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FOLIAR FERTILIZATION: MECHANISMS AND MAGNITUDE OF NUTRIENT UPTAKE

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Abstract

Foliar fertilization is a widely used method used to supplement soil applications to improve the yield and quality of field crops. However, questions and uncertainty surround this practice. Numerous field trials have clearly demonstrated the uptake of foliar-applied nutrients by leaves and subsequent translocation to the fruit. In cotton, foliar-applied ^{15}N was rapidly absorbed by the leaf (30% within one hour) to which it was applied and translocated into the closest boll within 6 to 48 hours after application. The uptake of foliar-applied fertilizers highest in the early morning and late afternoon, and lowest at midday. Water deficit increases the amount of cuticular wax and changes the composition to longer-chain more hydrophobic waxes, and significantly reduces absorption of the foliar-applied nutrient. The cuticle represents the main barrier to absorption of foliar fertilizers. It is assumed that all liquid uptake of water and dissolved substances occurs exclusively through the leaf cuticle, and not through the stomates. There are two pathways by which exogenous chemicals may traverse the distance from the leaf surface into the symplast; a lipoidal route and an aqueous pathway. Compounds that penetrate the cuticle in the lipoidal-soluble form do so principally in the non-polar, undissociated form, whereas compounds that enter via the aqueous route move in slowly, and their penetration is greatly benefitted by a saturated atmosphere. Uptake of nutrient elements via the cuticle depends on whether the element it is in inorganic form or combined in an organic form, its ionic concentration, and on the existing environmental conditions which influence how long the nutrient remains in solution on the leaf. The cuticular layer can also function as a weak cation exchanger attributable to the negative charge of the pectic material and nonesterified cutin polymers. Foliar Fertilizer has the advantages of low cost and a quick plant response, and it is particularly important when soil problems occur and root growth is inadequate. On the other hand, it has disadvantages of possible foliar burn, solubility problems, and only a small amount of the nutrient can be applied at any one time. Variable yield responses to foliar fertilization have been reported. These are probably associated with incorrect timing of applications, the use of inappropriate fertilizer materials, and insufficient attention to soil available nutrients, the size of the fruit load, and environmental conditions. The efficiency of foliar fertilization can be influenced by the type of fertilizer, concentration and pH of the solution, the use of adjuvants, and compatibility with other agrochemicals. Attention also needs to be given to the ideal method and timing for incorporation of foliar fertilization into existing production practices.

Introduction

There is a wealth of literature about foliar fertilization that was first used as long ago as 1844 to correct plant chlorosis with foliar sprays of iron. Foliar fertilization has only caught on in row-crop production in the last two decades, although there is still some speculation about the benefits and correct implementation of this practice. Optimal crop productivity in cotton requires that nutrient deficiencies be avoided. However, deficiencies often occur for a variety of reasons, most of which can be rectified by timely application of the deficient nutrient. In crop production, this usually entails a soil application, or foliar applications may be appropriate after canopy closure or when a specific nutrient is urgently required. Foliar application of specific nutrients is a method used to improve the efficiency of fertilizer use and increase yields. The increased use of foliar fertilizers in crop production in the last decade is due in part to changes in production philosophy. In cotton, for example, the change to cultivars which fruit in a shorter period of time and mature earlier has placed greater emphasis on understanding plant uptake and utilization of nutrients. Current crop monitoring techniques also focus attention on plant development and make it easier to combine concomitant nutrient monitoring allowing remedial action on a timelier basis. Furthermore, cotton lends itself to foliar fertilization because of the large number of aerial applications that are already made for pest control. While there are many reports on research involving soil-applied fertilizer, there are relatively few definitive studies on the usefulness of foliar-fertilization in cotton.

The practice of foliar fertilization has the advantages of low cost and a quick plant response, and it is particularly important when soil problems occur and root growth is inadequate. On the other hand, foliar feeding has disadvantages of possible foliar burn, solubility problems, and only a small amount of the nutrient can be applied at any one time. Variable yield responses to foliar fertilization have been reported. These are probably associated with incorrect timing of applications, the use of inappropriate fertilizer materials, and insufficient attention to soil available nutrients, the size of the boll load, and environmental conditions. A reliable soil analysis constitutes the basis of a successful fertilizer program, and tissue analysis plays an integral part of this program for fine-tuning mid-season tissue nutrient concentrations and remedying any possible deficiencies. The efficiency of foliar fertilization can be influenced by the type of fertilizer, concentration and pH of the solution, the use of adjuvants, and compatibility with other agrochemicals. Attention also needs to be given to the rate and timing, and incorporation of foliar feeding into existing production practices.

Over the past decade there have been numerous studies devoted to understanding the mechanism of absorption of foliar fertilizers, nitrogen and potassium in particular, and the factors that effect the efficiency of uptake and utilization. There have also been comprehensive studies on the nature and characteristics of the cotton leaf cuticle and the interaction with environmental stress. Much of this has been summarized in a review of foliar fertilization in cotton by Oosterhuis and Weir (2002). Foliar fertilization of cotton is a viable means of applying certain fertilizers that can supplement traditional soil methods. Foliar fertilization can result in yield and fiber quality increases.

The Basis of Foliar Fertilization

The basis for this is that certain fertilizer nutrients are soluble in water and may be applied directly to the aerial portions of plants. The nutrient enters the leaf either by penetrating the cuticle or entering through the stomata before entering the plant cell where be used in metabolism. For successful foliar fertilization, nutrients must be successfully applied to the leaf, penetrate the cuticle or stomata into the leaf and enter cells and metabolic pathways. The cuticle is a waxy hydrophobic layer that protects all plant surfaces from the environment and thereby presents a barrier to the absorption of foliar-applied fertilizers. The surface morphology and cross section of the leaf cuticle have been well characterized for crops such as cotton. The cuticle has been shown to be very dynamic in nature. For example, water deficit has been shown to increase cuticle thickness 33%. In addition, and more importantly, water stress also changes the composition of the lipid constituents to more long-chain hydrophobic lipids and thereby further impedes the uptake of foliarly-applied nutrient.

Mechanism of Foliar Fertilization

In order for a foliar applied fertilizer nutrient to be utilized by the plant for growth, the nutrient must first gain entry into the leaf prior to entering the cytoplasm of a cell within the leaf. To achieve this, the nutrient must effectively penetrate the outer leaf cuticle and the wall of the underlying epidermal cell. Of the different components of the pathway of foliar-applied nutrients, the cuticle is believed to offer the greatest resistance. Once penetration has occurred, nutrient absorption by leaves is probably not greatly different from absorption of the same nutrient by roots, the major difference being the environment in which each of these plant parts exists.

There are two possible channels for penetration of foliar-applied compounds into the leaf before they can produce a response. One is through the stomata and the other is through the external cuticle. It is generally accepted that most nutrient uptake occurs through the cuticle, but solutes can also gain entry into the leaf indirectly through the stomata. However, there is some controversy about the importance of stomatal penetration into the interior of the leaf. Prior to 1970 there was considerable debate about the importance of stomatal uptake of foliar-applied nutrients. This debate largely subsided since it was shown that it was not possible for a water droplet to enter the stomata of leaves of higher plants due to the surface tension of water, the hydrophobicity of leaf surfaces, and the geometry of the stomate. Furthermore, ion uptake rates from foliar sprays are usually higher at night, when the stomata are closed, than during the day, when the stomata are open. Recently, new evidence was presented for the uptake of large anions through stomata indicating that stomata might indeed represent a possible pathway through which a limited amount of the nutrient might gain entry into the leaf. Generally, however, it is assumed that all liquid uptake of water and dissolved substances occurs exclusively through the leaf cuticle provided there are no surfactants present. Surfactants in agrochemical sprays typically provide surface tensions of about 30 Mn m^{-1}, which would usually not be sufficient to enable stomata to be infiltrated. However, organosilicone surfactants can reduce aqueous surface tensions to about 20 Mn m^{-1} and allow nutrient entry via the stomates. Furthermore, stomatal penetration can occur only in the brief period after application while spray deposits remain liquid. Thereafter cuticle penetration remains the sole pathway of uptake. In cotton, it is unlikely that direct penetration of solutes from the leaf surface through open stomata into the leaf tissue plays an important role, because cotton has pronounced stomatal ledges that partly cover the mature stomate, as well as an *internal cuticular* layer which extends through the stomatal pore and partially covers the mesophyl cells in the sub-stomatal cavity closest to the stomate. The cuticle is generally considered to be the rate-limiting step in the overall process of foliar penetration.

There are two pathways by which exogenous chemicals may traverse the distance from the leaf surface into the symplast; a lipoidal route and an aqueous pathway. Compounds that penetrate the cuticle in the lipoidal-soluble form do so principally in the non-polar, undissociated form, whereas compounds that enter via the aqueous route move in slowly, and their penetration is greatly benefitted by a saturated atmosphere. Absorption is partially by passive diffusion of molecules through the largely lipoidal cuticle and partially by a dynamic process of uptake dependent upon metabolic activity of the plant. Passive diffusion is believed responsible for most of the penetration of exogenous chemicals through the cuticle and underlying membranes. The movement probably follows Fick's first law whereby the rate of diffusion across a membrane is proportional to the concentration gradient across it, although current thinking is that the process is much more complex than this law entails. In accordance with Fick's law, the higher the concentration of solute which can be applied to a leaf surface without causing damage and the longer time it remains in an active state on the leaf surface, i.e., as a solution, the greater the likely rate and amount of penetration. Diffusion of a nutrient occurs mainly because of a gradient in concentration from the external leaf surface to the free space in the cell wall and in the cytoplasm within the cell. A distinct gradient occurs from low to high charge density, from the hydrophobic external surface toward the hydrophilic internal cell walls. Ion penetration across the cuticle is therefore favored along this gradient, an important factor for both uptake from foliar sprays and losses by leaching. Uptake of nutrient elements via the cuticle depends on whether the element it is in inorganic form or combined in an organic form, its ionic concentration, and on the existing environmental conditions which influence how long the nutrient remains in solution on the leaf. The cuticular layer can also function as a weak cation exchanger attributable to the negative charge of the pectic material and nonesterified cutin polymers.

It was proposed earlier that the movement of solutes across the cuticular layer took place in channels of a non-plasmic nature called *ectodesmata* or *teikodes* in which the fibrillar structure is more loose than the elsewhere in the wall. These bundles of interfibrillar spaces may be filled with coarse reticulum of cellulose fibrils extending from the plasmalemma to the cuticle and serve as polar pathways in foliar absorption and excretion. However, experimental evidence for the existence of these structures is lacking. It is now more commonly believed that plant cuticles are traversed by numerous hydrophilic pathways that are permeable to water and small solute molecules such as mineral elements and carbohydrates. The majority of these pores in the cuticle have a diameter of <1 nm and, with a density of about 10^{10} pores cm^{-1}, are readily accessible to low molecular weight solutes such as urea (radius 0.44 nm) but not to larger molecules such as synthetic chelates . These pores are lined with negative charges increasing in density from the outside to the inside of the cuticle, which facilitates the movement of cations along this gradient. Uptake of cations, therefore, is faster than anions and is also particularly rapid for small, uncharged molecules such as urea. The density of cuticular pores is highest in the cell wall system between the guard cells and subsidiary cells and serves as pathways for cuticular or peristomatal transpiration. This further explains the commonly observed positive correlation between the distribution of stomata and the intensity of nutrient uptake from foliar sprays.

Following penetration of the cuticle, the uptake of solutes into the cell interior depends primarily on the electrochemical gradient concentration gradient from outside into the cell, but also on the plasma membrane permeability coefficient of the molecule and the degree of cell-mediated active uptake. There are various fates of foliar-applied fertilizer nutrients including volatilization and loss to the atmosphere, crystallization and retention on the outer plant surface, loss in dew dripping from the leaf, absorption and retention inside the treated leaf including in the cuticle in solution in the lipoidal layer, penetration of the cuticle and then movement into the aqueous phase of the apoplast and diffusion into the inner leaf structure, penetration of the cuticle and then movement with the transpiration water into the mesophyll and into the symplast, translocation out of the leaf via the petiole. Solutes absorbed by the cells within a leaf can take either the apoplastic or symplastic pathways to reach the vascular tissues for outward translocation. Foliar-applied nutrients are transported through the phloem and take the pathway of photosynthetic assimilates. In a review of transport of foliar-applied nutrients, it was concluded that solutes absorbed by cells within the leaf can take either the apoplastic or symplastic pathways to reach the vascular tissues for outward translocation, and are transported from the palisade and mesophyll cells to the vascular tissues in a passive way. The most important consideration for efficient and profitable foliar fertilization is that this practice will only be affective if the applied nutrient ultimately reaches the target site for its use, i.e. the growing points in a vegetative cotton plant and the developing fruit in a more mature reproductive plant.

Rate and Timing of Foliar Fertilizers

The timing of foliar sprays, particularly in regard to growth stage, can be critical in relation to the optimum efficacy of the foliar treatment, and more attention should be given to it. This is because the seasonal pattern of uptake of nutrients varies with growth rate and growth stage but generally follows a sigmoidal pattern with sharp increases occurring as the boll load develops. The developing fruit load (the sink) has a high requirement for nutrients, N, P and K in particular, and this demand is not always completely met by the soil especially when adverse conditions occur, and as root growth declines.

Absorption of Foliar Fertilizers by Row Crops

Results of field research clearly demonstrated the uptake of foliar-applied ^{15}N urea by cotton leaves and translocation to the developing bolls. Foliar-applied ^{15}N was rapidly absorbed by the leaf to which it was applied (30% within one hour!) and translocated into the closest boll within 6 to 48 hours after application. The N moved progressively into adjoining bolls for the next few days with no translocation to other leaves. The uptake of foliar-applied ^{15}N by cotton was highest in the early morning and late afternoon, and lowest at midday. Water deficit (drought) significantly reduced the absorption of foliar-applied . Total leaf wax of field-grown cotton leaves increased with increase in leaf age and this was associated with a significant decrease in ^{15}N from foliar application. This may account for the decrease in yield response to foliar-applied urea three weeks after flowering as has been reported and may warrant the use of increased rates or frequency of application of N and the use of adjuvants. Research has shown the importance of pH on the efficacy of foliar-applied K fertilizers. Potassium fertilizers have a high pH in solution, and adjusting the solution to a pH of 4 to 6 significantly increased uptake and yield. Furthermore, KNO_3 and K_2SO_4 were superior to the other K fertilizers tested, whereas K_2CO_3 and KOH gave the poorest results.

Advantage and Disadvantages of Foliar Fertilization

Advantage of foliar feeding include low cost, quick plant response, the benefit of being able to respond immediately to plant conditions, lack of soil fixation, independent of root uptake, the use of only small quantities of fertilizer, the ability to combine with other agrochemicals in a single application, increased quality and increased yields. Whereas the disadvantages of foliar feeding include the possible occurrence of foliar burn, solubility problems especially with cold water, the requirement for correct weather conditions for application, inefficient absorption when the solution pH is too high (e.g., with boron, potassium), incompatibility with certain chemicals, the inability to supply sufficient chemical if deficiency is severe, and the possibility of inefficient absorption with increased leaf age in the canopy or with drought conditions.

Practical problems associated with foliar fertilization include the detrimental effects of drought and increased leaf wax, the possibility of foliar burn, optimal timing of the application foliar during the day, and effects of various plant organs and organ age on absorption. Nutrient absorption can also be affected by environmental conditions weather (wind, temperature, humidity) , the correct location of the spray in the canopy, leaf age (physiological activity), the crop fruit load. The efficiency of foliar fertilization can also be affected by such practical factors as the choice of salt, concentration of salt, the pH of solution, the use of adjuvants, and compatibility with other chemicals. Attention also needs to be given to the ideal method and timing for incorporation of foliar fertilization into existing production practices.

Conclusions

Proper plant nutrition for optimal crop productivity in cotton requires that nutrient deficiencies be avoided. However, nutrient deficiencies often occur for a variety of reasons, and can be rectified by timely application of the deficient nutrient. This usually entails some sort of soil application but after canopy closure, foliar application may be more appropriate. Foliar fertilization can be used to improve the efficiency and rapidity of utilization of a nutrient urgently required by the plant for maximum growth and yield. In this way the foliar fertilization supplements soil applications for a more efficient supply of nutrients to the developing cotton plant for optimum yields and fiber quality. In general, foliar applications should be made either early morning or late evening for maximum efficiency, and no foliar applications should be made to water-stressed plants. Foliar fertilization is a viable means of applying certain fertilizers that can supplement traditional soil methods. Foliar fertilization can result in yield increases. Foliar fertilization can cause improved fibre quality. Certain precautions should be observed.