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Review

Foliar nutrition in apple production

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In order to create conditions conducive to sustainable fruit production, involving optimum utilization of all sources of plant nutrients with minimum environmental pollution, it is necessary to reorient agricultural producers to use those types of fertilization that are environmentally safe and appropriate which can also satisfy all fruit tree nutrient requirements. This gives particular importance to foliar nutrition as this model poses the lowest risk of soil and groundwater contamination with undesirable mineral elements. The objective of this study was to provide a comprehensive review of research papers dealing with the effect of foliar feeding on development parameters in apple trees in an attempt to obtain a more thorough insight into the advantages and disadvantages of this fertilization type and facilitate the potential use of this practice for apple producers.

Key words: *Malus x domestica*, foliar fertilization, nutrient, leaves.

INTRODUCTION

Successful fertilization in the cultivation of apples and fruit crops in general requires not only definition of fertilizer application rates but also adequate use of suitable fertilization types. The fertilization type used can substantially alter and disturb the growth and development of a fruit tree if fertilizers are applied incorrectly, regardless of the adequately predefined fruit tree nutrient requirements (Hanić et al., 2009). Different types of fertilization are used in fruit production, including fertilization with mineral fertilizers (conventional type), fertigation, foliar nutrition and a range of other types. In order to achieve high yields and ensure simplicity of use, some producers use only conventional types of fertilization. These nutrition types, characterized by excessive use of mineral fertilizers and chemicals, and very often by injudicious fertilizer applications at plant phenostages, lead to increased yields, but indirectly adversely affect soil and crop quality (Khan et al., 2005; Abdelaziz et al., 2007).

A large part of the nutrients applied remain unused by the fruit tree and leach into deeper soil layers, causing soil and groundwater contamination. Groundwater contamination ranks among the most serious problems facing the world today since it entails risks for the supply of drinking water in the future, also leading to other environmental degradation problems such as disturbance of biological processes and prevention of the normal development of the flora and fauna of aquatic systems (Kang et al., 2008). Due to the aforementioned reasons, in the cultivation of apples and other fruit crops, scientists give priority to fertigation and foliar nutrition, as well as types that significantly improved the efficiency of fertilizers, with minimum adverse environmental impact (Zydlik and Pacholak, 1998; Naseri et al., 2002; Amiri et al., 2008).

Although fertigation is generally seen as a preferred type of fertilization, foliar nutrition has been used very often lately in fruit production. The main advantage of

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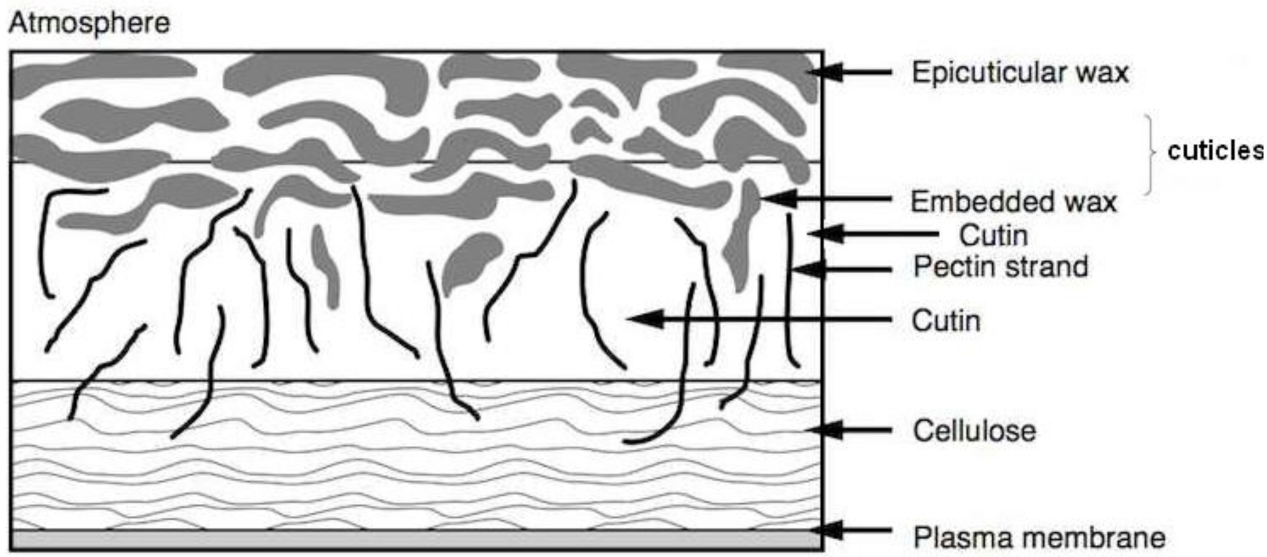

Figure 1. Structure of plant cuticle.

foliar nutrition is that it can be used under very limited root nutrient uptake conditions (root damage, long periods of dry weather, and stagnation of water on surface of soil). Furthermore, the degree and rate of nutrient utilization through foliar fertilizers are higher than those through soil fertilizers, particularly at low temperatures (Wojcik, 2004; Pfeiffer et al., 2008). Additionally, this type of fertilization largely contributes to environmental protection by reducing undesirable nutrient leaching from the soil, an accompanying manifestation of most other fertilization types (Dong et al., 2005; Totten et al., 2008). Using the advantages of foliar feeding in fruit cultivation requires knowledge of mechanisms of nutrient uptake through leaves as well as of factors governing nutrient entry into the leaf. Knowledge of these factors will enable adequate preparation of foliar fertilizers and their use in accordance with plant requirements in certain phenophases of plant development.

MECHANISM OF NUTRIENT UPTAKE THROUGH LEAVES

Nutrient uptake through leaves is based on the entry of dissolved salts mostly through the cuticle and to a much lesser extent through the leaf stomata (Kannan, 1980). Nutrient entry through the stomata is negligible as the openings are small, occupy little space, and their opening reduces due to leaf wetting (Zeiger, 1983). The entry of nutrients through the cuticle is also hampered since the cuticle, due to its structure, acts as a barrier to nutrient uptake. Nevertheless, some nutrients can pass through the cuticle, depending on the structure, chemical composition, age, thickness and hydration status of the cuticle, as well as on nutrient properties (Yamada et al., 1965; Schonherr and Huber, 1977; Franke, 1986).

The first knowledge of the mechanism of nutrient uptake through leaves dates back as early as the second half of the 18^{th} century, but this problem was given serious scientific attention in the second half of 20^{th} century. The long-held scientific belief was that nutrient uptake though leaves are impossible, mostly due to the cuticle which was deemed completely impermeable to water and dissolved substances. However, progress in the fields of chemistry, biochemistry and plant physiology has enabled better insight into the leaf anatomical structure and nutrient uptake potentials, leading to the knowledge that the penetration of substances through the cuticle and, hence, indirectly, into leaf mesophyll cells, is possible and highly effective (Franke, 1967).

The cuticle is the outer layer of leaf epidermal cells. The diagram in Figure 1 illustrates the basic structure of the plant cuticle of epidermal cells (Hess, 1991). The cuticle is composed of a matrix comprising cutin (a polymer of inter-esterified C_{16} and C_{18} hydroxyfatty acids) and cuticular wax (composed of long-chain hydrocarbons C_{22} to C_{34}, alcohols, fatty acids and esters) and on the surface of cuticle has a layer of epicuticular wax (Baker, 1982). This composition of the cuticle is a highly lipophilic character, which considerably impedes the entry of nutrients that is, dissolved ions through the cuticle. However, when hydrated, the cuticle becomes swollen, causing ectodesmata, that is, pores or spaces between the molecules which build cutin to increase, creating the pathway for ions to pass through (Schönherr, 2006). The older and thicker the cuticle, the lower the hydration ability; hence, the cuticle permeability (Bargel et al., 2006). Since the cuticle on the underside of the leaf is somewhat poorly developed, it is particularly important to treat this very part of the leaf for increased effect of foliar fertilizers (Abbott et al., 1990). Once they pass through the cuticle, the next obstacle the dissolved ions come across is part of the cell wall composed of cutin, hemi-cellulose and, to a large part, of pectin.

Pectin is a polymer of galacturonic acid whose molecules are negatively charged due to the high presence of free carboxyl groups. The difference in charge between pectin and upper layers of epidermal cells results in the creation of an electrochemical gradient which facilitates the passive transport of cations and water molecules (Baur et al., 1997). Estimates suggest that it is due to this negative charge of pectin that the ability of cations penetrates through the outer layer of the leaf epidermis which is thousand times that of anions (Tyree et al., 1990). As regards cations having the same valence, priority in the absorption process is given to smaller cations (McFarlane and Berry, 1974). Generally, it is suggested that this part of ion movement through these cell wall layers is attributed to both cuticle structure and the electrochemical gradient occurring due to charge differences between particular layers (Tyree et al., 1992). The next cell wall layer that ions come across is mostly made of hydrophilic cellulose molecules and as such it does not obstruct the movement of the ions until they reach the plasma membrane (Holloway, 1993).

The plasma membrane is the last obstacle to be overcome by nutrients, during their passage into the cell's interior. Nutrients are actually up taken by leaves only after permeation through the plasma membrane, which is physiologically analogous to root nutrient uptake mechanisms. The plasma membrane is a thin membrane having a highly organized structure which surrounds the cytoplasm of each cell; it consists of a lipid bilayer that has a fluid consistency with protein molecules embedded in it on both the outside and inside of the membrane (Robertson, 1960). Being largely hydrophobic in character, the lipid part of the plasma membrane is an unsurpassable obstacle to the movement of ions, regardless of their size (Mengel, 2002). This suggests that hydrophilic molecules can move only through the protein part of the membrane. As regards the position of proteins in the matrix of the plasma membrane, the hydrophilic ends of the proteins (an amino group and a carboxyl group) are always oriented towards the outside of the surface of membrane, and hydrophobic ends of the proteins (short-chain carbohydrates) towards the lipid parts of the membrane. This position of the proteins facilitates the passage of ions and hydrophilic molecules in general through the protein part of the plasma membrane without their coming into contact with the lipid parts of the membrane (Maurel, 1997; Burton et al., 2010).

Proteins involved in ion transport through the plasma membrane can either be channel proteins or carrier proteins (Chrispeels et al., 1999). Channel proteins are generally built from a single protein molecule that completely spans the plasma membrane. Also, channel protein can either be aqueous channels or ion channels. Aqueous channels are always open, showing poor selectivity and transporting most of the water and dissolved substances. Ion channels are highly selective, being involved solely in ion transport (Amtmann and Blatt, 2007). Ion channels have a highly specific structure; they are shaped like tubes with the middle part expanded and the tube lumen abruptly narrowing towards the surface of membrane into a very tiny openings. These openings which are called ion-selective filters allow only ions whose shape and size fit the filter to pass through the membrane (Krol and Trebacz, 2000). Importantly, the filters are generally closed, as they open only upon specific stimuli produced by the internal cell metabolism or a particular external stimulus which eventually, through hormones, lead to channel opening.

Calcium, chloride, sodium (Na) and potassium (K) ions are transported mostly through ionic channels (Chen and Eisenberg, 1993). Apart from ionic channels, the transport of ions through the plasma membrane is also regulated by protein carriers. Protein carriers also span the plasma membrane; they contain molecule- or ion-specific binding sites in their interior. Upon adhesion to the binding sites, the substance travels to the opposite end of the carrier protein and then it separated (Eisenberg, 2003). Whether passing through ionic channels or carriers, ions are transported through the plasma membrane via the active pathway; from a low concentration area (foliar fertilizers) to a high concentration area (leaf).

However, the use of foliar fertilizers containing a high concentration of active ingredients would disturb the osmotic equilibrium within leaf cells, and that would have negative impact on the functions of plant cells. This problem is seen as the key deficiency of foliar feeding because the need for some elements (nitrogen (N), phosphorus (P), K) are considerably higher than their concentrations that can be placed in the foliar fertilizers without toxic effects on the leaves (Marschner, 1995). The passage of nutrients through the plasma membrane is followed by their simple transport from one cell to another through membranes, as aforementioned, and through plasmodesmata, cytoplasmic strands that connect the protoplasts of adjacent cells (Sanders and Bethke, 2000). This is how all chloroplast-containing mesophyllic cells are supplied with nutrients vital for photosynthesis.

FACTORS GOVERNING NUTRIENT ENTRY INTO THE LEAF

Apart from the structure of the cell wall and that of the plasma membrane, nutrient uptake through the foliage is also dependent upon the following factors: Rate of nutrient uptake, nutrient mobility in the plant, temperature, and morphological and anatomical characteristics of the leaf. The efficiency of nutrient uptake through leaves increases with increasing rate of nutrient uptake and mobility in the plant. Mineral elements can be divided into three groups according to the rate of their uptake in leaves: high uptake rate (N, K, Na, zinc (Zn), and Cl), medium uptake rate (Ca, sulphur (S), P, manganese (Mn) and boron (B)) and low uptake rate [magnesium (Mg), copper (Cu), iron (Fe) and molybdenum (Mo)]. For most nutrients (N, K), their mobility in plant is positively correlated with the uptake rate (Bukovac and Wittwer, 1957; Tukey et al., 1962). Nutrient uptake is positively affected by increasing temperature until the optimum temperature for nutrient uptake is reached, the optimum value depending on the nutrient being up taken (Reed and Tukey, 1982).

When comparing nutrient uptake through the root and that through the leaf, many studies have confirmed higher nutrient uptake through the foliage at low temperatures. This is especially true of phosphorus which is, at low soil temperature almost solely adopted through the leaf (Hurewitz and Janes, 1983). Nutrient uptake is also largely affected by the morphological and anatomical structure of the leaf, primarily cuticle structure. Increasing age and increasing thickness of the cuticle lead to a decrease in cuticle swelling capacity and, hence, nutrient uptake ability. Therefore, it is best to use foliar fertilizers to treat young well-developed leaves, on their underside in particular, due to a thinner cuticle on this side. Nutrient entry into the leaf is also considerably dependent upon nutrient properties: Form of active ingredients, type of dissolved ions, pH, and content and ratio of mineral nutrients in the solution. The characteristics mentioned earlier govern the ability, rate and method of nutrient uptake from fertilization (Wojcik, 2004).

DISCUSSION AND PERSPECTIVE OF USE OF FOLIAR FERTILIZERS IN APPLE GROWING

Apple trees remain in the same positions for over ten years regardless of whether the extensive or intensive method of production is used. Soils, even those richest in nutrients, do not contain enough nutrients for regular and abundant yields on a yearly basis. Therefore, apple growers who are seriously engaged in fruit production need to incorporate additional nutrient amounts into the soil in order to achieve satisfactory fruit yield and quality. Due to the specific nature of fruit production, climate and edaphic conditions in an orchard, biological properties of apple fruit, and interactive effects of other environmental factors, there is simply no single recipe for fertilization. However, there is guideline on fertilization rates determined based on research findings. These rates are specific, relating only to the investigated site, and are defined based on soil pH, nutrient content in the soil and fruit requirements. Any fertilization recommendation which is not based on these parameters, in generally has a negative effect on plant development.

In order to create conditions conducive to sustainable fruit production involving optimum utilization of all sources of plant nutrients with minimum environmental pollution, it is necessary to reorient agricultural producers to use types of fertilization that are environmentally safe and appropriate. This gives particular importance to foliar nutrition as this model poses the lowest risk of soil and groundwater contamination with undesirable mineral elements. This model is being promoted through latest findings on mechanisms of absorption of foliar fertilizers, as well as through an abundant choice of structurally diverse clear solution, suspension and powder fertilizers which exhibit exceptional efficiency.

Most scientists share the belief that the main advantage of foliar feeding is that it can be used under very limited root nutrient uptake conditions. Hanić et al. (2009) highlighted the particular efficiency of foliar fertilizers in the uptake of ions that show antagonism in the soil solution or low mobility in the soil. Thalheimer and Paoli (2002) found that magnesium is very difficult to adopt through the root, mostly due to its antagonism with some elements, notably NH_4^+ ions. The same problem occurs with the uptake of Ca which is absorbed with difficulty from the soil solution due to its antagonistic relationship with K as well as with NH_4^+ and Mg ions (Trivedi, 2006). Foliar nutrition which contain Ca and Mg in greater amounts can help avoid these disadvantages while improving certain fruit quality parameters in apples, their storability in particular (Wojcik and Szwonek, 2002; Lanauskas and Kvikliene, 2006).

Calcium has a very important role in increasing fruit storability. It is reported that apple fruits have good storability if their Ca levels are above 4.5 mg/100 g fresh fruit (Dris et al., 1998). If the amount of Ca falls below this value, there is a high risk of damage to the skin, and consequently internal parts of the fruit. Namely, calcium is vital for fruit firmness, being involved in the formation of calcium pectinates and oxalates which provide firmness to the outer parts of cell membranes. When the membranes are weakened, there is an uncontrollable loss of water which contributes to the decay of the surface layer and, consequently, the inner layer of the tissue. Visual manifestations include the occurrence of dark brown or black bitter pits. Given the damage of the layer, these areas become susceptible to different pathogens (Freitas et al., 2010). Bitter pit incidence can be prevented by the supply of sufficient amounts of calcium to apple fruits (Pooaviah et al., 1998).

Rates and forms of calcium fertilizers to be applied should be defined based on the mechanisms of calcium uptake and movement within the plant. As opposed to most macronutrients, calcium has low mobility within the plant. Its mobility is somewhat more pronounced in the ascending direction, from the roots up to the leaves, whereas calcium movement in the opposite, from leaves to fruit is limited. When calcium is up taken through the root, during its ascending movement, the already absorbed calcium is being diluted, which results in decreased influx of Ca into the fruit. Given both the above and the potential antagonism of calcium in the soil solution with many elements (K, NH_4, Mg), it is clearly suggested that calcium nutrition should be carried out foliarly, by direct treatment of fruits with a calcium fertilizer containing more readily absorbable forms of calcium, such as calcium nitrate (Lodze et al., 2008) or calcium chloride (Shirzadeh et al., 2011). A positive effect of the combined use of 1% calcium nitrate and 0.5% calcium chloride on the storability of apple fruits has been reported by Moor et al. (2006).

The storability of apple fruits is dependent not only upon calcium levels, but also upon the content of other elements, including primarily phosphorus, potassium, magnesium and nitrogen (Perring, 1968). If phosphorus levels in apple fruits are below 9 mg/100 g fruit, there is a great risk of bitter pit occurrence, particularly at a very low Ca concentration in apple fruits (Johnson, 1980). The efficient use of foliar feeding with phosphate fertilizers in preventing bitter pit occurrence and increasing fruit quality in general has been reported by many scientists (Yogaratnam et al., 1981; Wojcik and Wojcik, 2007). The content of calcium versus phosphorus, a high concentration of potassium in apple fruit is not desirable, or more precisely is not desirable high ratio between content of potassium and calcium in apple fruit. The storability of apple fruits is considered to substantially decrease at the potassium to calcium ratio in apple fruits of over 30:1 (Winska-Krysiak and Lata, 2010). The high concentrations of nitrogen are equally undesirable in apple fruit since they cause increased susceptibility to pathogens, a decline in fruit firmness and an overall decrease in fruit storability (Blaszczyk and Ben, 1996). It is noteworthy that the foliar feeding of apple trees with macronutrients, including nitrogen, potassium and phosphorus, is not easily achievable, mostly due to the inability of foliar feeding to satisfy the large fruit demand for these elements.

However, foliar feeding has proven to be an extremely effective method for correcting deficiencies of micronutrients in plants, primarily boron and manganese as key biogenic elements in apple fruit development. Boron plays a very important role at the stage of pollination, contributing to pollen tube vitality and fruit development, whereas manganese is an important micronutrient involved in water photolysis and electron transport in the light-dependent stage of photosynthesis (Nešković et al., 2003). A positive effect of foliar feeding with B and Mn on development parameters in apples has been obtained by many scientists (El-Shazly, 1999; Stover et al., 1999; Naseri et al., 2002). Foliar feeding has also proven to be highly efficient in the uptake of Zn if apples are cultivated on alkaline and carbonate soils where the absorption of Zn from the soil solution is inactivated primarily due to excessive pH. Zinc deficiency can adversely affect bud formation; therefore, zinc should be supplied to the apple tree, the easiest and most efficient method on carbonate soils being foliar treatment of fruit trees with zinc in the sulphate ($ZnSO_4$) and chelated form (Neilsen and Hogue, 1983).

The positive effect of foliar feeding on the fruit yield and quality of apple has also been dealt with by other authors (Štampar et al., 1998; Tagliavini et al., 2000). Veberić et al. (2002) associate yield increases induced by foliar applications of phosphorus and potassium with certain photosynthetic parameters. Hanić et al. (2009) underline the favorable use of foliar fertilization in feeding old apple orchards where the possibility of receiving mineral elements from the soil solution decreased due to the exhaustion of soil. Although a large number of studies have proven the positive effect of foliar nutrition, if applied in accordance with fruit requirements, on fruit yield and quality, foliar nutrition is not recommended as a uniform fertilization type. The largest problem with foliar feeding is that is not able to completely replace the nutrition through the roots, primarily due to plant requirements for some elements (N, K, P) is considerably higher than their concentrations in the foliar fertilizers. As part of adequate nutrition, fruit trees should be frequently sprayed, which would however lead to an increase in production costs. Although it cannot be used as a uniform model of fertilization, foliar fertilization can serve as an excellent supplement to other fertilization types (Doring and Gericke, 1986).

Importantly, in order to ensure success of foliar applications, experts in this field should be consulted before foliar treatment to ensure the unobstructed development of the fruit tree and optimum quality of the fruit. Some advice that may be useful in foliar applications include the following: treatments should not be performed at high temperatures (above 23°C) due to the risk of dehydration of the solution out of the leaf surface, or during windy weather in order to prevent droplet drift and avoid mistakes in the treatment. Moreover, the leaf underside should preferentially be treated as much as possible due to the considerably thinner cuticle on this side. In order to enhance the adhesion of foliar fertilizers to the leaf, it is advisable to use agents that reduce the surface tension between the solution and the cuticle.

When mixing two or more foliar fertilizers, special care should be given to the ratio of elements in the fertilizer used so as to avoid adverse effects on nutrient uptake. When mixing foliar fertilizers with crop protection agents, one should avoid copper- and sulfur-based protection agents and those having a high pH in order to prevent their adverse effect on growth and development parameters in apple. If all of the aforementioned facts are considered and if foliar treatments are conducted in accordance with manufacturers' instructions and plant requirements during particular phenostages, a positive effect on the quality of apple fruits can be expected, particularly in terms of increasing their storability potential. Apart from positively affecting the growth and development parameters in apple trees, the use of foliar feeding in fruit production largely contributes to environmental protection as it reduces the risk of soil and groundwater contamination with undesirable mineral substances. In view of the current goal of agricultural policy to pave the way for sustainable agriculture and, therefore, fruit production, foliar feeding combined with adequate basal dressing can be recommended as a fertilization model which, if properly employed, can satisfy the criteria with regard to environmental protection and fruit tree nutrient requirements.

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