

UPTAKE OF MINERAL NUTRIENTS FROM FOLIAR FERTILIZATION (REVIEW)

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A B S T R A C T

The aim of this paper is to review the current knowledge on the uptake of mineral nutrients from foliar fertilization. Despite many studies carried out on mineral nutrient absorption by leaf tissues, many aspects of foliar fertilization are still unknown. At present, it is believed that such fertilization of plants is a valuable complement to the application of nutrients to the soil. Foliar fertilization is most effective when soil nutrient availability is low, topsoil dry, and root activity during the reproductive stage is decreased. Foliar fertilization is also successful in increasing content of fruit Ca^{2+} and cereal grain protein. It is proposed that this treatment should be recommended in the integrated plant production because it is environment friendly and increases productivity and yield quality. In the present paper, the penetration of mineral nutrients through the surface leaf layers and their uptake across the plasma membrane of the epidermal cells are discussed. In addition, environmental factors, aspects of plant biology and spray solution properties having a crucial effect on the efficiency of foliar fertilization, are presented.

Key words: foliar fertilization, nutrient uptake mechanisms, factors influencing nutrient absorption.

INTRODUCTION

The first reports on foliar application of mineral nutrients in plant production date back to the second half of the 18th century (after Weinbaum, 1988). Particularly many studies on the uptake of mineral nutrients and their translocation within a plant were carried out after the Second World War. According to Doring and Gericke (1986), and Tukey and Marczyński (1984),

a combined soil- and foliar- fertilization should be recommended in plant production to increase both plant productivity and yield quality. Knowledge of nutrient absorption mechanisms by above-ground plant parts is crucial to optimize foliar fertilization. Since leaves have a large surface area in relation to other above-ground plant parts, mineral nutrient uptake processes presented in this paper will be discussed in relation to a structure and leaf physiology. Special attention will be given to factors influencing absorption of mineral nutrients by leaves.

1. Penetration through the epicuticular wax and the cuticular membrane

The epicuticular wax is the outermost and most hydrophobic component on a leaf surface, consisting of ketones, esters of long-chain fatty acids, and long-chain alcohols placed parallel to one another (Fig. 1). Such structure helps to limit penetration of water molecules and ions across the membrane (Marschner, 1995). Even Brown's movements occurring in the epicuticular waxes do not facilitate the penetration of solutes. "Intracuticular" waxes within the cuticular membrane are considered as more polar than those epicuticular (Baker and Bukovac, 1971; Bukovac and Norris, 1967).

The cuticular membrane is under the epicuticular waxes and consists of the cuticle proper, and the cuticular and the pectin layer (Fig.1). The cuticular membrane covers not only the leaf surface, but also the mesophyll cells having contact to air spaces. Especially, the cells under the stomata have well-developed cuticular membrane. The hydrophobic cuticle proper that lies under the epicuticular waxes contains mainly cutin built of hydroxy fatty acids. However, cutin contains many free hydroxyl groups which weaken hydrophobic interactions and facilitate penetration of nutrients through the cuticular membrane.

The cuticular layer is located under the cuticle proper and consists of cutin, pectin and hemicelluloses. The two last components have dissociated hydroxyl and carboxyl groups causing polar features of the cuticular layer. The pectin layer, situated beneath the cuticular layer, is chiefly composed of negatively charged galacturonic acids. According to Franke (1967) a gradual increase in negative charge from the epicuticular wax to the pectin layer creates an electrochemical gradient that increases the movement of cations and water molecules. The flow of cations through the cuticular membrane is much easier than that of anions. It is estimated that cation ability to penetrate the cuticular membrane is ca. 1000 times higher than for anions (Mengel, 2002).

Mineral nutrients do not enter the epidermal cells through the surface of the epicuticular wax, but through the ectodesmata - pores with a diameter of less than 1 nm (Schönherr, 1976). These pores are readily permeable to solutes such as urea (radii 0.44 nm), but not larger molecules such as synthetic chelates. Ectodesmata are lined with fixed negative charges (presumably from

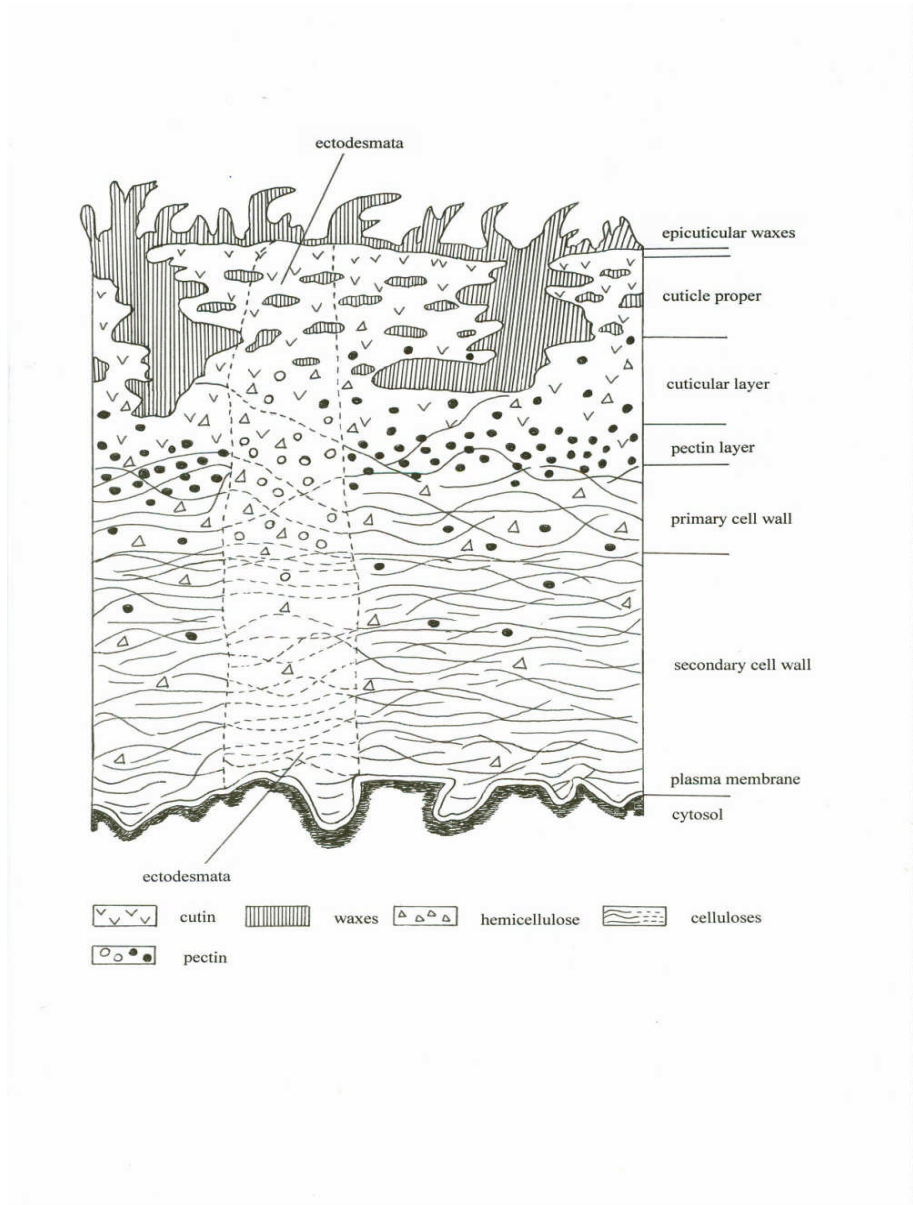


Figure 1. The scheme of the outer wall of an epidermal leaf cell based on Franke's study (1967)

polygalacturonic acids) which increases density from the outside of the cuticle to the inside. Accordingly, the permeation of cations along this gradient is enhanced, whereas anions are repulsed from this region (Tyree et al., 1990).

Therefore, the uptake of cations by the leaves is more rapid than that of anions. Ectodesmata are reported to have the highest density on a leaf along the anticlinal walls of the basal cells of hairs, and the epidermal cells surrounding hairs and guard cells (Maier-Maercker, 1979). The number of ectodesmata on the adaxial (upper) leaf surface is usually lower than on the abaxial (lower) surface. It is estimated that the number of ectodesmata per cm² of a leaf surface is approximately 10¹⁰ (Marschner, 1995). However, the number of ectodesmata is strongly affected by environmental conditions and the physiological state of the leaves. Stresses such as high air temperatures, intense solar radiation, drought, and pathogenic infections, decrease the number of ectodesmata on a leaf. As a leaf develops, the number of ectodesmata per unit of a surface area decreases. According to Schönherr and Bukovac (1978) not only the number of ectodesmata affects the leaf ability to absorb ions but also their permeability.

Generally, the movement of low-molecular-weight solutes (e.g. ions, organic acids, amino acids, sugar) from the leaf surface to the epidermal cell wall is a nonmetabolic process driven by diffusion and electrochemical potential formed by a negative charge increase across the cuticular membrane (Kannan, 1980; Tyree et al., 1992).

2. Penetration through the cell walls

The cell walls of a leaf are continuous and serve as a pathway for free-space (apoplastic) movement of nutrients. Crowdy and Tanton (1970) showed that free space occupied 3-5% of the volume of leaf tissues. The cell wall is mainly built of cellulose, hemicellulose, and pectin. The two last compounds contain large amounts of galacturonic acids rich in free carboxyl groups. At high pH values (>7) resulting in dissociation of carboxyl groups, the cell walls exhibit negative charges active in cation adsorption. The movement of mineral nutrients through the epidermal cell walls takes place in interfibrillar and intermicellar spaces, as well as in ectodesmata and is driven by diffusion and ionic exchange (Franke, 1986).

3. Penetration through the plasma membrane

The plasma membrane is mainly composed of proteins and lipids. It is an effective barrier to solutes of high molecular weight (Mengel, 2002). The plasma membrane is the site of selectivity and transport against the concentration gradient of solutes (Marschner, 1995). Selective transport of nutrients across the plasma membrane requires energy and specific carriers, permeases and channels. Nutrient transport through the plasma membrane may also be a passive process driven by diffusion. This “downhill” transport across a membrane is done with the aid of carriers, and/or aqueous pores and

is maintained as a result of lowering the ion activity in the cytoplasm by adsorption of ions at charged groups and/or by their incorporation into organic structures (Clarkson, 1985).

4. Chemical nutrient forms and their absorption by leaves

In most European countries, under field conditions plant deficiencies of trace elements can be observed only occasionally. Therefore, only macronutrients will be subjects of discussion in this part of the paper.

Generally, the absorption rate of mineral nutrients by the leaves strongly depends on chemical properties of the cations. The higher valence of a cation, the lower its ability to move into the cells (Mengel, 2002). However, among cations of the same valence, the penetration through a leaf surface decreases with the diameter of hydrated ion (Franke, 1967). Thus, the uptake of cations by the epicuticular cells decreases in the following order: $\text{NH}_4^+ > \text{K}^+ > \text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$.

In contrast to most mineral nutrients, leaf-absorbed N must be metabolized in the plant tissues before it is utilized. Plant N metabolism involves several reactions such as hydrolysis of urea, reduction of nitrate, and incorporation of ammonium/ammonia into amino acids. So far there has been no evidence indicating that metabolism of leaf-absorbed N is different than that of root-absorbed.

Rodney (1952) reported that foliar applications of urea, calcium nitrate and ammonium sulphate had similar effect on an increase of N concentration in apple (*Malus domestica* Borkh) tree leaves. Bowman and Paul (1992) also showed comparable N absorption rates by ryegrass (*Lolium perenne* L.) leaves as a result of foliar applications of urea, ammonium and nitrate. On the other hand, Wittwer et al. (1967) demonstrated a higher absorption rate of N by the leaves treated with urea than those treated with nitrate or ammonium. Also Furuya and Umemiya (2002) reported that peach (*Prunus persica* Batsch) leaf treatment with urea appeared to be more effective in increasing N content than other inorganic forms of N. On the basis of many study results Świetlik and Faust (1984) and Reickenberg and Pritts (1996) concluded that absorption of urea by the leaves of most crops is greater and faster than that of inorganic N forms. This phenomenon is related to the fact that the cuticular membrane is 10 to 20 times more permeable to urea than to inorganic ions (Yamada et al., 1965). Thus, penetration of urea molecules through the cuticular membrane is not driven by diffusion. Yamada et al. (1965) state that the specific penetration of urea is related to the loosening of chemical bonds of the cuticular membrane. According to Hinsvark et al. (1953) the rate of urea absorption by the leaves is influenced by the rate and speed of its hydrolysis to ammonium and CO_2 ; plant species rapidly hydrolyzing urea

have high ability to absorb this N form. It is also believed that urea molecules facilitate the penetration of other leaf-applied nutrients (Cook and Boynton, 1952; Kannan, 1980; Weinbaum, 1988). Therefore, many foliar fertilizers contain some addition of urea to improve the efficiency of absorption of mineral nutrients. However, Fisher and Walker (1955) showed no effect of urea on the absorption of Mg^{2+} and P by apple leaves. Kannan (1980) reported similar results indicating a lack of effect of urea on leaf absorption of some mineral nutrients.

Bowman and Paul (1992) reported no differences in the uptake rate of leaf-applied N in the form of ammonium versus nitrate. However, results reported by Komosa (1990) indicated higher absorption of N by tomato (*Lycopersicon esculentum*) leaves in the form of nitrate than that of ammonium. Generally, it seems that ability of leaves to absorb different N forms depends considerably on plant species.

Despite many studies on P absorption by different plant species, it is difficult to unambiguously state which of its chemical form is the most rapidly taken up by the leaves. According to Yogaratnam et al. (1981), P is the easiest absorbed as H_3PO_4 . Koontz and Biddulph (1957) showed that rates of P uptake by the leaves were as follows: $NaH_2PO_4 > K_2HPO_4 > NH_4H_2PO_4 = (NH_4)_2HPO_4 = Na_2HPO_4 = K_3PO_4 > H_3PO_4 > Na_3PO_4$. Okuda et al. (1960) reported the following order: $H_3PO_4 > NH_4H_2PO_4 = Ca(H_2PO_4) > (NH_4)_2HPO_4$. These data suggest that NaH_2PO_4 , $NH_4H_2PO_4$ and H_3PO_4 are rapidly absorbed by the leaves; although, their utilization is considerably dependent on plant species.

Wittwer and Teubner (1959) showed the highest uptake of leaf-applied K^+ from K-citrate solution. They speculated that citric acid radicals stimulated metabolism in leaf tissues which consequently led to increased K^+ absorption. Driver et al. (1985) demonstrated that leaf absorption of K^+ from K-sulphate was much lower than that of K-nitrate. Farlane and Berry (after Komosa, 1990) found that penetration of K^+ from the form K-chloride and K-nitrate through the isolated cuticular membrane was more rapid than that of K-sulphate.

It is commonly accepted that for most plant species leaf-applied Mg^{2+} is rapidly absorbed in the form of chloride and nitrate. For example, Fisher and Walker (1955) reported that apple leaf Mg^{2+} concentrations as a result of foliar applications of Mg^{2+} in the form of nitrate, chloride, acetate and sulphate were increased by 71, 66, 32 and 8%, respectively.

Many studies have shown that the efficiency of foliar sprays of Ca^{2+} in the form of nitrate and chloride was similar. However, Glenn and Poovaiah (1985) demonstrated more rapid movement of Ca^{2+} applied to apple fruit surfaces in the form of chloride than that of Ca-nitrate. These authors also proved that apple fruit sprayed with solutions of Ca-chloride and Ca-nitrate had higher flesh cell Ca^{2+} concentrations than those treated with Ca-acetate.

5. Factors influencing absorption of mineral nutrients

5.1. Environmental factors

5.1.1. *Light and temperature*

Macey (1970) showed that under conditions of intensive light exposure, cabbage (*Brassica oleracea* L.) leaves contained more epicuticular waxes than those shaded. Leece (1978) demonstrated that the seasonal build-up and development of secondary wax structures on the abaxial surface of plum (*Prunus domestica* L.) leaves positively corresponded with increasing light intensity. In addition, there have been shown greater depositions of surface waxes and a thicker cuticular membrane on the leaves at high rather than low light intensity (Hallam 1970; Reed and Tukey 1982; Tribe et al., 1968). However, Reed and Tukey (1982) did not find any relationship between light intensity and thickness of the cuticular membrane on carnation (*Dianthus*) leaves. Darnell and Ferree (1983) were also unable to find any effect of light intensity on the amount and chemical composition of the epicuticular waxes on apple leaves. Generally, it is believed that light favours absorption of mineral nutrients by the leaves. Rains (1967) proved increased uptake of K^+ by corn (*Zea mays* L.) leaves under conditions of high light exposure. Jyung et al. (1965) and Shim et al. (1972) also showed positive relationships between light intensity and ability of apple and bean (*Phaseolus vulgaris* L.) leaves to take up urea, Rb^+ , and PO_4^{3-} .

Skoss (after Wittwer and Teubner, 1959) reported increased depositions of surface waxes on the entire surface of tobacco (*Nicotiana tabacum* L.) leaves at high air temperatures. On the other hand, Leece (1978) showed a negative relationship between air temperatures and the amount of epicuticular waxes on a surface unit of plum leaves. This author states that high air temperatures during rapid leaf expansion may enhance the absorption of mineral nutrients by the leaves due to a lower amount of waxes on unit surface area of a leaf. However, Norris (1974) showed no relationship between the wax deposition and absorption of mineral nutrients by leaves. Author of that work speculates that differences in nutrient absorption rates depend on chemical composition and compound configuration of epicuticular waxes. Reed and Tukey (1982) also claims that under conditions of high air temperatures the surface wax components have vertical configuration and the leaf surface coverage decreases which consequently may increase nutrient absorption. This view is accepted by Kirkwood et al. (1972) and Lurie et al. (1996) who think that even slight alterations in the molecular configuration of surface waxes significantly affect nutrient absorption rate.

5.1.2. *Air humidity*

High air humidity usually stimulates the absorption of leaf-applied nutrients (Tukey and Marczyński, 1984). Bukovac and Wittwer (1959) showed that the uptake of P by bean leaves was doubled when the treated surface was kept moist, compared with similar treatments in which leaf surfaces were allowed to dry. Schönherr (2001) reported enhanced absorption of Ca^{2+} by pear (*Pyrus communis*) leaves with increasing air humidity within the range of 50-90%. According to Tukey and Marczyński (1984), positive influence of air humidity on nutrient absorption by leaves is related to the reduction in drying of droplets. Additionally, high air humidity causes the swelling of the cuticular membrane that loosens its components. This change of cuticle structure increases the absorption of hydrophilic compounds.

The dynamics of mineral nutrient uptake by leaves is inversely related to air humidity. Van Goor (1973) demonstrated that an increased penetration of Ca^{2+} through the cuticular membrane of apple fruit correlated with decreasing air humidity in the initial period of time. This phenomenon is explained by an increase in droplets' Ca^{2+} concentration as a result of their drying which consequently increased the concentration gradient for diffusion. However, despite initial enhanced absorption dynamics at low air humidity, the final uptake rates of nutrients from salts of low hygroscopicity are decreased because of rapid salt crystallization.

5.2. Factors related to spray solution

5.2.1. Solution concentration

Foliar application of nutrient solutions causes salt concentrations on a leaf surface to be higher than those of soil solutions. Increased tolerance of the epidermis to high spray solution concentrations is caused by the presence of the wax layer and the cuticular membrane. Since most mineral nutrients passively diffuse into the epidermal cells, absorption depends on their concentrations on the leaf surface. Knoche et al. (1994) states that there is a strong correlation between nutrient concentration on a leaf surface and the rate of its uptake by the epidermal cells. However, elevated nutrient concentrations cause leaf injury leading to the reduction in nutrient absorption. According to Marschner (1995) such absorption by damaged leaves is limited by the destruction of ectodesmata structures. Maximum concentrations of particular mineral nutrients in a spray solution depend on plant species, plant development stage, nutritional plant status, plant healthiness, and weather conditions (Wittwer and Teubner, 1959).

5.2.2. *Solution pH*

It is commonly believed that the optimal pH values of spray solutions for the maximum uptake of most mineral nutrients are within the range of 3.0-5.5 (Kannan, 1980). For example, Blanpied (1979) showed that the maximum Ca^{2+} absorption by apple leaves is at pH 3.3-5.2. However, Cook and Boynton (1952) demonstrated the greatest absorption of urea by apple leaves at pH 5.4-6.6. Lidster et al. (1979) reported that maximum Ca^{2+} absorption by sweet cherry (*Prunus avium* L.) fruit from CaCl_2 solution was at pH 7. Reed and Tukey (1978) found that maximum P absorption by chrysanthemum (*Dendranthema gradiflora*) leaves was at pH 3-6 for Na-phosphate and pH 7-10 for K-phosphate.

5.2.3. *Surfactants*

Surfactants are commonly used in pesticide formulations to improve physico-chemical characteristics of a spray solution and consequently to increase the efficiency of foliage-applied agrochemicals (Holloway and Stock, 1990). Surfactants belong to the surface-active agents possessing both hydrophilic and lipophilic groups. Such a structure has ability to create "bridges" between the aqueous solution and lipophilic waxes (Schönherr et al., 2001). Thus, surfactants decrease the surface tension between the liquid and leaf which leads to an increase in leaf wetting. Surfactants also eliminate/reduce the air layer between the liquid and leaf surfaces, increase penetration of solutes through the stomata, cuticular membranes and the cell walls, and limit the drying of droplets (Dybing and Currier, 1961; Grieve and Pitman, 1978).

The most frequently used surfactants in agricultural applications are ethoxylated alcohols, alkylphenols, sorbitan and alkylamines (Hellsten, 1987). The efficiency of nonionic surfactants in improving mineral nutrient absorption by leaves is mostly estimated by the value of hydrophilic-lipophilic balance (HLB). Theoretically, the higher HLB value of a given surfactant, the better penetration of a nutrient through the cuticular membrane. Practically, it is assumed that for nonionic surfactants the optimal HLB values determining a high efficiency of absorption of leaf-applied nutrients are within the range of 15-17 (Hull et al., 1975). However, it should be noted that the precise forecasting of the efficiency of nutrient uptake based on HLB values of surfactants may not be successful since their effects are dependent on many environmental and biological factors (Knoche, 1994).

It is believed that organosilicone surfactants have a high efficiency in increasing nutrient absorption by plant tissues (Knoche, 1994). Generally, two mechanisms of enhancement of leaf nutrient absorption by organosilicone surfactants have been reported (Stevens et al., 1992). First, they may induce mass flow of spray solutions through the stomatal pore. Second, surfactants

may directly or indirectly increase the penetration through the cuticular membranes. Stevens and Zabkiewicz (1990) showed that sprays of Ca-chloride and Ca-nitrate solutions with organosilicone surfactants such as Blend Silwet L-77 and Silwet M were more effective in increasing apple fruit Ca^{2+} content than those without surfactants. Weinbaum and Neumann (1977), and Rimmer et al. (1992) found an increased absorption of K^+ and Mg^{2+} using solutions containing Silwet L-77. However, applications of some organosilicone surfactants can also decrease nutrient uptake by the leaf tissues due to the damage of cellular membranes and/or precipitation of inorganic salts on a leaf surface (Neumann and Prinz, 1974; Rodney, 1952). Leece and Dirou (1977) were unable to increase plum leaf N concentration by the application of urea solution containing surfactant Silwet L-77. According to these authors, a lack of effect of this surfactant on N absorption by leaves was due to an increased run-off from leaf surface.

5.2.4. *Chelates*

Chelates are complex compounds consisting of a central metal atom linked by a few coordinating bonds with ligand. Metal ability to create chelates lowers with a decreasing electric charge ratio to ion radius (Marschner, 1995).

It is believed that chelation facilitates the mobility of nutrients within a plant. The use of chelated nutrient forms usually does not increase absorption in relation to inorganic salts (Abadia et al., 2002; Reed et al., 1988). Moreover, Beavers et al. (1994) found a lower absorption of Ca^{2+} from Ca-EDTA (ethylene-diamine tetraacetic acid) by apple fruit than that of Ca-chloride. Also Kannan and Wittwer (1965) showed a decreased iron absorption by the leaves treated with Fe-EDTA and Fe-EDDHA (ethylene-diamine di-O-hydroxyphenylacetic acid) as compared to those treated with FeSO_4 . Thus, it seems that an effect of chelates on leaf ability to take up nutrients is related to some properties of a chelate such as molecular weight of the complex, dissociation constant, and stability of the complex at various solution pH (Reed et al., 1988).

5.3. Biological factors

5.3.1. *Species and variety*

According to Marschner (1995) absorption of mineral nutrients by plants is species dependent. Picchioni et al. (1995) showed that the rate of B absorption by apple leaves was two to three times higher than that of pear, plum and sweet cherry. These authors state that differences in the uptake rates of mineral nutrients by leaves of different plant species result not only from

the specific cuticular membrane structure, but also from various amounts of ectodesmata on a leaf surface. Świetlik and Faust (1984) suggest, however, that the rate of nutrient absorption is related to plant requirements; plants that require more of a specific nutrient have a higher ability to absorb it.

Among fruit tree species, peach, plum, sour cherry (*Prunus cerasus* L.) and sweet cherry leaves have a lower ability to absorb nutrient absorption than apple leaves (Norton and Childers, 1954; Leece, 1978). For example, Świetlik and Słowik (after Świetlik and Faut, 1984) demonstrated that apple leaves were able to absorb about two to three times more N per unit of dry leaf weight than sour cherry.

Absorption rate of mineral nutrients by above-ground plant parts considerably differs not only among plant species but also between varieties within the same species. Wójcik et al. (1996) indicated that an increase in apple fruit Ca^{2+} concentration as a result of Ca^{2+} solution sprays depended on variety; 'Idared' apples took up less Ca^{2+} than 'Jonagold' and 'Gloster'. Also Van Goor (1973) showed significant differences in Ca^{2+} absorption by apples of different varieties; 'Cox's Orange Pippin' absorbed five times more Ca^{2+} than 'James Grieve'.

5.3.2. Leaf surface and leaf age

It is well documented that the lower leaf surface takes up mineral nutrients more rapidly than the upper side. For example, Schlegel and Schönherr (2002) found for four plant species, that within the first 24 hours the absorption of Ca^{2+} by the lower leaf surface was much higher than that of the upper. According to Hull (1970) the high dynamics of nutrient absorption by the lower leaf surface results from the presence of a thin layer of the cuticular membrane and large number of stomata. Boynton et al. (1953) concluded that both leaf surfaces differ only in the dynamics of nutrient absorption. In the study of those authors, urea absorption by the lower leaf surface was rapid within the first 24 hours and then decreased dramatically. The upper leaf surface absorbed urea steadily for 7 days and finally the rate of this absorption was similar as for the lower leaf surface.

It is accepted that the absorption rates of most mineral nutrients by young leaves are greater than those of old ones. For example, Cook and Boynton (1952) found that terminal apple leaves were able to take up almost twice as much urea as did basal leaves. Fisher and Walker (1955) also reported a higher P absorption by young apple leaves than that of old ones. Lower nutrient uptake by basal leaves was attributed to a decreased metabolic activity and/or a lower amount of ectodesmata on the surface of a leaf. However, according to Leece (1978) the reduced uptake of mineral nutrients along with the leaf age is related to the environmental conditions determining an increase in amounts of the epicuticular waxes.

5.3.3. *Nutritional status and plant development stage*

Leaf ability to take up mineral nutrients also is dependent on the nutritional status of a plant. Clarkson and Scattergood (1982) proved that the absorption rate of P by the leaves of P-deficient barley (*Hordeum vulgare* L.) plants was twice as high as that of plants well supplied with P via the roots. In addition, in P-deficient plants much more P was translocated from the leaves, particularly to the roots. Naseri et al. (2002) found that the exogenous B uptake rate by apple leaves was negatively related to leaf B status. Komosa (1990) reported that under conditions of low nutritional status of tomato plants, absorption rates of leaf-applied nutrients were higher as compared to those of plants well-supplied with nutrients via the roots; this was particularly pronounced for N, K⁺ and Mg²⁺. However, Świetlik and Faust (1984) quoted results of some experiments that demonstrated a positive relationship between the nutritional plant status and leaf ability to absorb nutrients. For example, Cook and Boynton (1952) reported that apple leaves with high N content absorbed more urea than those low in N. According to Marschner (1995) if the amount of any mineral nutrient in the leaves is drastically low, leaf ability to absorb this nutrient is limited because of irreversible changes in the leaf tissues.

According to Alexander (1986) there is a significant relationship between the ability of leaves to absorb mineral nutrients and the plant development stage. He listed the development stages of selected plant species having high needs to particular mineral nutrients. This author states that foliar sprays of a given nutrient are most successful when applied at plant development stages requiring high amounts of this nutrient.

CONCLUSIONS

Presently, foliar fertilization is frequently applied in agricultural practice. This fertilization mode should be recommended in an integrated plant production because it is environmental friendly and gives the possibility to achieve high productivity and good quality yields. This treatment is successful for perennial fruit crops with deep-rooting systems since soil-surface application of most fertilizers has little effect on rapid improvement of plant nutrition (Weinbaum et al., 2002). Foliar fertilization should be applied under conditions of decreased nutrient availability in soil, dry topsoil, and decreased root activity during the reproductive stage. It also is beneficial to increase amount of calcium in fruits and cereal grain protein. However, the efficiency of foliar fertilization depends on nutrient mobility within a plant. For nutrients which are phloem-mobile the efficiency of this measure is particularly successful.

Recently, results of studies on foliar application of some products for plant nutrition, such as seaweed extracts, hydrolysed proteins, and amino

acids has been published (Norrie et al., 2002; Quartieri et al., 2002; Thalheimer and Paoli, 2002). However, the use of these products frequently leads to several problems, e.g.: (1) low absorption rates, especially in the leaves with thick cuticles; (2) run-off from the hydrophobic surface; (3) rapid drying of the spray solution and (4) leaf damage.

Despite many performed studies on foliar application of mineral nutrients, many aspects of the uptake and nutrient translocation within a plant are unfamiliar. Therefore, further research in this area are needed.

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POBIERANIE SKŁADNIKÓW MINERALNYCH Z NAWOŻENIA POZAKORZENIOWEGO

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S T R E S Z C Z E N I E

Celem publikacji jest przedstawienie aktualnego stanu wiedzy o pobieraniu składników mineralnych stosowanych dolistnie. Mimo wielu badań nad pobieraniem składników mineralnych przez tkanki liści, wiele aspektów tego zagadnienia nie jest dobrze poznanych. Uważa się, że dolistne stosowanie składników mineralnych jest cennym uzupełnieniem nawożenia doglebowego. Nawożenie dolistne jest szczególnie efektywne w warunkach niskiej dostępności składnika w glebie, stresu wodnego oraz ograniczonej aktywności systemu korzeniowego w okresie rozwoju generatywnego roślin. Nawożenie pozakorzeniowe jest także skuteczne w zwiększaniu zawartości Ca^{2+} w owocach oraz białka w ziarnach zbóż. Nawożenie pozakorzeniowe powinno być polecane w integrowanej produkcji owoców, ponieważ powyższy sposób aplikacji jest przyjazny dla środowiska, a jednocześnie polepsza produktywność roślin oraz jakość owoców. W prezentowanej pracy przedstawiono mechanizmy przenikania składników mineralnych przez powierzchniowe warstwy liścia, a także plazmolemmę komórek epidermy. Omówiono także czynniki środowiskowe, biologiczne oraz związane z właściwościami roztworu opryskowego mające istotny wpływ na efektywność nawożenia pozakorzeniowego.

Słowa kluczowe: dolistne nawożenie, pobieranie składników mineralnych, czynniki wpływające na pobieranie składników