FOLIAR FEEDING
Another Successful Way of Feeding Plants

Foliar feeding is a reliable method of feeding plants when soil feeding is inefficient. In this article, the author highlights when foliar feeding should be considered, how nutrients actually penetrate plant tissue, and some technical limitations to this method of plant feeding.

By Eyal Ronen

Plant nutritionist have traditionally considered the obvious way to feed plants is through the soil, where plant roots are meant to uptake water and nutrients, but in recent years foliar feeding has been developed to supply plants with their nutritional needs.

The development of pressurised irrigation equipment such as drip irrigation has promoted the need for water-soluble fertilisers, as clean and purified as possible in order to diminish the possibility of emitters clogging. It is not really clear when foliar feeding started, but after the development of water-soluble and liquid fertilisers farmers have begun to use these fertilisers with sprayers, the same as it is used with applications of pesticides. At the beginning, this technique of spraying nutrients was used for correcting deficiencies of minor elements. However, fast curing has shown that plants can absorb some elements through their tissue. As a result, foliar feeding has gone through further development.

These days foliar feeding is considered among the major techniques used for plant nutrition, supplementing the ground application. In this article I will review the whole concept of foliar application - when it should be considered, how nutrients actually penetrate plant tissue, and some technical limitations of this method of plant feeding.

The case for foliar feeding

Foliar feeding is a 'by-pass' approach, overtaking conventional ground fertiliser applications whenever it does not perform well enough. Foliar application overcomes soil fertilisation limitations like leaching, insoluble fertiliser precipitation, antagonism between certain nutrients, heterogenic soils unsuitable for low dosages, and fixation/absorption reactions like in the case of phosphorus and potassium. Foliar feeding can also be used to overcome root problems when they are suffering from limited activity due to low/high temperatures ($<10^0$, $>40^0C$), lack of oxygen in flooded fields, nematode attack damaging the vascular system, and a decrease in root activity during the reproductive stages where more of the photosynthetic creation is transferred for reproduction with less for root respiration (Trobisch and Schilling, 1970). Foliar feeding has proved to be the fastest way of curing nutrient deficiencies and boosting plant performances at specific physiological stages. With plants competing with weeds, foliar spraying focuses the nutrient application on the target plants. Fertilisers have also been found to be chemically compatible with pesticides, thus saving labour costs. Certain types of fertilisers can even slow down the hydrolysis rate of pesticides/growth hormones (GA3) owing to lowered pH of the solution and this may improve performance or cut costs.

Fertilisers applied through the plant leaf canopy have to face several structural barriers, unlike pesticides which are mainly oil-based and don't face difficulties to penetrate the leaf tissue. Nutrients, which are salt based (cations/anions) may face some problems penetrating the inner plant tissue cells. General leaf structure is based on several cellular and non-cellular layers. The different layers support protection against desiccation, UV radiation and various kinds of physical, chemical and (micro) biological agents. Several layers can be identified in *Figure 1*.

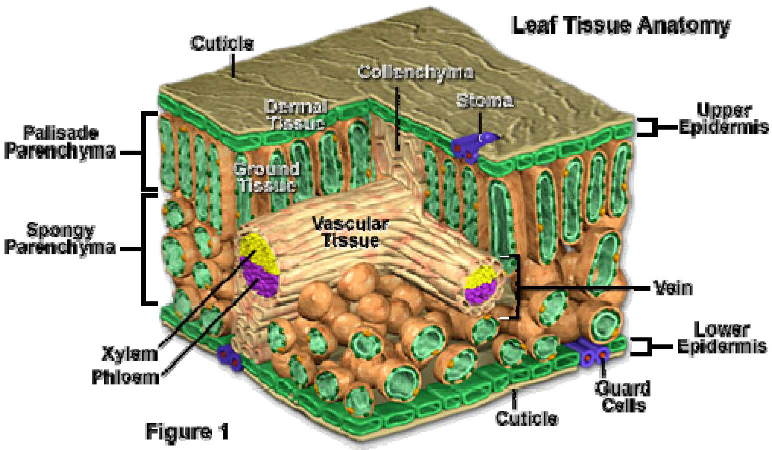

Figure 1

The different layers are characterised by electrical negative charge, which influences the way and rate of penetration of different ions. Some layers are hydrophobic and therefore repulse water-based spray (see *Figure 2*).

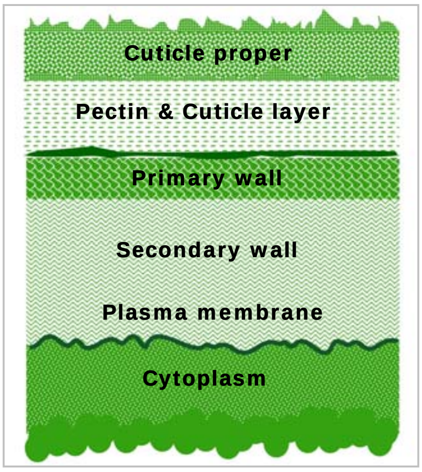

Figure 2

The first layer from outside is a wax layer, which is extremely hydrophobic. The epidermal cells synthesize the wax and it crystallises in an intricate pattern of rods, tubes or plates. The wax layer can change during the plant growth cycle.

The second layer, referred to as the 'cuticle proper', is a non-cellular protective layer surrounded by wax to the upper side and the bottom one as well and made mainly from 'cutin' (macromolecule polymer consisting of long-chain fatty acids creating a semi-hydrophilic character).

The following layer is 'pectin', negatively charged and made of Polysaccharides that form sugar-acid based gel-like tissue (cellulose and pectic materials).

Next is the outer side of the cells starting with the primary wall. The cuticle has negative charge density as well due to the pectin and cutin (Franke, 1967; Marschner, 1986).

How do nutrients penetrate plant tissue?

When we refer to penetration of nutrients we can define two movements – into the tissue from outside, which is referred to as absorption, and movement from the point of penetration to other parts of the plant that is referred to as translocation.

Penetration/absorption can be done through several organ elements that exist in the tissue. Main penetration is done directly through the cuticle. The penetration is done passively. First to penetrate are the cations as they are attracted to the negative charge of the tissue, and they move passively in accordance to the gradient – high concentration outside and low one inside. After a certain period the cations that have moved inside change the electrical balance in the tissue causing it to be less negative and more positive. From this point on the anions start to penetrate the tissue in the same manner as described for the cations (Figure 3). Since the penetration is a passive one, the rate of diffusion across the membrane is proportional to the concentration gradient, therefore achieving a high concentration without scorching the tissue - may dramatically improve the penetration.

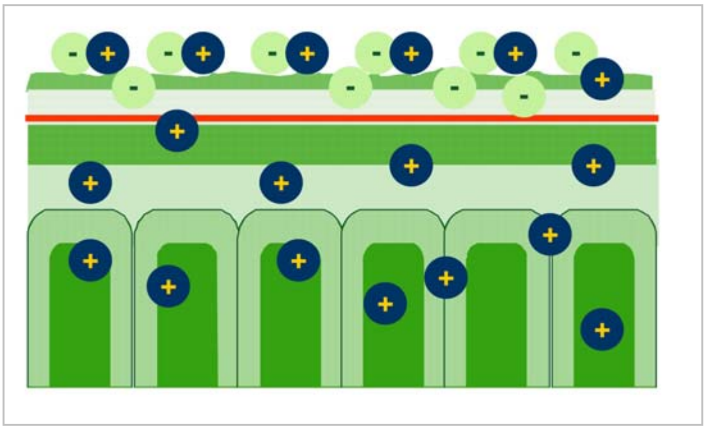

Figure 3

Penetration also occurs through the stomata, which are aperture controlled for gas exchange and transpiration. It is known that these apertures differ between different plant species, their distribution, occurrence, size and shape. In broadleaf crops and trees, most of the stomata are on the lower leaf surface, while grass species have the same number on both surfaces. Size may differ, for example, sorghum stomata are four times larger than bean stomata. High penetration is estimated to be due to high cuticle pore density in cell walls between guard cells and subsidiary cells (Maier-Maercker, 1979). In addition, the pores near the stomata guard cells seem to have different permeability characteristics (Schonherr and Bukovac, 1978). An opposite opinion exists, claiming that penetration through open stomata does not play a major role since a cuticle layer also covers the surface of the guard cells in stomata cavities and because ion uptake rates are usually higher at night when the stomata are relatively closed.

Another path that nutrients can penetrate is through hair-like organs known as 'trichomes', which are epidermal outgrowths of various kinds. The importance of this pathway depends on the trichomes rate and position, dependent on leaf age and its origin (Hull *et al.*, 1975; Haynes and Goh, 1977).

Translocation

After the ions have penetrated, transportation to different parts of the plant starts and this is referred to as translocation. Translocation is done through two mechanisms: cell-to-cell transport is referred to as 'Apoplast movement', and transport through the vascular channels is referred to as 'Symplast movement'.
The Apoplast movement describes the ion movement from one cell to another. This is done by three mechanisms (*Figure 4*):

- Passive transport involves diffusion according to the gradient and mass flow through the water/fluid movement between cells.
- Absorption by cytoplasm membrane surface via plasmodesmata, which are microscopic channels connecting one cell wall to another, enabling transport and communication between them.
- Active transport (ATP) against the gradient, enabled due to energy investment of ATP molecules.

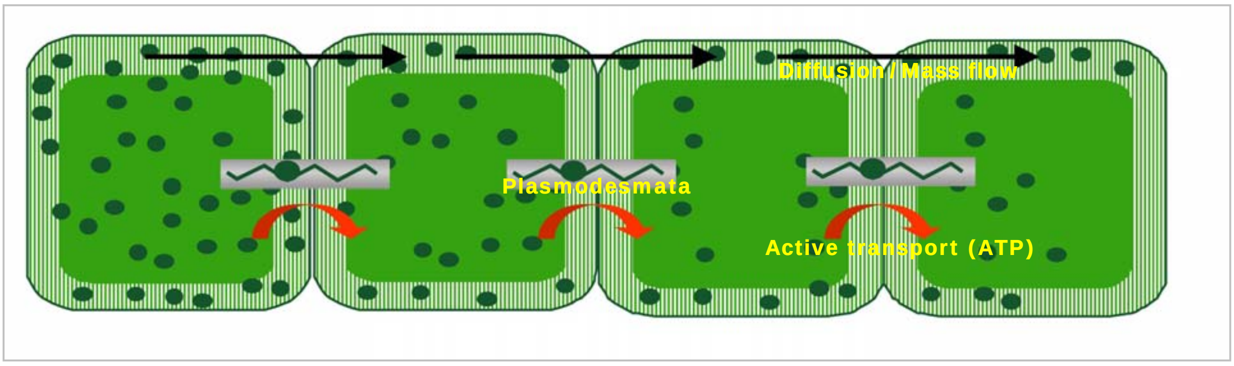

Figure 4

The Symplast movement describes the ion discharge into the vascular system. This is done through two systems (Figure 5):

- Phloem – translocation is energy dependent and more suitable to the divalent cations (C^{2+}); anions are very limited since the cell wall is negatively charged (Van Steveninck and Chenoweth, 1972). Phloem transport is important for distribution from mature leaves to growing regions in the roots and shoots. Phloem movement regularly follows the 'sink-source' relationship, from locations where carbohydrates are created (source) to places where they are consumed (sink).

- Xylem – translocation is flux regulated and driven by water potential differences between soil, leaf and atmosphere.

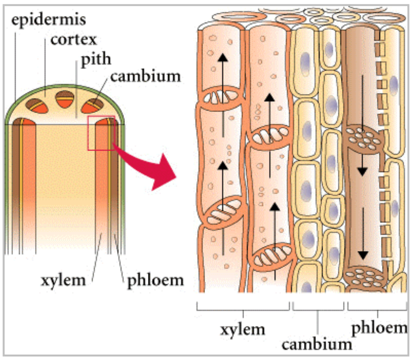

Figure 5

Translocation differs between different ions, thus, nutrients are divided into three groups (Bukovac and Wittwer, 1957) – mobile, partially mobile and not mobile.

Table 1.

Mobility	Plant nutrients				
Mobile	N	P	K	S	Cl
Partially mobile	Zn	Cu	Mn	Fe	Mo
Not mobile	Ca	Mg			

(Bukovac and Wittwer, 1957; Kunnan, 1980)

Foliar feeding limitations

Although foliar feeding is described as a very powerful application method that may overcome a lot of problems, which may be encountered through ground application, it is not a perfect way and has its own limitations:

- Low penetration rates, particularly in leaves with thick wax/cuticles.
- Run-off from hydrophobic surfaces.
- Washing off by rain.
- Rapid drying of spray solutions disabling the penetration of solutes.
- Limited rates of translocation of certain mineral nutrients.
- Limited amounts of macronutrients, which can be supplied by one foliar spray.
- Possible leaf damage (necrosis and burning). Forcing extra cost and time for repeated applications.
- Spray drift on non-targeted sites.
- Limited available effective leaf area (seedlings or damaged plants).

The effectiveness of foliar feeding may be subjected to several factors. These factors can be divided into four major groups – spray solution, environmental conditions, leaf characteristics and plant state.

Several factors play a role for spray solution:

- Solution pH – pH mainly affect the solubility level of several elements such as phosphorus, which improves its solubility as pH decreases. pH may affect the ionic form of the elements and this may affect the penetration rate as well. Regardless of the penetration aspects, low pH may reduce the alkaline hydrolysis rate of different pesticides (*Table 2*).

  pH has its effects on the tissue as well. Plant cuticles are polyelectrolytes with isoelectric points of around 3.0. At pH values below the isoelectric point, cuticular membranes carry a net positive charge and are selective to anions and above the isoelectric point; they carry a net negative charge and are selective to cations (Schonherr and Huber, 1977). These findings support the hypothesis of 'hydrophilic channel', which is used by some surfactants.

Table 2

Trade name	Common name	Solution pH	50% breakdown
Benlate	Benomyl	7.0	1 hour
		5.6	>30 hours
Guthion	Azinphos-methyl	9.0	12 hours
		7.0	10 days
		5.0	17 days
Captan	Captan	10.0	2 minutes
		4.0	4 hours
Furadan	Carbofuran	9.0	78 hours
		7.0	40 days
		6.0	200 days

- Ionic stage/molecule type – materials with high molecular weight penetrate much slower than those with low molecular weight (Haile, 1965; Kannan, 1969).
- Solution water tension – decrease in the interfacial surface tension of a water droplet increases the exposure sites for uptake into the leaf (Leece, 1976). Lower water tension improves penetration through the stomata as well (Greene and Bukovac, 1974). Usage of surfactants may help in reducing the water tension as they carry a non-polar lipophilic tail (oil lover), which aligns itself with the cuticle and the hydrophilic head (water lover) with the water droplet causing it to spread its contact angle and reach higher wetting surface with the leaf.
- Spray droplet size – different drop size may affect the interaction with the targeted surface and the possible drift of the solution from the targeted plant. Bigger drops may resist drift but decrease penetration through the plant canopy.

The environment can influence leaf absorption, cuticle development or physiological reactions related to active absorption mechanism (Flore and Bukovac, 1982), among the major factors:

- Humidity – it has direct influence on the rate of dehydration of the spray drop. In high humidity, the solution will be active for a longer period enabling solutes to penetrate before it dries completely. To a certain extent, dehydration may accelerate the penetration rate as it increases the concentration of the solutes, thus the gradient increases until it is dry when penetration is delayed and the solutes crystallise. Humidity influences the development and physiological status. In low humidity conditions, stomata are closed and plants may develop a thicker cuticle, yet in high humidity conditions the stomata are open and plants may develop a thinner cuticle.

- Temperature – when solution dehydration is not a limiting factor, temperature rise increases absorption (Jyung *et al.*, 1964). Temperature may have negative relations with humidity - as temperature decreases, humidity may rise (Cook and Boynton). Another idea claims that increased temperature lowers the cuticle viscosity and by that, increases the penetration ratio.
- Light – in high light levels the cuticle and the wax layers are thick compared to low light levels (Macey, 1970; Hallam, 1970; Reed and Tuley, 1982), yet the light effect can be related to the stomata opening and the temperature resulting from the radiation.

Effects of the plant characteristics, mainly leaf structure:

- Leaf age – as the leaf ages it tends to thicken with more wax and broader cuticle tissue. This increased barrier reduces penetration rate.
- Leaf surface – some plants have high density hairs (trichomes), which may cause the spray drops not to contact with the actual leaf surface – the water drops 'stand' on the hairs. Leaf surface texture may differ between plants. Smoother surfaces may cause the spray to slide with a lower wetting rate, while rough surfaces will hold the spray drop and have a greater wetting rate.
- Leaf disposition –leaf angle towards the ground influences spray solution retention on the leaf surface (De Rutter *et al*., 1990).
- Leaf shape – different leaf shapes may determine the effective surface in contact with the spray drops.
- Plant species – Plants can be divided into those that grow in wet habitats (hydromorphic) and dry habitats (xeromorphic) and differ in cuticle thickness, stomata position (adaxial=upper side/abaxial=lower side), and shape.

The physiological state of plants may have an effect, where plants with lower metabolic activity have been shown to have a lower 'sink' activity, resulting in lower translocation.

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It is clear that reaching a successful foliar feeding application is dependent on many factors; some are within the control of the grower and may be wisely used, and some are not. In general, spraying during early morning or late afternoon is recommended when radiation and temperature are low (18-19^{0}C; ideal 21^{0}C), wind speed is low (less than 8kph), and humidity is high (greater than 70% relative humidity). Better timing will be late afternoon as it enables more effective absorption hours before the solution becomes dry and inactive. Even when following the rules described in this article, some problems may still exist, which should be handled in the following way:

- Drift – if spray drifts away from the target, droplet size should be increased.
- Poor coverage – if coverage is poor, larger spray volumes should be used with higher spray pressure.

- Poor wetting or cuticular penetration – addition of low surface tension surfactant may help.
- Poor retention – spray droplet size should be decreased and solution viscosity should be increased by addition of polymeric stickers.
- Rapid drying – eventually inhibits further penetration as the solution dries. The addition of oil and emulsifier may preserve the needed moisture.
- Non-effective concentration – importance is high as the penetration is done passively, dependent on the gradient. Application should follow the highest concentration possible without burning/scorching the leaves. Pre-test to determine phytotoxicity and threshold of damage. If lower concentration is in use, compensation should come with high number of applications.

Phototoxicity mainly appears as leaf burning. The toxicity results from the osmotic effect of a highly concentrated salt solution when water evaporates from the spray droplets. In addition, the local nutrient imbalance in the leaf is another factor that may cause the toxicity. For example, urea damage can be prevented by adding sucrose, despite the additional increase in the osmotic potential of the foliar spray (Barel and Black, 1979).

It has to be stated that if phytotoxicity is not immediately observed, it can appear in later stages of the crop if spray applications are too rapid and the interval is too short, resulting in tissue accumulation of toxic elements. Plants may show phytotoxicity symptoms even when solution concentration is in the right level when they are physiologically stressed, either because of thirst, attack by insects, or disease occurrence.

Conclusion

In this article I have reviewed the concept of feeding plants through foliar spraying. It is obvious that foliar feeding is a good, reliable method of feeding plants when ground application is not efficient enough. However, it is important to understand that this method cannot substitute the supply of nutrients through the root system when the uptake of all plant nutrients through leaves involves considerable labour with a high risk of phytotoxicity. The foliar application method has its limitations and in some cases it may be considered a laborious approach. Nonetheless, over the years foliar feeding has captured a place of honour in different plant feeding schemes. Using highly soluble fertilisers and pure nutrients is essential to achieve the best performance from this approach. As mentioned earlier, fertilisers and pesticides are compatible and can be mixed in the same sprayer to save labour costs, and this advantage should be used whenever pesticides are sprayed.

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