Journal of Plant Nutrition, 32: 1044–1064, 2009

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904160902872826

Foliar Fertilization of Crop Plants

N. K. Fageria,[1] M. P. Barbosa Filho,[1] A. Moreira,[2] and C. M. Guimarães[1]

[1]National Rice and Bean Research Center of EMBRAPA, Santo Antônio de Goiás, Brazil
[2]Southeast Cattle Research Center of EMBRAPA, São Carlos, Brazil

ABSTRACT

Essential plant nutrients are mainly applied to soil and plant foliage for achieving maximum economic yields. Soil application method is more common and most effective for nutrients, which required in higher amounts. However, under certain circumstances, foliar fertilization is more economic and effective. Foliar symptoms, soil and plant tissue tests, and crop growth responses are principal nutrient disorder diagnostic techniques. Soil applications of fertilizers are mainly done on the basis of soil tests, whereas foliar nutrient applications are mainly done on the basis of visual foliar symptoms or plant tissue tests. Hence, correct diagnosis of nutrient deficiency is fundamental for successful foliar fertilization. In addition, there are some more requirements for successful foliar fertilization. Foliar fertilization requires higher leaf area index for absorbing applied nutrient solution in sufficient amount, it may be necessary to have more than one application depending on severity of nutrient deficiency. Nutrient concentration and day temperature should be optimal to avoid leaf burning and fertilizer source should be soluble in water to be more effective. Foliar fertilization of crops can complement soil fertilization. If foliar fertilization is mixed with postemergence herbicides, insecticides, or fungicides, the probability of yield response could be increased and cost of application can be reduced.

Keywords: annual crops, solution concentration, foliar deficiency symptoms, micronutrients

Received 22 April 2008; accepted 6 August 2008.
Address correspondence to N. K. Fageria, National Rice and Bean Research Center of EMBRAPA, Caixa Postal 179, Santo Antônio de Goiás, GO, CEP 75375-000, Brazil. E-mail: fageria@cnpaf.embrapa.br

INTRODUCTION

Crop plants require 17 nutrients to complete their life cycle. Essential plant nutrients are divided into macro and micronutrient groups. Macronutrints are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S). Micronutrients include zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni) (Fageria, 1992; Brady and Weil, 2002). Further, the essentiality of silicon (Si), sodium (Na), vanadium (V), and cobalt (Co) has been considered, but is not yet proven (Mengel et al., 2001; Fageria et al. 2002; Epstein and Bloom, 2005). Macronutrients are required in higher amounts compared to micronutrients. However, from the plant essentiality point of view, all the nutrients are equally important for plant growth. First three macronutrients (C, H, and O) are supplied to plants by air and water. Hence, their supply to plants is not a problem. Hence, the remaining 14 nutrients should be present in the plant growth medium in adequate amount and proportion for plant growth (Fageria, 2005; 2007; Fageria and Baligar, 2005).

Research on foliar fertilization was possibly started in the late 1940s and early 1950s (Fritz, 1978; Haq and Mallarino, 2000; Girma et al., 2007). Unlike many technologies, its pace followed an unpredictable sequence of events. In the early 1980s, studies on foliar application of fertilizers investigated for selected crops, including cereals (Girma et al., 2007). However, the research was limited to micronutrients in high-value horticultural crops (Fritz, 1978) such as potato (*Solanum tuberosum* L.; Lewis and Kettlewell, 1993) and tomato (*Lycopersicon esculentum* L.; Kaya et al. 2001).

Soil application is most common method to supply essential nutrients to plants. In this case applied nutrients are absorbed by plant roots. However, higher plants can also absorb mineral nutrients when applied as foliar sprays in appropriate concentrations. However, in modern high yielding cultivars, nutritional requirements (macronutrients) are rarely met with foliar applications. Furthermore, foliar application of macronutrients requires several sprays, can also be washed off by rain, plant should have sufficient leaf area for absorption and leaf damage by high nutrient concentrations is a serious practical problem. Despite these drawbacks, under certain circumstances foliar application is most effective methods to correct nutritional disorder. For example, iron deficiency in calcareous soils can be corrected by foliar application of ferrous sulfate or iron chelates solution more efficiently than the soil application of iron sources. Other advocated foliar fertilization as a visible economic way to supplement the plants' nutrients for more efficient fertilization (Girma et al., 2007). Furthermore, interest in foliar sprays increased because the development of high concentration soluble fertilizers and the increasing use of machinery for spraying fungicides, herbicides, and insecticides and overhead irrigation further facilitate the application of nutrients to crops in the form of sprays. Advances in agriculture include reducing the cost of crop production, maintaining soil quality, and potential increasingof agro-ecosystems, human, and animal health. Use of nutrients in adequate amounts and its methods of application associated with these objectives. The objective of this review is to discuss latest advances in foliar fertilization and reveal gaps in the existing knowledge and to reflect on both.

DIAGNOSTIC TECHNIQUES FOR NUTRIENT AVAILABILITY

Diagnostic techniques for nutrient availability refer to the methods for identifying nutrient deficiencies, toxicities, or imbalances in the soil plant system (Fageria and Baligar, 2005). Nutritional deficiency can occur when there is insufficient nutrient in the medium or when it cannot be absorbed and utilized by plants as the result of unfavorable environmental conditions. Nutritional deficiencies are very common in almost all field crops worldwide (Fageria and Baligar, 1997; Fageria et al., 1997, 2002). The magnitude varies from crop to crop and region to region. Even some cultivars are more susceptible to nutritional deficiencies than others within a crop species (Fageria et al., 1997; Fageria and Baligar, 2005; Fageria et al., 2006). Proper identification of nutritional status of crop species is important to maximize production efficiency. Inadequate knowledge of the crop nutrient status can frequently result in excessive fertilizer applications and nutrient imbalances as well as undetected deficiencies or excesses within the crop. Four methods to assess nutrient availability or sufficiency of mineral nutrients for plant growth: i) visual symptoms; ii) soil testing; iii) plant analysis; and iv) crop growth response.

The four approaches are becoming widely used separately or collectively as nutrient availability or deficiency or sufficiency diagnostic aids. They are extremely helpful, yet are not without limitations. Fageria and Baligar (2005) give a detailed discussion of these techniques. However, a synthesis of this nutritional diagnostic technique is presented here.

VISUAL SYMPTOMS

When the supply of a particular nutrient is at an inadequate level in the soil or when plant roots are not able to absorb required amounts, due to unfavorable conditions in the rhizosphere, plants show certain growth disorders. These disorders may be expressed as to reduced height, reduced tillering in cereals, leaves discoloration reduced root growth and reduced growth of newly emerging parts of the plant. Visual symptoms are the cheapest nutritional disorders diagnostic technique compared to other three methods. However, it needs a lot of experience on the part of the observer, because deficiency symptoms are confused with drought, insects and disease infestation, herbicide damage, soil salinity and inadequate drainage problems. Sometimes, a plant may be on borderline with respect to deficiency and adequacy of a given nutrient. In this situation there are no visual symptoms, but the plant is not producing at its capacity. This condition is frequently called hidden hunger.

Deficiency symptoms normally occur over an area and not on an individual plant. If a symptom is found on a single plant, it may be due to disease or insect injury or a genetic variation. Also, the earlier symptoms are often more useful than late mature symptoms. Some nutrients are relatively immobile in the plant while others are more mobile. In general, deficiency symptoms caused by immobile nutrients first appear on the younger or upper leaves. The older leaves do not show any symptoms because immobile nutrients do not move or translocate from older to newer leaves. Immobile nutrients are calcium, zinc, boron, copper, iron, manganese, and molybdenum.

In contrast, when there is a deficiency of a mobile nutrient, the symptoms first appear on the older leaves of the plant. This is because the mobile nutrients move out of the older leaves to the younger part of the plant. The mobile nutrients are nitrogen, phosphorus, potassium, and magnesium. Sulfur may behave as mobile or immobile nutrient. However, in rice plants sulfur deficiency first appears in younger leaves.

In conclusion, the use of visible symptoms has the advantage of direct field application without the need of costly equipment or laboratory support services, as is the case with soil and plant analysis. A disadvantage is that sometimes it is too late to correct a deficiency of a given nutrient because the disorder is identified when it is too severe to produce visible symptoms. For some disorders, considerable yield loss may have already occurred by the time visible symptoms appear. Further, several publications are available in which nutritional disorders have been described and illustrated with color photographs for important field crops. Readers may refer to these publications to get acquainted with nutrient deficiencies/toxicities symptoms in important field crops.

SOIL TEST

Soil test is most common practice in agricultural soils for making fertilizer and lime recommendations. It is only valid for immobile nutrient in the soil, like P and K. Mobile nutrients like N, availability to plants changes periodically with the mineralization of organic matter and losses due to leaching, denitrification, and volatilization in soil-plant systems (Fageria and Baligar, 2005). Hence, to develop a sound soil test for identifying N deficiency or sufficiency is rather difficult. In the literature some authors have mentioned that N recommendations can be done on the basis of ammonium (NH_4^+) or nitrate (NO_3^-) analysis. However, in the author's opinion it is not a very precise method to identify N nutritional disorder in crop plants.

Generally, soil samples are taken at 0–20 cm soil depth for food crops. This depth is recommended because about 80% of root systems of food crops remain in this soil volume (Fageria et al., 2006). Soil test to be most effective tool to identify deficiency or sufficiency of a given nutrient, important considerations are that area should be properly samples, care should be taken in preparation of soil samples in the laboratory for analysis and use of proper extracting solution. In addition, soil calibration data should be available to compare the soil analysis results for a particular nutrient and crop species.

PLANT TISSUE TEST

Plant tissue test is also used to identify nutritional disorders in crop plants. However, it is the most expensive technique to identify nutritional deficiency or sufficiency. For plant tissue tests to be most effective and reliable, it is necessary to have plant analysis results under different agroecologocal regions for each crop species to make interpretation of analytical results. Plant analysis results vary with crop species, plant age and plant part analyzed. Hence, special care should be taken while adopting plant tissue test for identifying nutrient deficiency or sufficiency. Many factors such as soil, climate, plant and their interaction affect absorption of nutrients by growing plants. However, the concentrations of the essential nutrients are maintained within rather narrow limits in plant tissues. Such consistency is thought to arise from the operation of delicate feedback systems, which enable plants to respond in a homeostatic fashion to environmental fluctuations (Fageria and Baligar, 2005). Hence, it can be concluded that plant analysis results are more stables compared to soil testing results. Hence, results from one location to another location for a same crop species can be used for interpretation purposes. Sometimes, even from one country to another, plant analysis results for a given crop species are comparable.

CROP GROWTH RESPONSES

Visual symptoms, soil and plant analyses are the common practices for identifying nutritional disorder in crop plants. The best criterion, however, for diagnosing nutritional deficiencies in annual crops is through evaluating crop responses to applied nutrients. If a given crop responds to an applied nutrient in a given soil, this means that the nutrient is deficient for that crop (Fageria and Baligar, 2005). Relative decrease in yield in the absence of a nutrient, as compared to an adequate soil fertility level, can give an idea of the magnitude of nutrient deficiency. For example research conducted on Oxisol of central Brazil provided evidence of which major nutrient is most limiting for upland rice, common bean, corn, soybean, and wheat. The conclusion was that P deficiency was the primary yield-limiting nutrient for annual crop production (Fageria and Baligar, 1997).

MECHANISMS OF UPTAKE OF FOLIAR APPLIED NUTRIENTS

Green leaves are organs whose important functions are photosynthesis. However, sufficient evidences are available which show that absorption of inorganic and organic materials can also take place through the surfaces of leaves (Franke, 1967). Nutrient absorption process by leaves may be different than roots because leaf cell walls are covered by a cuticle, which are not found in the root structure. Franke (1967) reported that cuticular membranes are permeable to both organic and inorganic ions and undissociated molecules. The penetration of ions is determined by the kind of charge, adsorbability, and ion radius. Under normal conditions uptake of ions constitutes an accumulation against a concentration gradient in leaves as in roots. The energy required for active absorption can be derived from respiratory metabolism, or as in green leaves from photosynthesis proves (Franke, 1967). The light quality and intensity improves the rate of ion absorption by leaves (Franke, 1967). Franke (1967) suggested that ion uptake by leaves may be completed in three stages. In the first stage, substances applied to the leaf surface penetrate the cuticle and the cellulose wall via limited or free diffusion. In the second stage, these substances, having penetrated the free space, are adsorbed to the surface of the plasma membrane by some form of binding, while in the third stage the absorbed substances are taken up into the cytoplasm in the process requiring metabolically derived energy.

Previous research showed that a foliar-applied nutrient passes through the cuticular wax, the cuticle, the cell wall, and the membrane in that order (Middleton and Sanderson, 1965; Franke, 1967). Sometimes the nutrient will pass through these various layers, whereas at other times it may pass through the spaces between these layers, which are typical for inorganic ions (Dybing and Currier, 1961). However, now it is also proved that ions also absorbed by leaves stomata's (Eichert et al., 1998; Eichert and Burkhardt, 2001). When the stomatas are open, foliar absorption is often easier (Burkhardt et al. 1999).

Remobilization of mineral nutrients is important during ontogenesis of a plant. For example, if a nutrient is not able to be transported from the sprayed tissues to those developing after the spray treatment, the spray treatment should be repeated every time when a new flush of growth appears (Papadakis et al., 2007). In other words, if a nutrient is immobilized after its foliar application, the positive effects of the spray would be limited only to the sprayed tissues. Hence, deficiency symptoms will appear in the shoots growing after spray. Macronutrients mobility in plant tissue is reasonable, except Ca and S. However, most of the micronutrients mobility in plant tissues is poor. For example, Gettier et al. (1985) reported that two or more foliar sprays may required within the growing season for soybean since Mn is poorly remobilized and its mobility in the phloem is low. According to Guzman et al. (1990), Fe is immobile in tomato, cucumber, and navy bean, but mobile in muskmelon. In all these three species, however, Mn was reported to act as an immobile nutrient. Marschner (1995) also reported that mobility of Fe and Mn in the plant phloem is considered to be low or intermediate, respectively. Garnett and Graham (2005) reported that Fe shows a high reproductive mobility in wheat, the remobilization evidence for Fe was much greater than found for Mn. Hence, it can be concluded that large difference exist among nutrients and plant species in remobilization in plant tissues.

CROP RESPONSES TO FOLIAR FERTILIZATION

Much of the research work reported on crop responses to foliar fertilization was done on soybean and wheat. Crop responses to foliar fertilization have been mixed both positive, negative or no responses depending on crop species and nutrient applied. Extensive research conducted during the 170s and 1980 on foliar fertilization of soybean during early vegetative growth stages or during late reproductive growth stages showed inconsistent grain yield increases (Parker and Boswell, 1980; Poole et al., 1983; Haq and Mallarino, 1998; 2000; Mallarino et al., 2001; Nelson et al., 2005). Garcia and Hanway (1976) reported yield increases of 27 to 31% when a liquid N-P-K-S fertilizer was sprayed at late reproductive stages (R5 to R6). These authors suggested that root activity decreases during pod fill and that nutrient uptake is not enough to meet the seed demands for nutrients.

Modest soybean yield increases from n additions were obtained by Syverud et al. (1980) but little effect of PKS was noted. These authors also reported that seed weight and seed N concentration were also increased by the foliar N treatments. Boote et al. (1978) on the other hand failed to increase either soybean yield or seed number and noted slight burn and necrotic spots on the laves. Leaf damage due to foliar applications of N-P-K-S was sufficiently severe in studied by Parker and Boswell (1980) to reduce soybean yield in most cases. Haq and Mallarino (1998) reported that foliar fertilization with various rates of N-P-K at the R5 growth stage increased soybean grain yield in 7 of 48 field trials and reduced yields slightly in 2 trials, with mean yield increase of 54 kg ha^{-1} across all the trials. Similarly, Poole et al. (1983) reported that foliar applications of fertilizer N-P-K-S to soybean during the podfill stages (R4 to R7) of growth has been shown to increase yields.

Numerous studied conducted at about the same time and afterwards did not replicate these results and showed that foliar fertilization of soybean either did not influence or decreased yield (Boote et al., 1978; Parker and Boswell, 1980). These authors reported that leaf damage due to foliar fertilization sometimes was severe enough to cause yield reductions. However, Wesely et al. (1998) reported that soybean yield was significantly increased with the foliar fertilization of ammonium nitrate solution at the rate of 22 kg N ha^{-1} during the R3 growth stage. Mallarino et al. (2001) reported that foliar fertilization of N in soybean at early growth stages do not inhibit N fixation and P and K uptake can be improved at the time when root system is not well developed. These positive effects may improve plant growth and consequently grain yield. Some nutrients when applied as foliar fertilization may interact positively with other nutrients and may improve crop yields. For example, S alone applied as foliar fertilization to soybean did not increase grain yield. However, when this nutrient is applied in a mixture of N-P-K, soybean responded positively (Garcia and Hanway, 1976).

A foliar N application applied as a liquid spray resulted in higher grain protein concentration levels than when n was broadcast as dry granular fertilizer at late growth stages on wheat (Alkier et al., 1972; Strong, 1982). Similarly, Bly and Woodard (2003) reported that grain protein and yield from plots without foliar N were inversely related ($R^2 = 0.57$) and 9 of the 12 sites had significant grain protein concentration responses to foliar N application. Many researchers have reported increase in grain protein concentration from application of late-season N either as foliar sprays or dry topdress fertilizers even though early-season N application were more than sufficient for potential grain yield (Pushman and Bingham, 1976). Finney et al. (1957) reported that foliar N applied after flowering resulted in highest grain protein concentration levels in wheat. An increase in grain protein concentration with foliar fertilization at late growth stage in wheat could prevent price deduction and possibly could result in premium returned to the producer in favorable years (Bly and Woodard, 2003).

Studies conducted by Chesnin and Shafer (1953) in Nebraska did not indicate consistent positive response to foliar applied N and P on soybeans. Tennessee Valley Authority (TVA) coordinated 180 foliar fertilizer comparisons on soybeans in 11 states in the USA and in a subsequent report (Peele, 1977) indicated that average yield among states varied from 27 kg ha^{-1} increase to 396 kg ha^{-1} decrease. In Florida, Boote et al. (1978) reported that the nutrient concentration of soybean was increased by foliar applications of N, P, K, and S, but yields were not affected significantly and photosynthesis duration was not extended. These authors further reported that control soybeans yielded 3825 kg ha^{-1} as compared to 3617 kg ha^{-1} for foliar treated soybeans.

Iron deficiency chlorosis is a common problem when soybean is grown on calcareous soils. There are two most important management practices to reduce iron chlorosis in soybean grown on calcareous soils. One is use of iron efficient cultivars and second is application of iron as foliar sprays. Goos and Johnson (2000) reported that application of 1.1 kg ha^{-1} iron ethylenediaminetetraacetic acid (FeEDTA) in 140 L ha^{-1} of water increased grain yield by 8% across 4 locations and three cultivars compared to control treatment (no spray). These authors concluded that cultivar selection remains the most practical control measure for Fe-deficiency chlorosis of soybean grown on calcareous soils in narrow rows.

Phosphorus is applied much less in foliar sprays compared to N. This may be because field crops require phosphorus early in the season when there is only a small leaf-area to retain spray, and because many phosphorus compounds have low water solubility. Girma et al. (2007) studied response of corn to foliar fertilization in corn during V4 (collar of fourth leaf visible), V8 (collar of eight leaf visible), and VT (last branch of the tassel completely visible but silks not yet emerged) growth stages. Foliar P rates were 0, 2, 4, and 8 kg ha^{-1}. Foliar P applied at the VT growth stage improved grain and forage P concentration, which was reflected in increase grain yield in some experiments. A foliar P rate of 8 kg ha^{-1} improved yield to some extent and increased forage and P concentrations more than the lower rates. These authors concluded that foliar P could be used as an efficient P management tool in corn when applied at the appropriate growth stage and rate.

The application of K through foliar sprays is much lower than N and P. The reasons may be that K is required in very higher amount by most crop plants and K responses to field crops are limited. However, in Alaska potato yields were increased from weekly K sprays (Tisdale et al. (1985). These authors reported that as with P, however, the problem of adding sufficient amounts becomes critical. Further, foliar application of P used less than N largely because most P compounds are damaging to leaves when sprayed on in quantities large enough to make the application beneficial (Tisdale et al. 1985). Application of micronutrients by foliar spray is more effective because of the small amounts required.

ADVANTAGES AND DISADVANTAGES OF FOLIAR FERTILIZATION

Foliar fertilization provides more rapid utilization of nutrients and permits the correction of observed deficiencies in less time than would be required by soil application. According to authors experience crops respond to soil applied fertilizers in five to six days if climatic conditions are favorable. On the other hand, crop responses to foliar application of nutrients can be seen in 3 to 4 days. The soil applied nutrient has long influence on plant growth. However, plant response to foliar application is often only temporary. This means in case of severe nutrient deficiency several foliar applications are necessary. The foliar application is most successful for micronutrients, whereas soil application is effective for both macro and micronutrients.

For some of the immobilized nutrients in the soils, such as iron, foliar application is more effective and economical compared to soil application. At early growth stage when plant roots are not well developed, foliar fertilization is more advantageous in absorption compared to soil application. However, for foliar application an appropriate leaf area index (LAI) for maximizing spray interception is a primary requisite. In wheat, it has been reported that a leaf LAI of 2–4 seems adequate (Thorne, 1955; Gooding and Davies, 1992). The possibility of foliage burning if salt solution concentration is higher than leaves can tolerate exists. Such chances are remote in case of soil application. In foliar fertilization, wind is a major cause of variability in spray deposition. Hence, on a windy day care should be taken to avoid nonuniform distribution of the nutrient solution. Such problems did not occur with soil fertilization.

Gooding and Davis (1992) reported that there are several potential benefits of providing N to cereals via the foliage as urea solution. These include reduced N losses through denitrification and leaching compared with N fertilizer applications to the soil, the ability to provide N when root activity is impaired, e.g., in saline or dry conditions, and uptake late in the season to increase grain N concentration. The importance of foliar fertilization may lie in the localization and regulation of the enzyme systems involved in nitrogen assimilation. It is known that molybdenum ions are important component of co-factor of the key enzymes of assimilatory nitrogen metabolism-nitrogen fixation, nitrate uptake, and reduction (Gupta and Lipsett, 1981; Campbell, 1999; Hristozkova et al., 2007). Foliar sprays of urea have reduced the severity of certain diseases, (Gooding et al. 1988; Peltonen et al. 1991), which may result in yield benefit. Additionally, sprays of fertilizer provide opportunities to apply other agrochemical in the same operation as tank mixes allowing saving in labor, machinery, and energy cost (Gooding and Davies, 1992). It is widely assumed that high rates of foliar uptake are also dependent on high relative humidities, as rapid drying can lead to crystallization on the leaf surface (Gamble and Emino, 1987).

Foliar application, like soil application is also less effective when soil moisture is limited. Using present spraying technology, foliar application of N can have benefits over soil treatment in increasing grain protein content and the breadmaking quality of wheat when applied at an appropriate timing, like at and after antithesis (Gooding and Davies, 1992). Foliar application of nutrients solution after flowering may result in severe discoloration spikelets in rice (author's personal observation) and should not be recommended. Tom et al. (1981) also reported that applications of fertilizer solution high in urea content to rice after flowering has resulted in severe discoloration of the lemma and paella and in desiccation of rice. Soil application of N after flowering may not create such problem. Foliar application will not only increase efficiency of nutrient uptake and decrease cost of production, but also reduce runoff of soil applied P that is responsible for eutrophication of many of lakes and streams (Sharpley et al. 1994). Micronutrients are required in small amounts and foliar application of these nutrients is more uniform compared to soil application.

PRINCIPAL SOURCE OF MACRO AND MICRONUTRIENTS FOR CORRECTING DEFICIENCIES

To correct nutrient deficiencies by foliar fertilization soluble sources of these nutrients are more efficient compared to insoluble or slightly soluble sources.

In addition, chelate sources of micronutrient are more efficient compared to non-chelated sources. However, chelated sources are very expensive and may not within the reach of farmers. The principal sources of macro- and micronutrient fertilizers and their solubility have been listed in Tables 1 and 2. The concentrations of macro and micronutrients major salts used for foliar spray are presented in Table 3.

Selecting appropriate sources of inorganic fertilizer for foliar sprays is not only important for uptake efficiency but also for foliage burning. Considerable differences have been reported among fertilizer sources in burning foliage with foliar application of inorganic fertilizers, especially N (Phillips and Mullins, 2004). Phillips and Mullins (2004) reported that any foliar N solution applied to cereal plants may result in visual damage described as leaf "scorching", "burning", or "tipping" even at low rates of N application (15 kg ha^{-1}) (Gooding and Davies, 1992). The risk of foliage burning is more likely when the N source is something other than urea, such as ammonium nitrate or ammonium sulfate (Alkier et al., 1972). The reason for this is because urea has a low salt index and, therefore, desiccation of leaf cells through osmosis is reduced (Gooding and Davies, 1992). Depending on the severity of the damage, yield reduction may result. Poulton et al. (1990) reported wheat grain yield reduction to severe leaf scorching occurred following foliar N applications compared with a soil application of an equivalent amount of N. Powlson et al. (1989) reported that no leaf damage or grain yield in wheat occurred when 40 kg N ha^{-1} was applied at one of six different growth stages (Zadoks, 1974) ranging from GS 39 (ligule of last leaf just visible) to GS 73 (approximately 2 weeks after anthesis). Leaf damage was only observed when a foliar spray was applied at a rate of 0 kg ha^{-1} at GS 65 (anthesis), which also reduced grain yield 460 kg ha^{-1} compared with plots that did not receive a foliar N application (Scharf and Alley, 1993). Gooding and Davies (1992) reported that the risk of foliar damage appeared to be less when using a urea (46-0-0) solution rather than other forms of n fertilizer such as ammonium nitrate (34-0-0) and ammonium sulfate (21-0-0). Woolfolk et al (2002) reported that a tendency for increased foliar burn when an ammonium sulfate (AS) solution was foliar applied compared to urea ammonium nitrate (UAN). However, no grain yield differences were observed when UAN and AS solution were applied at equal rates (Woolfolk et al., 2002).

DAY TIMING OF FOLIAR FERTILIZATION

Day timing of foliar fertilization is an important aspect for efficient absorption and also to avoid leaf injury of applied fertilizer materials. For efficient absorption of foliar fertilization, leaf stomata's should be open and temperature should not be too high to cause burning of plant foliage. In the afternoon when air temperature is low (after 2–3 P. M.) is the best time for foliar fertilization. Another factor that may affect foliar fertilization is a windy day, which can

Table 1
Principal fertilizer carriers of N, P, and K

Nutrient	Common name	Formula	Element (%)	Solubility
N	Ammonium sulfate	$(NH_4)_2SO_4$	21	Soluble
	Urea	$CO(NH_2)_2$	46	Soluble
	Anhydrous ammonia	NH_3	82	Soluble
	Ammonium chloride	NH_4Cl	26	Soluble
	Ammonium nitrate	NH_4NO_3	35	Soluble
	Potassium nitrate	KNO_3	14	Soluble
	Sodium nitrate	$NaNO_3$	16	Soluble
	Calcium nitrate	$Ca(NO_3)_2$	16	Soluble
	Calcium cyanamide	$CaCN_2$	21	Soluble
	Ammonium nitrate sulfate	$NH_4NO_3(NH_4)_2SO_4$	26	Soluble
	Nitrochalk	$NH_4NO_3 + CaCO_3$	21	Soluble
	Monoammonium phosphate	$NH_4H_2PO_4$	11	Soluble
	Urea ammonium nitrate	$CO(NH_2)_2 + NH_4NO_3$	32	Soluble
	Diammonium phosphate	$(NH_4)_2HPO_4$	18	Soluble
P	Simple superphosphate	$Ca(H_2PO_4)_2 + CaSO_4$	18–22	Soluble
	Triple superphosphate	$Ca(H_2PO_4)_2$	46–47	Soluble
	Monoammonium phosphate	$NH_4H_2PO_4$	48–50	Soluble
	Diammonium phosphate	$(NH_4)_2HPO_4$	54	Soluble
	Phosphoric acid	H_3PO_4	55	Soluble
	Thermophosphate (yoorin)	$[3MgO.CaO \cdot P_2O_5 + 3(CaO \cdot SiO_2)]$	17–18	Insoluble
	Rock phosphates	Apatites	24–40	Insoluble
	Basic slag	$Ca_3P_2O_8 \cdot Cao + CaO \cdot SiO_2$	10–22	Insoluble
K	Potassium chloride	KCl	60	Soluble
	Potassium sulfate	K_2SO_4	50	Soluble
	K-Mg sulfate	$K_2SO_4 \cdot MgSO_4$	23	Soluble
	Potassium nitrate	KNO_3	44	Soluble
	Kainit	$MgSO_4 + KCl + NaCl$	12	Soluble

Table 2
Principal sources of micronutrient fertilizers to correct deficiencies

Nutrient	Common name	Formula	Element (%)	Solubility
Boron	Boric acid	$H_3BO_3[B(OH)_3]$	17	Soluble
	Borax	$Na_2B_4O_7 \cdot 10H_2O$	11	Soluble
	Na borat (anhydrous)	$Na_2B_4O_7$	20	Soluble
	Na pentaborate	$Na_2B_{10}O_{16} \cdot 10H_2O$	18	Soluble
	Na tetraborate	$Na_2B_4O_7 \cdot 5H_2O$	14	Soluble
	Boron frits	Fritted glass	1.5–2.5	Slightly soluble
Zinc	Zinc sulfate (monohydrate)	$ZnSO_4 \cdot H_2O$	36	Soluble
	Zinc sulfate (heptahydrate)	$ZnSO_4 \cdot 7H_2O$	23	Soluble
	Zinc chloride	$ZnCl_2$	48–50	Soluble
	Zinc oxide	ZnO	50–80	Insoluble
	Zinc chelate	$Na_2ZnEDTA$	9–14	Soluble
	Zinc frits	Fritted glass	4–9	Slightly soluble
Copper	Copper sulfate (monohyd.)	$CuSO_4 \cdot H_2O$	35	Soluble
	Copper sulfate(pentahyd.)	$CuSO_4 \cdot 5H_2O$	25	Soluble
	Copper chloride	$CuCl_2$	47	Soluble
	Cuprous oxide	Cu_2O	89	Insoluble
	Cupric oxide	CuO	75	Insoluble
	Copper chelate	$Na_2CuEDTA$	13	Soluble
	Copper chelate	NaCuHEDTA	9	Soluble
Iron	Ferrous sulfate (monohyd.)	$FeSO_4 \cdot H_2O$	33	Soluble
	Ferrous sulfate (heptahyd.)	$FeSO_4 \cdot 7H_2O$	19	Soluble
	Ferric sulfate	$Fe_2(SO_4) \cdot 4H_2O$	23	Soluble
	Iron chelate	NaFeEDTA	5–14	Soluble

	Iron chelate	NaFeHEDTA	5–9	Soluble
	Iron chelate	NaFeDTPA	6	Soluble
	Iron frits	Fritted glass	2–6	Slightly soluble
Manganese	Manganese sulfate (anhyd.)	$MnSO_4$	23–28	Soluble
	Manganese sulfate (tetrahyd.)	$MnSO_4 \cdot 4H_2O$	26–28	Soluble
	Manganese chloride	$MnCl_2$	17	Soluble
	Manganese oxide	MnO	41–68	Insoluble
	Manganese chelate	$Na_2MnEDTA$	5–12	Soluble
	Manganese fritts	Fritted glass	2–10	Slightly soluble
Molybdenum	Sodium molybdate	$Na_2MoO_{24} \cdot 2H_2O$	39	Soluble
	Ammonium molybdate	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	54	Soluble
	Molybdic acid	$H_2MoO_{24} \cdot H_2O$	53	Soluble
	Mo frits	Fritted glass	0.1–0.4	Slightly soluble

Table 3
Amount of fertilizers and water volume used in foliar spray of macro and micronutrients

Nutrient	Formulation or salt	Kg per 500 liter of water
N	$CO\ (NH_2)_2$	3–5
N	$(NH_4)_2SO_4$; NH_4NO_3; $(NH_4)_2HPO_4$; NH_4Cl; $NH_4H_2PO_4$	2–3
P	H_3PO_4; others see N above	2–3
K	KCl; KNO_3; K_2SO_4	1.5–2.5
Ca	$CaCl_2$; $Ca(NO_3)_2$	1.5–2.5
Mg	$MgSO_4$; $Mg(NO_3)_2$	3–10
Fe	$FeSO_4$	3–6
Mn	$MnSO_4$	1–2
Zn	$ZnSO_4$	1.5–2.5
Cu	$CuSO_4$	0.5–1
B	Sodium borate	0.25–0.5
Mo	Sodium molybdate	0.1–0.15

Source: Adapted from Fageria et al. (1997); Fageria and Barbosa Filho (2006).

drift the spray solution. Hence, windy days should be avoided for foliar spray. There should be at least 3 to 4 hours for the applied nutrient to be absorbed by plant foliage. Hence, there should not be rain for at least 3 to 4 hours after application of the nutrient solution. When applying a nutrient solution as a spray, some sticking material should be added to the solution to stick the spray drops to plant foliage.

Woolfolk et al. (2002) reported that foliar N applications are often associated with leaf burn when applications are made early morning and dew is still on the crop. Goding and Davies (1992) found higher levels of leaf burn with ammonium nitrate (NH_4NO_3) and ammonium sulfate [$(NH_4)SO_4$] compared with urea [$(CO(NH_2)_2$]. It should be noted that their work did not include urea ammonium nitrate [$CO(NH_2)_2 + NH_4NO_3$], which is now a common foliar N source (Woolfolk et al., 2002). A positive relationship between leaf injury and yield depression of soybean by the various NPKS materials was noted, especially when the fertilizer materials were applied during midday rather in the early morning or late afternoon hours (Poole et al., 1983). Phillips and Mullins (2004) reported that foliar application of 34 or 67 kg N ha^{-1} at GS 30 or GS 32 (second node visible) in wheat applied by UAN or UAN-S, leaf burn increased with increasing N rate; however, no effect on grain yield was observed for ether UAN (30-0-0) or UAN-S (20-0-0-4) compared with soil applied fertilizers at either N rate. In addition, no difference in leaf burn between the two foliar sources was observed at GS 30.

Foliar application should be made when the plant is not in water stress, either too wet or too dry (Denelan, 1988). Nutrients are best applied when the plant is cool and filled with water (turgid) (Girma et al. 2007). Applications that are misapplied or too late in the season may not be effective. The most critical times to apply are when the crop is under a given nutrient stress. Stress periods occur during periods of active growth activity. This is likely when the plant is changing from a vegetative to a reproductive stage (Cantisano, 2000).

CONCLUSIONS

Foliar application of nutrients is an important crop management strategy in maximizing crop yields. It can supplement soil fertilization. When nutrients are applied to soils, they absorbed by plant roots and translocated to aerial parts. In case of foliar application, the nutrients penetrate the cuticle of the leaf or the stomata and then enter the cells. Hence, crop response occurs in short time in foliar application compared to soil application. The rate by which an ion passes through the cuticle, and generally the epidermal tissues of the leaves, depends on many factors, including the concentration and the physical and chemical properties of the sprayed ion. Macronutrients, which are required in high amounts by crop plants are rarely met by foliar application. Hence, so far the most important use of foliar sprays has been in the application of micronutrients. In foliar sprays, macronutrient concentrations of generally less than 2% are used to avoid leaf burning. Macronutrient solution concentrations vary from 0.1 to 1.2% depending on the nutrient. Plant age should also be considered in selecting nutrient concentration. Older plants are more tolerant to higher concentrations of salts compared to younger plants. In foliar fertilization, droplet size and fertilizer solubility should be carefully controlled since it will affect crop response. Foliar fertilization in food crops may not increase yield but may increase protein content of grains, if applied during anthesis or flowering.

The yield response of field crops to foliar fertilization of macro and micronutrients is highly variable. Positive results with foliar fertilization of N, P, and K in soybean have been associated with high yielding environments. Yield responses to foliar fertilization are generally not positive when yield is low or nutrients are at an optimum level in the soil. There may be exceptions to this rule, such as iron. In Brazilian Oxisols, iron content is quite high, however, when soil pH is higher than 6.0, iron deficiency in upland rice is frequently observed. This may happen due to immobilization of iron due to precipitation at higher pH. Leaf damage due to higher concentration of foliar fertilization may be one of the reasons for either yield decreases or the lack of yield increases. Foliar spray of nutrients should be avoided at high temperature during the day to avoid leaf burning. Similarly, windy days may drift the applied nutrient solution and rain immediately after application may washout the sprayed material and reduce its efficiency. In rice, foliar spray of nutrients should not be done after flowering because this may cause spikelet discoloration. Foliar fertilization cannot substitute for soil application. It is simply a nutrient corrective technique in crops during growth cycle when soil application is ineffective due to immobilization of soil applied nutrients or cost or methods of application are prohibitive.

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