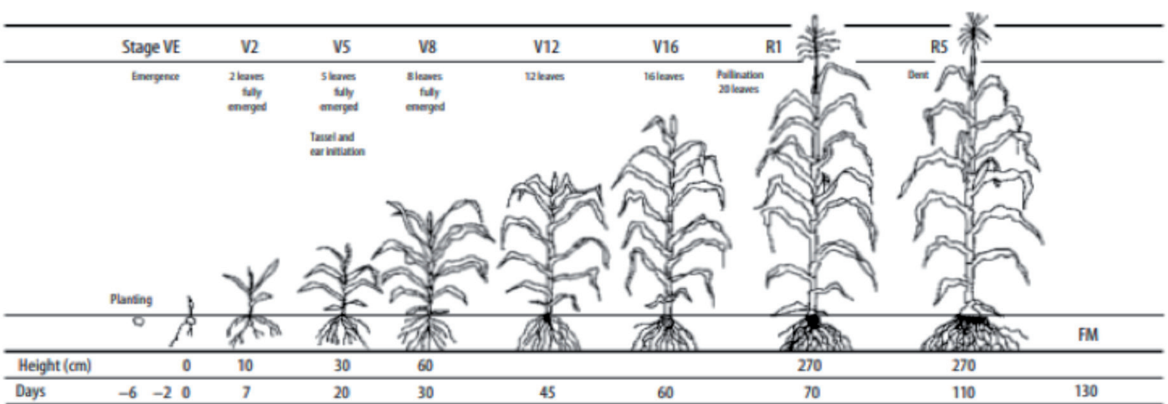
Split N application increases NUE and reduces N losses as there is a synchronization between the time of application and the crop nutrient demand. The main objective of timing N application to corn is to supply an appropriate amount of N depending on the requirement of the crop at that particular time. If the corn is lacking N supply during active vegetative growth stages, yield losses are unavoidable. On the other hand, if N applied exceeds the crop's demand, the cost of production will increase, which will reduce farm income and increase the risk of environmental pollution.

The split application of N plays an important role in the growth, development and yield of corn by lowering leaching and gaseous losses. Corn takes up 60% of the N requirement during V8 to V16 stages (Figure 2). Pre-planting application or application before the V2 stage increases the risk of leaching loss (Butzen, 2011).

Effects of split N application on N losses reduction

Split N applications decrease loss potential and increase the N availability for the crop. Lower N loss was recorded from three split applications (12.7%) than in single applications (27.9%) (Wang et al., 2016). This loss difference is due to the proper synchronization between N availability and crop N demand under the split N applications. At the V9 stage, the corn plant demands massive N nutrients to upkeep the rapid growth of biomass, leading to higher NUE by supplying N. In addition, the application of N at the peak of plant N demand can increase the grain yields and NUE, reducing the soil N loss potential. The N losses are closely associated with the N application method and dose. Moreover, deep placement of N fertilizers can reduce N loss potential than surface application (Cui et al., 2008; Liu et al., 2015).

Figure 2. Demand of NPK and water requirement of corn in its life cycle (Colless, 1992).



% Water	1	2	4	5	7	10	11	12	12	11	8	6	5	3	2	1	1
% N	1	1	1	2	7	11	14	15	16	12	10	6	4	2	1	1	1
% P	1	1	1	1	2	4	7	10	11	15	13	11	9	8	5	2	1
% K	1	1	1	3	9	16	21	20	16	8	5	1	–	–	–	–	–

Effects of split N application on growth and development of plant

Split N application is effective in the corn production system by improving the yield contributing parameters and yield. Split N application effectively minimizes soil N losses and competent N use at critical growing and developing stages of corn. Three split applications of N resulted in higher growth and development of corn than single or double split applications due to continuous N availability and achieved higher NUE (Hammad et al., 2011; Olaiya et al., 2020). In addition, leaf color chart (LCC) based N application was more economical to reduce N losses from soil ensuring higher NUE, preferably in the rainfall prone areas and coarser textured soils where N is more susceptible to be lost (Vetsch and Randall, 2004; Davies et al., 2020; Gharge et al., 2020). The split application of LU resulted in higher growth and development of grain corn than that of the GU application (Motasim et al., 2022).

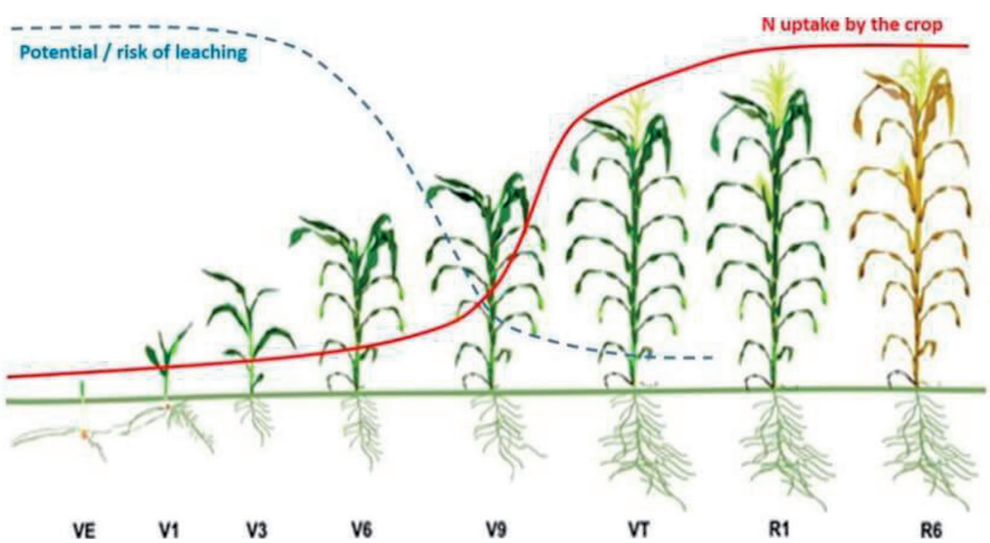
Split N application promotes N accumulation, and physiological NUE by promoting N accumulation after tasseling and N movement to grain (Liu et al., 2019).

Effects of split N application on yield and NUE

The yield of corn is significantly affected by the split application of N fertilizers. The corn yield was increased with the increasing N application frequency, and three split applications of N at the V2, V16, and R1 stages resulted in the highest yield compared to single or two split applications (Hammad et al., 2011). This higher grain yield with split N application is mainly due to the higher growth and development of corn plants. Split N application also increases the uptake potential and reduces loss potential (e.g., leaching) of N, which leads to higher growth, development and NUE of corn. Root zone application of N increased corn yield by about 7% more than the broadcast method, with a significant increase of the N uptake from the fertilizer by 28.5% because this application method increased the N recovery by 28.7% and reduced the loss potential by 30.2% (Jiang et al., 2018).

Split application of N improves effective synchronicity between crop-N requirement and soil-N availability, improving NUE while reducing N loss potential. Application of N before the V9 stage increased the N loss potential (mainly leaching), though the N loss potential decreases and N uptake potential increases in the N application after the V9 stage (Figure 3). From the V9 stage, the corn plant is physiologically active to uptake sufficient N from the soil. Application of N in the R1 stage increased the corn yield; later stage (R3 stage) application also increased the corn yield in case of severe N deficiency situation though the yield was not economical. The application of LU in the split recorded higher results in higher corn yield and NUE than the GU application (Motasim et al., 2022). The yield and economic potentiality may depend upon the severity of N deficiency (Binder et al., 2000; Hammad et al., 2011).

Figure 3. Nitrogen uptake and loss potential of corn in its growing stages (Jones, 2020).



CONCLUSIONS

The use of liquid urea (LU) fertilizer is another effective technology to improve the N use efficiency (NUE) of urea fertilizer by increasing N uptake and decreasing losses from the soil. The use of LU fertilizer as an alternative to granular urea (GU) is expanding as it reduces the possible loss potential and increases the NH_4^+ and NO_3^- concentration in soil which improves N availability. It has been recommended for profitable cereal production because it gave a better performance in crop yield, and the use of liquid fertilizer has been recommended for more economical corn production. Liquid N fertilizers can be transported, stored and calibrated easily for a precise application. It can also be combined with other chemicals and irrigation water. The LU is more ecofriendly, more efficiently taken up by crops and has 19% higher NUE than the GU. The use of LU was found to have less NH_3 loss and higher DM yield and increased NUE in corn than the GU. The split application of LU also increased the corn yield and use efficiency of applied urea. The appropriate rate of LU application in synchronization with the appropriate crop stage plays a vital role to maximize corn yield, NUE and reduce the possible environmental pollution.

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