EFFECTS OF FOLIAR UREA FERTILIZER: A REVIEW

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SEGES has made a review on the effects of foliar urea fertilizer application for winter wheat.

It was found that, compared to other foliar fertilizers, foliar urea fertilizer solutions have a high permeability, can be a promoter of permeability when applied together with iron or phosphate and decreases the risk of foliage burning. This review also discussing foliar application timing to reduce ammonia volatilization and winter wheat response to foliar urea application at different growth stages.

LEAF UPTAKE OF FOLIAR UREA FERTILIZER

Many studies have focused on the effects of applied foliar urea fertilizers and the mechanisms of foliar penetration through foliage. Compared to nitrate or ammonia (NH_3)-treated leaves, urea has a higher absorption rate of N, which is due to the cuticular membrane being 10-20 times more permeable to urea than to inorganic ions (Fernández et al., 2013). This phenomenon occurs because urea molecules have a small uncharged nature. In a publication by Fernández *et al* (2013), they discuss that the hygroscopic behavior of urea can result in swelling of leaf cuticles, if the air relative humidity alternates between high and low, which promotes urea absorption. Furthermore, repeated drying and wetting of leaves can also cause an increase in cuticle pore size, making cuticle penetration of water solutions. However, the urea spray water volume does not necessarily affect urea absorption because, after the leaves absorb foliar urea, it is converted into ammonia by the enzyme urease and incorporated into glutamate by the enzyme glutamine synthetase (Fernándezet al., 2013).

The degree of hydrophobicity and polarity of the plant surface depends on the species, chemistry and topography, which are influenced by the epidermal cell structure. The parts of the plant responsible for nutrient and water transport are the stomata and cuticle, which is the covering of the epidermal cells on the outer surface (Figure 1). Foliar uptake by the leaf will likely occur via the cuticle or stomatal pores, with higher contact area between fertilizer drops and the plant surface. Studies have found that urea penetrates the cuticular membrane with a velocity higher than simple diffusion and can also increase permeability for foliar absorption of ions applied together with urea, such as iron and phosphate (Wolfgang, Franke, 1967; Fernández et al., 2013; Fernández and Brown, 2013).

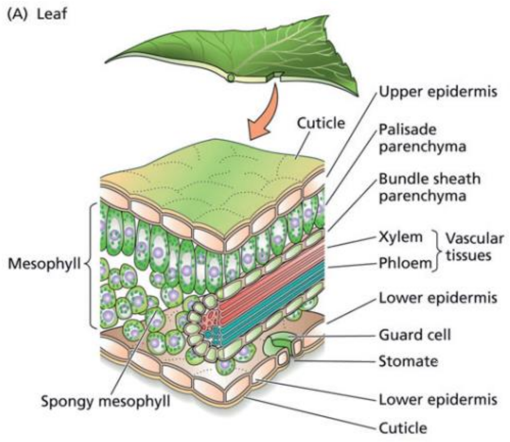

Figure 1. Typical structure of dicotyledonous leaf including vascular bundle in a leaf vein

(Fernández et al., 2013).

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AMMONIA VOLATILIZATION

Once foliar application of urea has occurred, some can volatilize as NH_3 from the leaf surface soon after (Powlson et al., 1989). Urea fertilizers, as well as liquid fertilizers containing urea, have the greatest potential for NH_3 volatilization- when N is lost to the air as NH_3 gas. NH_3 volatilization from urea is significantly different from mineral fertilizers because urea must be hydrolyzed before volatilization begins. Late N applications of foliar urea to boost grain protein in wheat have been suggested as the principal cause of volatilization (Powlson et al., 1989).

Normally, volatilization occurs within two to three weeks after application Jones, C. *et al* (2013), but there are multiple environmental and soil conditions that affect volatilization (Table 1). It is imperative to consider soil conditions affecting ammonia volatilization because applied foliar fertilization will also end up on the soil surface. Smith, C. J. *et al* (1991) studied nitrogen losses from irrigated wheat, grown on heavy clay soil, following foliar urea applications at heading (growth stage 50). They observed that the rate of NH_3 loss increased briefly from <11 g N ha^{-1} hr^{-1} to >19 g N ha^{-1} hr^{-1}, following 3 and 2 mm of rainfalls which washed 34% of the applied N from the plant onto the soil and increased the pH of the surface soil. In this study, the total NH_3 loss was 4.3% of the applied N (Smith, C. J. et al., 1991).

Table 1. Soils conditions affecting ammonia volatilization from urea.

High risk conditions	Low risk conditions
Moist soil or heavy dew	Dry soil
High soil pH (>7.0)	Low soil pH (<6.0)
High soil temperature (>21°C) or frozen soil	Cool soil temperature
Crop residue, perennial thatch or sod	Bare soil
Low cation exchange capacity soil (sandy)	High cation exchange capacity soil (silt or clay-dominated)
Poorly buffered soils (low SOM, low bicarbonate content, high sand content)	Highly buffered soils (high SOM, high bicarbonate content, high clay content)

(Jones et al., 2013; Sommer et al., 2004)

Sprayed liquid urea has a lower volatilization potential than granular urea because, after spraying, it is less concentrated than prills (Jones et al., 2013). Nitrate concentration and leaching losses decrease with increasing proportions of N applied as urea sprays (Readman et al., 2002). Readman *et al* (2002) studied the N recovery and physiological N use efficiency (NUE) of different amounts of urea spray applications at stem extension on winter wheat, over three years, and found no difference in physiological NUE for N applied foliar urea and no effect as applied urea sprays increased. However, there was a significance in N recovery, where the treatment with early N applied as urea sprays in the morning indicated a lower N recovery. They suggest that it is possible to reduce N losses through volatilization by evening application of urea sprays under cool conditions (Readman et al., 2002).

Hydrolysis of urea can be delayed by using urease inhibitors, which allows time for urea to infiltrate into the soil by diffusion or convection after rainfall and, in turn, reducing NH_3 emissions (Sommer et al., 2004). In a review written by Sommer et al (2004), they found that the most useful urease inhibitors are the phosphoryl di- and triamides, (N-(n-butyl)thiophosporictriamide (NBPT) or phenylphosphorodiamidate (PPD). These inhibitors applied with urea were tested on rice fields, where the treatments reduced NH_3 emission from 15 to 3% of the applied N. Additionally, the concentration of a chemical inhibitor used to suppress hydrolysis decreases with increasing granule size of the fertilizer. Inhibitor formulations are accessible to treat liquid forms of urea.

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TRANSPORT OF AMMONIA BETWEEN LEAVES AND ATMOSPHERE

The major source of NH_3 in plants is total ammonia nitrogen (TAN) dissolved in water film in the mesophyll cell walls of leaves (Sommer et al., 2004). The TAN concentration is affected by plant developmental stage, climate and fertilization. Sommer *et al* (2004) describes the NH_3 flux between a single plant leaf and the atmosphere as:

$$NH_3 \text{ Flux} = g_{leaf}(X - NH_{3,a})$$

where g_{leaf} is the conductance to diffusion of NH_3 between the atmosphere and interior of the leaf, X is the NH_3 concentration of the air in the substomatal cavities and intercellular air spaces within the leaf and, if $NH_{3,a}$ equals X, there is no net NH_3 flux occurring between the leaf and the atmosphere. In wheat, oilseed rape and barley, accumulated NH_3 loss over a growing season was between 1-4% of the applied N, (or between 1-4% of the total shoot N) and increased under with a high N concentration in the foliage (Sommer et al., 2004). Due to the multiple physiological processes that take place in different cell organelles and in different tissues, that results in spatial and temporal variation in NH_4^+ concentration in tissue, it is difficult to predict the proportion of the NH_4^+ in the plant leaves will be contributing to NH_3 emissions.

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WINTER WHEAT RESPONSE TO FOLIAR UREA APPLICATION AT DIFFERENT GROWTH STAGES

With the use of foliar fertilizer, the efficiency of nitrogen assimilation through leaves differs depending on crop variety and genotype (Shah et al., 2003) and growth stage (Rehman et al., 2014; Wagan et al., 2017; Fageria et al., 2009). Shah *et al* (2003), applied three different foliar urea fertilizer concentrations to two different wheat genotypes (Soghat-90 and Sind-81), at different growth stages, and found significant differences in yield. Both wheat varieties had a higher yield from the foliar spraying of urea. The three different concentrations of foliar urea fertilization were 2, 4 and 6% urea solution, which was sprayed at peak tillering stage, when the leaves were dry. The data collected by Shah *et al* (2003) indicates that spraying foliar urea fertilization at tillering and heading produces significantly higher yields. These results are consistent with results observed by Rehman *et al* (2014), who analyzed the response of wheat in two different foliar urea application treatments receiving 20 kg ha^{-1} of N in soil at crop emergence and received foliar spray of 1% and 2% urea. They observed a significant increase in the number of effective tillers m^{-2}, spikelets $spike^{-1}$, grain $spike^{-1}$, thousand-grain weight and grain yield with foliar application of urea (Table 1). The maximum number of effective tillers m^{-2}, spikelets spike^{-1}, grain spike^{-1} and grain yield occurred with 2% foliar urea application and the maximum thousand-grain weight resulted from the application of 1% foliar urea fertilizer (Table 1). With the application of foliar urea, grain yields in both treatments were significantly higher than the controlled, however they were not significantly different within each treatment, (1% foliar urea =3.01 t ha^{-1} and 2% foliar urea = 3.03 t ha^{-1}).

Table 1. Effect of foliar application of urea on yield contributing characters and grain yield of wheat (Rehman et al., 2014).

Treatment	Tillers m^{-2}	Spikelets spike $^{-1}$	Grains spike^{-1}	1000-grains weight (gm)	Grain yield (t ha^{-1})
N_0	218	15	40.40	43.10	2.85
FN_{38}	243	17	47	46.32	3.01
FN_{77}	250	18	48	46.17	3.03
LSD	**14.54**	**1.03**	**0.96**	**0.65**	**0.08**

N0= No Nitrogen, FN38 and FN77 are the application of N at 1% and 2% urea, respectively in each time.

During anthesis (growth stage 65), foliar application and N uptake is more appropriate than soil applications of urea because it allows for a rapid and efficient transportation of N to the grain (50% absorption within 6 hours) Wagan *et al*. (2017) and guarantees higher yields (Rehman et al., 2014; Fageria et al., 2009). Wagan *et al*. (2017) applied foliar urea fertilizer treatments from 5% foliar applied urea and all treatments had a significant difference on the growth and yield of winter wheat. The foliar applied urea at 5% resulted in the highest result of all treatments, with a maximum plant height of 97.1 cm, a mean plant tillers value of 10.0, 12.4 cm average spike length, 65.4 grains per spike, 73.2 g seed index, 6275.3 kg ha^{-1} straw yield and 5774.6 kg ha^{-1} grain yield. The plant height and grain weight per spike from foliar applied urea at 5% were not significantly different than the results at 3 and 4%, however, results from foliar applied urea at 1 and 2% were significantly lower. Furthermore, foliar applied urea at 5% had significantly higher straw and grain yield than in any other treatment.

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These results are cohesive with a study by Readman *et al* (2002) that investigated the effects of different amounts of spray application of urea fertilization at stem extension on winter wheat over three years. In this study, within the urea spray treatments, the treatment with 120 kg N ha^{-1} (100%) foliar applied urea indicated the highest grain yield on average throughout the three years. Fageria *et al* (2009) reviewed studies which concluded that foliar applied N after flowering of wheat resulted in the highest grain protein concentration levels. Other studies that have also concluded higher grain protein concentration levels at late growth stages of wheat are Powlson *et al* (1989), Rawluk *et al* (1999) and Phillips *et al* (1999). Phillips et al (1999) found that protein contents ranging from 15-17% were significantly increased to 18-20% with foliar N application rates from 7-26 kg N ha^{-1}. Powlson *et al* (1989) measured recovery of N from ^{15}N-labelled foliar urea to wheat winter at 6 different times from growth stage 39 to growth stage 73, with each treatment receiving 40 kg N ha^{-1} (20 kg N ha^{-1} first, then 20 kg N ha^{-1} 1-2 days after) (Table 2).

Table 2. Treatments from field experiment observing uptake of foliar-applied urea by winter wheat (Powlson et al., 1989)

Treatment code	Nitrogen fertilizer applied (kg N ha-1)			Time of foliar application	
	Top dressing applied to soil (unlabeled 'Nitro-Chalk')	**Foliar sprayb,c (15N-labelled urea)**	**Total Napplied**	**Date**	**Growth stage (GS)**
N_0	0	0	0	-	-
N_1	170	0	170	-	-
N_2	210	0	210	-	-
N_3	250	0	250	-	-
T_1	210	40	250	5 June, 6 June	39
T_2	210	40	250	11 June, 13 June	53
T_3	210	40	250	16 June, 19 June	61
T_4	210	40	250	24 June, 26 June	65
T_5	210	40	250	1 July, 4 July	69
T_6	210	40	250	7 July, 9 July	73
T_4 (20)	210	20	230	24 June, 26 June	65
T_4 (60)	210	60	270	24 June, 26 June	65

a The following herbicide and fungicide treatments were applied. On 30 April, 'Vulcan' (clopyralid and bromoxynil) at 1.4 liters ha^{-1}, 'CMPP' (mechlorprop) at 4.2 liters ha^{-1}; 'Hytana 500 FW' (isoproturon) at 4.2 liters ha^{-1}; 'Sportak Alpha' (prochloraz and carbendazim) at 1.5 liters ha^{-1}- On 26 June, 'Tilt 250 EC' (propiconazole) at 0.5 liters ha^{-1}.

b Table shows nominal application rates of urea foliar sprays. The actual quantities of ^{15}N-labelled urea applied to each plot were measured and used in calculating recoveries; in all cases the actual applications were within 2% of the nominal value.

c Labelled urea was enriched at 4.693 atom % excess ^{15}N. The volume of labelled urea solution applied was equivalent to 1021 liters ha^{-1} containing 2.13, 4.18 or 6.31% urea (w/v) for the 20, 40 and 60 kg N ha^{-1} at 10% urea, 227 liters ha^{-1} at 19.9% and 454 liters ha^{-1} and 14.9%, respectively, to the three treatments.

Seventy-percent of the foliar-applied N given at growth stage 65 was recovered at harvest in the above ground crop including 64% in grain (Powlson et al., 1989). They found that applying foliar fertilizer of 60 kg N ha^{-1} at anthesis increased grain percentage N more than the corresponding 40 kg ha^{-1} and, the smaller foliar application (20 kg N ha^{-1}), did not increase the percentage of N in grain. All the foliar urea fertilizer treatments increased grain protein concentration compared to the treatments where top dressing was applied to soil. At growth stage 65, with 40 kg N ha^{-1} labelled foliar urea application, the N recovered from the final harvest was 58-70%, which was the greatest crop recovery of N out of all treatments (Powlson et al., 1989).

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Table 3. Yields and nitrogen contents of grain and strawa (Powlson et al., 1989).

Treatment code[b]	Yield, t ha^{-1} at 85% DM		Mean grain mass (mg)	% N in dry matter [c]		Total N uptake (kg ha^{-1})		Grain protein content (%[d])
	Grain	Straw + chaff		Grain	Straw + chaff	Grain	Straw + chaff	
N_0	5.63	3.83	45.9	1.49	0.29	71.1	9.5	7.3
N_1	9.64	6.09	40.3	2.13	0.46	174.3	24.0	10.4
N_2	9.60	6.07	39.9	2.31	0.53	188.1	27.2	11.3
N_3	9.45	6.32	39.5	2.39*	0.60**	192.4	32.1	11.7
T_1	9.26	5.89	40.2	2.41**	0.57	190.0	28.7	11.8
T_2	9.45	5.83	39.8	2.43**	0.56	194.9	27.5	11.9
T_3	9.43	5.75	40.3	2.42**	0.56	194.2	27.2	11.9
T_4	9.74	6.36	41.6*	2.41**	0.59**	199.6	31.9*	11.8
T_5	9.37	6.07	40.8	2.43*	0.57	193.9	29.3	11.9
T_6	9.76	6.32	40.4	2.47***	0.57	204.8*	30.9*	12.1
T_4 (20)	9.51	5.94	41.3	2.31	0.55	186.9	27.6	11.3
T_4 (60)	9.14	5.89	39.9	2.51***	0.65***	195.4	32.6*	12.3
LSD 0.05	**0.518**	**0.410**	**1.53**	**0.069**	**0.042**	**13.01**	**3.07**	**0.34**

a Each value is the mean of three replicate plots *, ** and *** indicate values significantly different from the N_2 treatment at the 5%, 1% and 0.1% levels, respectively. The N_0 treatment was excluded from the analysis of variance.
b See Table 2.
c Nitrogen concentration determined on four separate subsamples of plant material from each plot.
d % N in grain dry matter x 5.7, expressed on a 14% moisture basis.

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CONCLUSION

Foliar fertilization is a more efficient fertilization technique because it enhances the availability of nutrients, compared to soil fertilizers, making it more likely to obtain higher yields. An advantage of using foliar urea fertilizer is a lowered risk of foliage burning than with the use of ammonium nitrate or ammonium sulfate because urea has a low salt index, which causes the dehydration of leaf cells through osmosis to reduce. Foliar-applied urea solutions have a high permeability, which results in N metabolites easily transporting from mature leaves to sink organs. In addition to the permeable properties of urea, it can also be a promoter of permeability when applied together with iron or phosphate. The interaction between droplet and leaf depends on the physico-chemical properties of spray formulation plays a major role in determining the efficacy of uptake of nutrient solutions by leaves. Foliar urea uptake by foliage is also affected by environmental factors, such as humidity, temperature, and light.

Multiple studies have observed better vegetative growth of wheat when foliar N is applied, with a rapid uptake of the urea solution on the leaf surface within the first 6-12 hours after application. The effect foliar urea fertilization has on a crop, such as winter wheat, is influenced by the crop variety, genotype and growth stage. Late application of foliar urea (around anthesis-growth stage 65) is correlated to increased grain protein content and the greatest crop recovery of N. Studies have controversial results on whether delaying application time can affect wheat grain yield, however delaying application can increase NH_3 volatilization rate.

Loss of N by volatilization and denitrification increases with increasing temperature and wind, but studies suggest that evening application of foliar urea (or in cool weather conditions) can reduce the potential for volatilization and leave more urea solution on the leaf surface. Fageria *et al* (2009) suggests the best application time for foliar fertilizer to be after 15:00, to avoid burning of plant foliage. Many studies suggest that foliar fertilization can complement soil fertilization of crops, but further research is required to confirm this.

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