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REVIEW

# Effects of Foliar Fertilization: a Review of Current Status and Future Perspectives

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**Abstract**

The use of large amounts of chemical fertilizers promotes high-yield agriculture, but is also associated with a number of problems, such as low fertilizer utilization rates, soil acidification, and soil salinization. Comprehensive studies have shown that spraying chelated fertilizer on leaves can reduce the total amounts of fertilizer applied and achieve high fertilizer efficiency. Foliar fertilizer application after soil fertilization is an effective method to increase the contents of trace elements in crops and crop yield, and to improve the soil environment. However, the application of inorganic foliar fertilizer results in difficulties in nutrient absorption and migration in plants. Chelated foliar fertilizers are effective for improving element utilization efficiency, crop yield, and quality. The physicochemical properties, molecular structure, chelating strength, and chelating rate of chelating agents modulate the effects of application of nutrients. This study reviews and discusses the effects and problems associated with sugar alcohol–containing chelated fertilizers and foliar fertilizers.

**Keywords** Foliar fertilization · Chelated fertilizers · Nutrient uptake and utilization · Crop quality · Soil salinity

## 1 Introduction

In the world, 20% of cultivated land and 33% of irrigated land are salt-affected and degraded (Almeida Machado and Serralheiro 2017), which affect the availability and supply of soil nutrients to crops, resulting in a reduction of both yield and quality, and it has been one of the most important factors contributing to crop losses worldwide (Litalien and Zeeb 2020). In order to increase production, more chemical fertilizers are applied to soil, but due to inappropriate application of mineral nutrients, soil degradation, including acidification, secondary salinization, nutrient imbalance, and an abnormal accumulation of nitrogen (N), phosphorus (P), and potassium (K), is common in soils (Cai 2019), with secondary salinization being the most prominent of these phenomena (Yu et al. 2005). Therefore, to alleviate the adverse effect of soil salinization and degradation on crop yield and quality, avoid secondary salinization, and promote sustainable agriculture, a knowledge-based fertilization method is needed.

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Fertilization methods can be divided into root fertilization and foliar fertilization ones, according to the way by which crops absorb nutrients. The utilization of soil fertilizer nutrients is affected by a number of factors, including soil temperature, humidity, salinity, and microbiota (Li et al. 2009). When inorganic salts are applied alone or in combination with other fertilizers to the soil, both nutrient fixation and antagonism between the nutrients occur (Montalvo et al. 2016). For example, excess P becomes “fixed” in soil, where it forms chemical bonds with other elements, including calcium (Ca), magnesium (Mg), iron (Fe), and zinc (Zn), and becomes unavailable for plant uptake (Raliya et al. 2018). Therefore, although nutrients may be abundant in soil, low bioavailability will restrict plant growth and reduce fertilizer utilization (Xiao et al. 2018), with unused nutrients temporarily accumulating in the soil or being lost to air or water. Compared with root fertilization, foliar fertilization, as a supplementary fertilization strategy, can deliver nutrients directly to the target through aerial plant parts, thereby helping to reduce negative impacts on the soil (Bindraban et al. 2015; Fernández and Eichert 2009). Although foliar fertilizers have traditionally been used to correct nutritional deficiencies, the trend toward foliar spray application is increasing (Fernández and Eichert 2009). Foliar fertilization strategies can achieve higher nutrient use efficiency, reduce the negative impact on the

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environment, and potentially enhance consumer health benefits (Otálora et al. 2018).

Reviews focusing on the mechanisms of the penetration of foliar-applied nutrient solutions through the leaf surface as well as on the major factors affecting its absorption and mobility in plant tissues have been published (Fernández et al. 2013; Fernández and Brown 2013; Fernández and Eichert 2009). This review presents an overview of the effects of the application of foliar fertilization, focusing on the efficiency comparison between inorganic and chelated fertilizers. The review also provides insight into the advantages of high-efficiency foliar fertilizers, such as sugar alcohol–chelated leaf fertilizers compared with others, and identifies the future research prospects.

## 2 Advantages of Foliar Fertilizers

Since the Green Revolution, a higher crop production per area has resulted in a large depletion of soil micronutrients. Micronutrient deficiencies have become a limiting factor for crop productivity in agricultural land worldwide (Khoshgoftarmanesh et al. 2010), and mineral malnutrition has a considerable negative impact on individual well-being, social welfare, and economic productivity (Stein 2010). Root nutrient supply is restricted in arid and saline soils because of the negative effects of abiotic stresses, such as low water availability, extreme temperatures, high pH, and high salt levels on nutrient availability (Hu et al. 2008; Martínez-Ballesta et al. 2010). The availability of some micronutrients in the soil is also influenced by other elements. Considering the advantages of foliar fertilization, it is clear that supplying nutrient elements via foliage fertilization is a good strategy, with higher efficacy than soil fertilization, being more target-oriented and environmentally friendly since nutrients can be applied in controlled quantities and at a specific period of plant growth. The positive effect of foliar fertilizers compared with soil-applied ones can be explained by three different mechanisms.

First, nutrient elements can be absorbed directly through the leaves and transported to other organs (Gao et al. 2018), thereby replenishing essential nutrients more quickly and efficiently compared with soil fertilization. For example, using the $^{15}N$ tracer technique, Sun et al. (2017) reported that the level of $^{15}N$ in leaves was higher in grape seedlings treated with foliar fertilization than with soil fertilization at the mature stage in new shoots. Foliar applications of urea in root N-limited plants increased the total N concentration in sweet pepper fruits and their quality, with no significant differences being found with respect to soil-applied N (del Amor et al. 2009). Foliar-applied gold nanoparticles could be taken up by watermelon through direct penetration and transport through the stomatal opening (Raliya et al. 2016), and foliar application of $TiO_2$ and ZnO nanoparticles was found to be more effective than the soil application on the uptake of the nanoparticles by tomato (Raliya et al. 2015). Soil Zn application (at a rate of 50 kg of $ZnSO_4 \cdot 7H_2O$ $ha^{-1}$) was effective in increasing grain Zn concentration in a Zn-deficient location, but not in the locations without Zn deficiency, while foliar application of Zn significantly increased Zn concentration in whole grain and in each grain fraction in all locations, with the grain Zn concentration increasing from 11 to 22 mg $kg^{-1}$ in Zn-deficient locations and Zn being transported to the endosperm through the crease phloem (Cakmak et al. 2010). Foliar Zn application resulted in higher grain Zn recovery than soil Zn application when determining the potential for increasing the Zn concentrations in maize and wheat grain (Wang et al. 2012). Wang et al. (2013) reported that supply of Se by foliar spraying was associated with maximum grain Se recovery rates of 52‰ and 106‰ for maize during the first and second growing seasons, respectively, whereas soil Se application achieved rates of only 1.69‰ and 0.95‰. Due to the high availability of foliar application, Se levels can be kept sufficiently low to avoid posing a health risk (Schiavon et al. 2013).

Second, high-potency nutrients can be sprayed at optimum timing and concentrations according to the needs of different crops at different growth stages, which can be more closely matched to the crop requirements compared to soil-applied fertilizers. For example, cotton relies mainly on roots to take up nutrients from the soil. Due to the poor nutrient uptake capability of the root system at the seedling stage and the reduced root activity in later stages, it is often difficult for root uptake to meet the nutritional needs, with leaf fertilization being a good way to replenish roots in these two periods (Li et al. 2014b). Manganese (Mn), Mg, and Fe, which are all involved in shoot-specific processes such as chlorophyll biosynthesis and photosynthesis, are good nutrient candidates for foliar fertilization (Bindraban et al. 2015). Both leaf chlorophyll and photosynthesis were reported to increase by spraying Mg on newly developing leaves, and thus had an important influence on the pod formation of faba beans (Neuhaus et al. 2014). Therefore, further research regarding appropriate spray timing and target tissues will improve the reproducibility of the effects of foliar sprays to facilitate commercial use (Fernández and Eichert 2009). For example, foliar application of K fertilizer is effective to improve the physiological indexes of grapes, where higher K levels are required at the berry expansion stage than at the full blooming stage (optimum spraying concentrations of 0.5–0.8% and 0.2–0.5%, respectively) (Zhang et al. 2016). In addition, better increases in grain Zn via foliar application were achieved when Zn was applied at the late growth stage of wheat and rice (e.g., milk and dough stages) (Cakmak et al. 2010; Phattarakul et al. 2012). The Ca content of peach treated with Ca fertilizer was significantly higher than that at the swelling stage (Yu et al. 2017), and spraying amino acid–chelated selenium (Se) fertilizer at the full flowering stage was better than spraying it at the young fruit development stage to increase the Se content of the peel, pulp, and seeds of kyoho grapes (Zheng et al. 2016).

Finally, foliar application can be beneficial by exploiting synergistic effects between different nutrients (Bindraban et al. 2015; Xiao et al. 2004). For example, addition of Zn sulfate ($ZnSO_4$) to foliar Fe increased both the Fe and Zn content in rice (Wei et al. 2012a), and application of Fe, Zn, and Se, alone and in combination, promoted the accumulation of Ca in maize seeds (Li et al. 2018). Leaf spraying of Mn associated with silicon (Si) increased micronutrient accumulation, and physiological and biochemical indexes, and reflected resulted increases in dry mass production of corn and sorghum plants (Oliveira et al. 2020). Wu et al. (2011) suggested that the effect of combined application of copper (Cu) and Zn on the biomass and chlorophyll content of *Salvia* was better than those of single applications of Cu and Zn. Among the treatments with different trace elements, combined application of boron (B) and molybdenum (Mo) showed the best effect, with significant increases achieved in the aboveground and underground biomass of strawberry (Zhang et al. 2017). A recent study showed that foliar application of 0.2% nickel sulfate ($NiSO_4{\cdot}7H_2O$) significantly increased the growth, yield, and the Fe, Cu, Mn, and Zn content of barley (Kumar et al. 2018). However, another study suggested that Mn and Zn have opposing effects; moreover, Se promoted the accumulation of Zn, whereas Fe and Zn slightly inhibited Se accumulation in potato (Barben et al. 2011).

However, other research (Wu et al. 2011) indicated that spraying Cu was better than soil base application and soil topdressing, whereas soil base application of Zn was better than foliar application, mainly due to the relatively high content of available Cu and the severe shortage of available Zn in the soils tested; under an acceptable soil Cu supply, early basal application and mid-term topdressing had little effect on the growth of *Salvia miltiorrhiza*, while mid-term foliar spraying had a better effect. When the available Zn in soil was lower than the critical level, the soil could supply Zn steadily after early basal and topdressing to meet the Zn requirement for the whole growth period. However, only spraying Zn on the leaf surface in the mid-term is unlikely to meet the Zn requirements during the early growth stage of *Salvia*. Therefore, the types and formulations of foliar fertilizer used should be based on the soil nutrient status and the interaction between the foliar-applied nutrient and the uptake of soil-applied fertilizers should be taken into consideration for an integrated management of soil fertility (Wang et al. 2015).

## 3 Effects of Foliar Fertilizers

### 3.1 Effects on Crops

There is abundant evidence that foliar fertilizers play an active role in improving the quality, yield, and metabolism of crops (Fernández and Brown 2013). Hydroponics experiments showed that leaf application of macro- or micronutrients can effectively alleviate nutritional deficiencies in plants, increase the trace element content of leaves and fruits, improve crop yield, and promote produce quality (Gao et al. 2018; Roosta 2014; Roosta and Hamidpour 2013). Pot and field experiments showed that spraying micronutrients could increase leaf number, plant height, leaf diameter, and the chlorophyll content of leaves, and reduce the nitrate content of vegetables such as lettuce and Chinese cabbage (Guo et al. 2008; Zhang et al. 2011). Recent studies have shown that foliar-applied nano-fertilizers are better than normal salt fertilizers for improving the quality, yield, and metabolism of crops. For example, low doses of a Ca nano-fertilizer were better than high doses of calcium chloride ($CaCl_2$) in reducing pomegranate fruit cracking, and the fruit quality was improved more with the nano-nitrogen fertilizer at a rate of 1.8 kg N $ha^{-1}$ than with two applications of urea at a rate of 16.3 kg N $ha^{-1}$ (Davarpanah et al. 2017). $ZnSO_4$ can be transported into the endosperm through the crease phloem of wheat (Cakmak et al. 2010), but zinc oxide (ZnO) nanoparticles penetrate the leaf surface easily compared with $ZnSO_4$ (Rossi et al. 2018), and studies have shown that foliar-applied nanoparticles such as gold nanostructures can be taken up and transported by the phloem (Raliya et al. 2016).

In addition to meeting crops' nutrient demand, recent studies have shown that foliar application of nutrient elements can be an effective method to improve the stress resistance of crops. Foliar application of Si can stimulate plants to grow under stress conditions including salinity, deficiency or excess of water, and high or low temperature (Artyszak 2018). A review on the effect of N application on sunflower under water stress argues that future research is needed for a better understanding of interactions between foliar and soil-applied N under drought conditions (Ahmad et al. 2014). A brief summary of the effect of foliar sprays with different nutrients on crops grown under abiotic stresses such as salinity, drought, or heat is presented in Table 1.

### 3.2 Effects on Soil Quality

Leaf spraying enables plants to absorb nutrients directly from their leaves instead of roots, which can reduce the adverse effects of chemical fertilizers on soils and improve the soil environment. Some studies have shown positive effects of foliar fertilization on the soil ecosystem. For example, after spraying with Si fertilizer,

Table 1 A brief summary of the effects of foliar-applied elements on crops grown under abiotic stress

| Abiotic stress | Element | Crop | Ref. |
|---|---|---|---|
| Salinity stress | Se, B, Fe | Stevia | (Shahverdi et al. 2020) |
| | Se, B, Fe | Stevia | (Shahverdi et al. 2018) |
| | N | Cotton | (Luo et al. 2015) |
| | K, Zn | Wheat | (Zafar et al. 2016) |
| | Fe, Zn | Bean | (Abou-El-Nour et al. 2017) |
| | Se | Lettuce | (Shalaby et al. 2017) |
| | Se | Strawberry | (Zahedi et al. 2019) |
| | Macro- and micronutrients | Tomato | (Camen et al. 2017) |
| Drought stress | Zn, Mn | Wheat | (Shams 2019) |
| | Ca | Maize | (Naeem et al. 2018) |
| | Ca | Sugar beet | (Hosseini et al. 2019) |
| | Ca, B, Fe, Mn, Mo, Zn | Spring barley | (Januškaitienė and Kacienė 2017) |
| Water deficit | Fe, Mn | Canola | (Pourjafar et al. 2016) |
| | Si | Soybean | (Teodoro et al. 2015) |
| Heat stress | K | Wheat | (Shahid et al. 2020) |
| | N | Bean | (Hassan et al. 2015) |
| Drought and heat stress | N, P, K, B | Pear and apple | (Zargar et al. 2019) |
| Low-temperature stress | N or P, K | Pears | (He et al. 2012) |

bacteria levels in wheat and maize were 77% and 67% higher, while fungi levels were 31% and 39% lower, than those in controls, respectively (Xu et al. 2018). Compared with the controls, foliar applications with monopotassium phosphate on potato can significantly increase the soil actinomycete communities while significantly decrease soil fungi communities (Moon et al. 2019). The foliar application of 5.0 g $L^{-1}$ ZnO nanoparticles can increase the soil microbial counts and enzyme activities in rice cultivated under low soil Zn concentrations (Bala et al. 2019). Xiao et al. (2018) reported that Fe fertilization of potato leaves had a significant effect on the beta diversity of fungi; foliar addition of Fe was suggested to influence plant Fe levels, entering the root system to affect rhizosphere fungal communities. Moreover, the application of foliar fertilizers can reduce salt accumulation in the soil to a certain extent. Reducing soil fertilization and increasing foliar fertilization have been shown to have no effect on tomato yield, but to effectively reduce the residual nitrate N and available P in the 0–20-cm soil layer (maximum reductions of 58% and 32%, respectively) (Sun et al. 2011). When urea and organic K fertilizer were sprayed on leaves (reducing the amount of soil fertilizers used), the yield of cucumber did not decrease but the content of nitrate N in the soil decreased significantly (Xu et al. 2004). However, other studies reported increased soil electric conductivity (EC), as some Si fertilizers were not effectively absorbed and utilized by crops after spraying (Xu et al. 2018). Therefore, better fertilization schemes are required to improve crop nutrient uptake and reduce the accumulation of salts in the soils.

### 3.3 Effects of Foliar Fertilization on the Uptake of Soil-Applied Nutrients

Many studies have suggested that the nutrient elements and other constituents of foliar fertilizer formulations may stimulate the uptake of soil-applied fertilizers, which could account for the decrease of salt accumulation in the soil. Experiments using the $^{15}N$ isotopic tracer technique showed that N accumulation of cotton via root uptake was approximately 11.35 mg with ammonium N treatment after foliar application, with the N uptake efficiency increasing by 28% compared with the water control treatment (Zheng et al. 2018). Moreover, spraying K at the budding stage of potato can promote the absorption and utilization of soil K (Zheng et al. 2007). Wei et al. (2013) reported that, under conditions of insufficient N and P application via base fertilizer, spraying urea on leaves met the demand for N in potato, thus promoting plant growth and the absorption and utilization of available soil nutrients (especially N and P). Foliar application of some trace elements showed the same effect. Roosta and Mohsenian (2012) reported that the P content in the shoots and roots of pepper was significantly affected by Fe foliar application, as were the concentrations of K, Mg, and Ca in shoots. Foliar B application on tartary buckwheat can promote its uptake and utilization of soil available N and Pl (Wang et al. 2018).

Therefore, although the effect of foliar spraying is sometimes inferior to that of soil fertilization due to the limitation in the amount of nutrients that can be sprayed (Reed et al. 1988), leaf nutrients can be absorbed and transported to the roots through the stem, improving root activity and preventing premature senescence of roots therefore enhancing root absorption capacity, with this interaction making the combination of soil and leaf fertilization a relevant practice. For example, the combination of soil application and foliar application is superior to either soil-applied or foliar-applied alone in increasing the Zn concentrations in brown rice (Phattarakul et al. 2012) and grain (Poblaciones and Rengel 2016). Soil or foliar N fertilization can improve biomass, leaf area per plant, and leaf photosynthesis of cotton, and a combination of soil- plus foliar-applied N was superior to either soil-applied or foliar-applied alone under salinity stress (Luo et al. 2015). Compared with soil or foliar fertilization alone, combined soil and foliar application of N + Zn resulted in the highest fruit yield and quality (Amiri et al. 2008), while the application of Cu-based foliar fertilizer with added Zn and controlled-release urea promoted plant growth and soil mineral N absorption (Zhu et al. 2012). Therefore, the combination of soil fertilization and leaf fertilization is a promising method to reduce the utilization of N, P, and K. Foliar $ZnSO_4$ combined with macronutrient fertilization can reduce the conventional N application rate by 15%. This reduction can be compensated by increasing the number of times the leaves are sprayed with fertilizer, and to obtain greater economic benefits, the leaf fertilizer should be sprayed more than three times (Li and Liu 2015). Pot experiments showed that 1.0% foliar fertilizer with basal fertilizer and half the typical amount of N had the best effect on the nutrient content, yield, and quality of brassica rape (Fan et al. 2010). Soil inoculation using phosphate-solubilizing bacteria (PSB) or foliar spraying using mono-ammonium phosphate (MAP) or nano-phosphorus (NP) resulted in significant increases in the performances, physio-biochemical attributes, and antioxidative defense system components in *Phaseolus vulgaris* plants in calcareous soils. However, integrative PSB+MAP or PSB+NP treatment further improved all abovementioned parameters in plants (Rady et al. 2019).

In summary, foliar fertilization is an effective measure to improve the soil environment and crop quality, especially under restricted soil nutrient utilization and high soil nutrient loss rates (Fernández and Brown 2013), and when crops are in a special growth period, such as root senescence at the later growth stage. Spraying of foliar fertilizers is a fast, efficient, and targeted fertilization method, which can be combined with soil fertilization to reduce the use of chemical fertilizer and soil salinity accumulation. To maximize the effects of foliar nutrition, attention should be paid to the timing and concentration of formulation (including the interactions thereof), according to the characteristics of the crops treated and the soil fertility. Further studies of these issues are still required, especially with regard to the combination of soil and leaf fertilization.

## 4 Disadvantages of Inorganic Leaf Nutrition

The effectiveness of spraying fertilizer has been shown to be influenced by many factors, including the plant species and growth status, the composition and physicochemical properties of foliar fertilizer, and environmental factors such as temperature and illumination (Fernández and Brown 2013; Fernández and Eichert 2009; Li et al. 2009). More detailed information regarding the environmental, physiological, and biological factors affecting plant response to foliar fertilization can been found in the small book published by Fernández et al. (2013). Overall, foliar treatments are associated with two main problems: uptake of nutrients by leaves and transport of nutrients from leaves to other plant parts.

Many factors affect the nutrient absorption capacity of leaves. For example, transpiration loss of leaf Se solution may occur, and some Se may be assimilated into organic Se and volatilized on the leaf surface; therefore, soil application of Se can be superior to leaf spraying of Se with respect to Se bioaccumulation and the nutritional quality of rice grain (Zhang and Zhou 2019). The effectiveness of Fe sulfate ($FeSO_4$) can be due either to reductase activity once the applied Fe(II) has been oxidized to Fe(III) or to direct uptake of Fe(II) through a transporter (Álvarez-Fernández et al. 2004); Fe supplied via certain compounds may be readily immobilized in the leaf apoplast due to ionic binding or the formation of insoluble Fe compounds (Fernández et al. 2005). Under short-term drought or salt stress, the application of foliar fertilization did not promote plant growth, because drought reduced the uptake of K, Ca, Mg, and P, possibly due to reduced transpiration (Hu et al. 2008). Moreover, the short contact time of a solution on the leaf surface and fast drying on the crop surface will also affect the absorption of foliar nutrients.

The mobility of foliar-applied nutrients in plants is another important factor in determining the efficacy of foliar fertilizer. A study performed on beans in 1957 indicated that all elements applied to leaves were absorbed and translocated, but not at the same rate or according to the same pattern; moreover, elements such as Ca, B, Fe, Mn, and Zn had little phloem mobility (Bukovac and Wittwer 1957). Subsequent studies were performed to examine the underlying mechanism. Will et al. (2011) suggested that B was immobile in phloem, and the distribution of B in plants mainly followed the transpiration flow; within the cell wall and cytoplasm, B rapidly formed stable complexes and contributed to the water-insoluble portion. Vicosi et al. (2020) found that foliar application of B significantly influenced the content and accumulation of B in the shoot and the root system of snap bean, but did not change the contents in pods. However, the tested doses did not influence significantly the growth variables and productivity, though they affect the physiology of snap bean plants, with the high B doses causing symptoms of phytotoxicity. Zn in wheat leaves showed limited mobility and moved less than 25 mm from the point of application after 24 h, and X-ray absorption near-edge structure (XANES) data showed that Zn was then complexed by ligands in the leaves, potentially in response to localized Zn toxicity (Doolette et al. 2018). In Zn-deficient plants, the mobility of Zn was restricted to an even greater extent as the concentration of Zn reached background levels within a distance of 2 mm; the limited mobility could also be attributed to the immobilization of Zn within Zn–ligand complexes with high stability constants (log K) at pH 6.0–8.0 (Du et al. 2015; Marešová et al. 2012). In conclusion, the re-translocation of nutrients from leaves to sink organs is not easily accomplished in crops under conditions of high pH in phloem, poor transpiration rate, and especially the immobilization of complexes with high stability.

## 5 Effects of Foliar Spray Chelating Foliar Fertilizers

### 5.1 Advantages of Chelating Leaf Fertilizer

Metal chelates have been used in agriculture for more than 50 years to compensate for the deficiencies of common inorganic foliar fertilizers (Montalvo et al. 2016). When nutrient elements and chelating agents form stable chelate fertilizers, the utilization rate of nutrient elements can be usually increased, leading to remarkable improvements in plant stress resistance, promotion of early crop maturity, high yield, and improved quality (Gong 2002). Low application rates of highly phytoavailable products minimize the release of nutritionally essential, but potentially ecohazardous, metals into the environment (Peryea 2006).

#### 5.1.1 Effects of Chelating Agents on Crops

Chelating agents, such as humic acid, amino acid, and sugar alcohol, can enhance crop stress resistance, promote the growth of crop roots, and improve the ability of crops to absorb nutrients (Cheng et al. 2011; Wang et al. 2019; Yuan et al. 2009); e.g., in pot experiments, the contents of Mn and B in leaves sprayed with humic acid and Mn-B mixed liquor were 7.9% and 6.9% higher than those sprayed with Mn-B mixed liquor (Xiao et al. 2004). Compared with controls, the rape yield was increased by 25%, 31%, and 35% by spraying with sorbitol, sodium gluconate, and glycine, respectively. Spraying appropriate low molecular weight organic compounds could markedly improve the uptake of nutrients (N, P, K), enhance the contents of soluble sugar and protein, and decrease the nitrate content of rape (Yu et al. 2014). Compared with $ZnSO_4$ spraying alone, the Zn uptake of brassica rape increased by 26%, 50%, and 67% when sprayed with glycine, glutamic acid, and threonine along with $ZnSO_4$, respectively (Shen et al. 2017).

#### 5.1.2 Promoting the Adsorption and Migration of Elements

Firstly, the rate of foliar-applied nutrient retention or repulsion depending on the interactions between the fertilizer drops and plant surfaces is the first step in the absorption of foliar fertilizers, which predominantly relies on the contact area between the fertilizer drops and the plant surface (Fernández and Brown 2013). The polarity and hydrophobicity of nutrient elements chelated with different chelating agents can be more suitable for the dispersion of nutrient elements on leaves, thereby avoiding burning of leaves due to excessive local concentrations and increasing the absorption of nutrients by leaves. Secondly, due to the special structure of chelates, the rate of crossing the cuticle of leaves after spraying can be usually faster than that of inorganic ions. Due to the high stability of the complex, nutrient elements can be absorbed and transported in chelated form (Mu et al. 2006), thus promoting the migration and transformation of elements in crops; e.g., the shoot Fe concentration was significantly influenced by the foliar application of all Fe sources, but the Fe concentration in roots of pepper was only affected by ethylenediaminetetraacetic acid–chelated Fe (Fe-EDTA) (Roosta and Mohsenian 2012). In addition, high concentrations of nutrients in foliar fertilizers may strongly affect chemical speciation and mobility due to localized toxicity in crop leaves. Therefore, the application of chelating leaf fertilizers with slower release rates is likely to reduce toxicity on a local scale (Doolette et al. 2018). Moreover, the high stability of the chelating leaf nutrients with slower release rates is likely to contribute to the close nutrient release rate synchronous with crop absorption, which facilitates high utilization of nutrient elements compared with common inorganic foliar fertilizers. Following foliar spraying of amino acid–chelated Fe fertilizer, the average Fe concentration in all cultivars of brown rice tested was increased by 14% compared with control (Yuan et al. 2013). Similarly, the Fe content of strawberries treated with small molecular organic-chelated Fe and Fe-EDTA increased significantly, by 35% and 27%, respectively, while the effect of spraying Fe sulfate on Fe content was not significant (Yu et al. 2016). Similar to Fe treatments, the grain Zn and protein content of wheat plants sprayed with amino acid–chelated Zn (Zn-AA) was on average 14% higher than that of plants sprayed with inorganic $ZnSO_4$ (Ghasemi et al. 2013).

Therefore, the effect of foliar spray chelating fertilizers can often be better than inorganic foliar fertilizer on crop yield and quality improvement (Souri et al. 2017; Wang et al. 2014). Compared with $FeSO_4$ spraying, chelated Fe spraying achieved higher yield and improved the symptoms of Fe deficiency in soybean (Dong et al. 2011). The fertilizer was supplemented with $MnSO_4$, amino acid–chelated Mn, or Mn-EDTA; the application of an appropriate amount of chelated Mn had a better effect on improving the quality, increasing the soluble protein and vitamin C (VC), and reducing the nitrite and nitrate content of *Brassica pekinensis* (Han et al. 2011). The effectiveness of amino acid–chelated K in improving nut yield and quality was higher than that of potassium sulfide ($K_2SO_4$), and the best nut quality and highest yield were obtained with foliar application of lysine plus methionine (Hamze et al. 2018).

### 5.2 Disadvantages of Chelating Fertilizer

Spraying chelating fertilizer can also have unsatisfactory effects due to a number of factors (Álvarez-Fernández et al. 2004; Modaihsh 1997), such as light, stomata, leaf age, and species (Rodríguez-Lucena et al. 2009; Schlegel et al. 2006; Wallace and Wallace 1982). Nutrient elements are not easily absorbed by crops after chelation due to the high molecular weight of some chelating agents; in the presence of Fe-EDTA, aqueous pores are reduced in size and the penetration rate of $CaCl_2$ is also significantly decreased (Schönherr et al. 2005). Rios et al. (2016) used the Perls blue method to trace Fe uptake pathway in leaves of Prunus rootstock and found that inorganic Fe salts caused larger leaf Fe concentration increases than Fe-EDTA. Under conditions of Fe deficiency, the highest Fe uptake and distribution thereof in leaves were recorded after foliar spray treatment with $FeSO_4$ followed by Fe-citrate and Fe-EDTA (Chakraborty et al. 2014a). Similarly, all Fe sources significantly increased the leaf chlorophyll of peach, as well as both the "physiologically active" and total Fe concentrations of the leaves compared with controls; the highest values were noted with foliar-applied 1% $FeSO_4$ (Chakraborty et al. 2014b). Early season foliar $FeSO_4$ have better effects on pomegranate yield and quality than Fe-EDDHA (Davarpanah et al. 2020). Inorganic Mn ($MnSO_4$) was more effective than Mn-EDTA with regard to improving the content of Mn in the leaves under the same concentration of Mn (Papadakis et al. 2005). A multi-year field study (Peryea 2006) of the phytoavailability of Zn in 11 commercial products indicated that foliar application of inorganic Zn preparations, such as Zn phosphate, Zn oxide, and Zn oxysulfate, was more effective than of chelated/organically complexed Zn.

Chelating agents with different structural characteristics show different ion chelation activities, and differences in stability according to temperature and pH. For example, although all lignosulfonates (LS) can complex Fe, only spruce LS shows good ability to maintain significant amounts of soluble Fe above pH 8 (Rodríguez-Lucena et al. 2011), which may underlie differences in efficiency: ultrafiltered LS and phenolated LS showed slightly better ability to supply foliar-applied Zn to navy beans than the others, while those with lower pH stability but higher complexing capacity were slightly more suitable as chelating agents providing Zn (Benedicto et al. 2011). Therefore, the effects of foliar-applied chelated fertilizers vary according to the chelating agents used. For example, mature *Tempranillo tinto* leaves sprayed with Fe-EDTA showed higher Fe concentrations than those sprayed with Fe-ethylenediamine disuccinic acid (Fe-EDDS) (Yunta et al. 2013), while Fe-diethylenetriaminepentaacetic acid (Fe-DTPA) was better than Fe-N-(2-hydroxyethyl)ethylenediaminetriacetic acid and Fe-EDTA with regard to improvement of Fe concentration and bioavailability (He et al. 2013). Foliar-applied Zn-AA showed greater effects than Zn-EDTA and Zn-citrate in improving the Zn concentration (Wei et al. 2012b), and higher levels of Zn uptake and mobilization to leaves and stems were achieved with Zn-EDTA than with Zn-LS (Benedicto et al. 2011). After the foliar application of 15 products, including 10 natural complexes and 5 synthetic chelates, the greatest regreening effect was observed for plants treated with synthetic chelates and amino acid complexes; translocation to the roots only occurred for Fe-LS (Rodríguez-Lucena et al. 2010). In addition, some synthetic chelating agents cannot be absorbed and utilized well by crops despite good Fe chelation activity; addition of the calcium chelating agent ethylenebis(oxyethylenenitrilo)tetraacetic acid (EGTA) to nutrient solution decreased the dry weight of wheat seedlings and the total Ca content in underground parts (Wang et al. 2000). Besides, they can also be poorly biodegradable and may mobilize toxic heavy metals from contaminated sediments (Tucker et al. 1999; Yuan and VanBriesen 2006).

The main chelating agents are humic acid, amino acid, LS, sugar alcohol, polysaccharides, and synthetic chelating agents, such as EDTA and DTPA. Their reported ability to improve the bioavailability of nutrient elements varies among studies, and it is not yet clear which chelating agent has the best performance and lowest cost. Therefore, to improve the quality of chelating fertilizer, it would be necessary to select an environmentally friendly chelating agent with appropriate chelating capacity, while considering differences in maintenance of solubility and release of metal elements to plants under different acidity and alkalinity conditions (Lucena 2003), thus optimizing the absorption, utilization, and mobility of these elements in plants, which is help for improving the utilization rate of fertilizers and alleviating environmental problems caused by excessive fertilization.

### 5.3 New Sugar Alcohol–Chelated Leaf Fertilizer

Due to the alkaline environment of phloem, the solubility and mobility of many metal mineral nutrients are poor, thus decreasing the fertilizer utilization rate (Bukovac and Wittwer 1957; He et al. 2017); meanwhile, sugar alcohols are the primary product of photosynthesis and exist in stable liquid form, and the migration of mineral nutrients is better in the alkaline environment after forming complexes with sugar alcohols (Brown and Hu 1996). For example, foliar B can be long distance transported from leaves to roots via phloem by forming a B-sucrose complex in citrus plants (Du et al. 2020). The B source affects the assimilation of the nutrient uptake of eucalypt, and the assimilation was higher when applied with sorbitol (Muller da Silva et al. 2015). Compared with wild-type tobacco, the flow of B in plants of transgenic tobacco containing sorbitol increased significantly, which improved the growth and yield of tobacco with limited or interrupted soil B supply (Brown et al. 1999).

Many experiments have examined the fertilizer efficiency of sugar alcohol chelating fertilizers. Compared with conventional fertilization and Ca nitrate treatment, spraying sugar alcohol–complexed Ca increased the yield of eggplant by 9% and 2%, respectively, and the VC, soluble solid, and sugar acid content increased as well (Wu et al. 2013). The application of small-molecule organic chelating Ca fertilizer, developed from amino acids and sugar alcohol, can increase the biomass, VC, and soluble protein content of Chinese cabbage and tomato, and reduce the nitrate nitrogen content; it can also effectively promote the absorption of Ca and increase the total Ca content of plants compared with the application of calcium nitrate (Ding et al. 2015; Shen et al. 2016). Table 2 summarizes the research results on the effect of foliar spray of sugar alcohol–chelated fertilization.

The table shows that, during the past years, the focus of research about sugar alcohol–chelated leaf fertilization was mainly on two issues: (i) the fertilizer efficiency comparisons between sugar alcohol–chelated leaf nutrients and other leaf nutrients including inorganic leaf fertilization, EDTA-chelated fertilization, nanoscale nutrients, and amino acid–chelated fertilization. A general trend might be derived that the effect of the sugar alcohol–chelated nutrients tends to be better than that of other kinds of foliar nutrient; (ii) the spraying methods of sugar alcohol–chelated leaf nutrients including spray stages, spray frequencies, and concentrations. Nevertheless, almost all of the research did not pay attention to the interreaction between the foliar-applied sugar alcohol–chelated nutrient and the uptake of soil-applied fertilizer, since some studies have suggested that nutrient elements and other constituents of foliar fertilizer formulations may stimulate the uptake of soil-applied fertilizer and the effect of foliar-applied fertilizer could be affected by the soil nutrient status and crop nutrient deficiency (see section: Effects of Foliar Fertilization on the Uptake of Soil-Applied Nutrients).

In addition, the evaluation indexes for the effects of foliar-applied sugar alcohol–chelated nutrients include the growth, yield, and quality of crops, the nutrient content in crops, the morpho-physiological characteristics of crops, and the content absorption and migration of foliar-applied nutrient elements (Table 2). Sugar alcohol–chelated fertilization has a tendency to be superior to inorganic leaf fertilization and other chelating foliar fertilizers in those evaluation indexes. However, there is evidence that in soybean the addition of polyols may increase the absorption of B, while having little effect on B translocation (Will et al. 2011, 2012), although whether there is a distinct effect of B-sorbitol complexes on B translocation apart from the pure adjuvant effect is uncertain. Therefore, more attention should be paid to the migration and transformation of nutrient elements chelated with different chelating agents in comparison to inorganic foliar fertilizer.

Furthermore, studies on sugar alcohol chelating fertilizer have largely focused on its fertilizer efficiency, and few have focused on the fertilizer efficiency difference between chelating fertilizers with different chelation strengths and chelation rates. The chelation rate can be detected by quantitative determination methods such as spectrophotometric (Yan et al. 2018b) and conductivity measurement (Yan et al. 2018a). A detailed overview about the methods of separation and detection of chelates has been published by Bai et al. (2020). Chelation reactions can be divided into simple complexation, chelation, and multinucleus complexation reactions according to the ligands and coordination atoms (ions) involved. Their stability and biological value are affected by both their physical and chemical coefficients, including the chelation rate in particular, as well as the chelation strength (among other parameters) (He et al. 2019a), which can be affected by chelation conditions, such as the reaction temperature, reaction time, and pH value of reaction system (He et al. 2019b). Plot and field experiments (Li et al. 2020a; Li et al. 2020b) have shown that the application effects of sorbitol-complexed Ca on potato vary by its chelating process. Therefore, it is necessary to find out the effect of chelation conditions on the chelating fertilizer efficiency.

## 6 Concluding Remarks

Compared with inorganic foliar fertilizers, chelated foliar fertilizers may improve the migration ability and utilization efficiency of inorganic mineral salts. Efficacy often differs among fertilizers, but most studies only examine

**Table 2** A summary of the effect of foliar spray sugar alcohol–chelated fertilization

| Element | Crop | Factor | Indexes | Results | Ref. |
|---|---|---|---|---|---|
| Ca | Chinese cabbage | Ga sources | Growth, quality, nutrient uptake | (AA+SA)-Ga > SA-Ga, $Ca(NO_3)_2$ | (Shen et al. 2016) |
| | Tomato | Ga sources | Yield, quality, nutrient uptake | (AA+SA)-Ga > SA-Ga > $Ca(NO_3)_2$ | (Ding et al. 2015) |
| | Peach | Ga sources | Ga content, quality | (AA+SA)-Ga > SA-Ga > $Ca(NO_3)_2$ | (Yu et al. 2017) |
| | Eggplant | Ga sources | Growth, yield, quality | SA-Ga > $Ca(NO_3)_2$ | (Wu et al. 2013) |
| | Peach | Ga sources | Quality, split-pit | SA-Ga > $CaCl_2$, $Ca(NO_3)_2$ | (Li et al. 2014a) |
| | Grape | Ga sources | Ca content, fruit quality | SA-Ga is suitable for cluster spray $Ca(NO_3)_2$ is suitable for foliar spray | (Guan et al. 2014) |
| | Grapevine | Ga sources | Photosynthesis, enzymes activities | SA-Ga > EDTA-Ca > $CaCl_2$ > $Ca(NO_3)_2$ | (Yang et al. 2014) |
| | Tomato | Ga sources | Photosynthesis under heat stress | SA-G, Nano-Ca > $CaCl_2$ | (Qi et al. 2014) |
| | Apple | Ga sources | Fruit firmness, enzymes activities | SA-Ga > AA-Ca, $CaCl_2$, $Ca(NO_3)_2$ | (Pei et al. 2018) |
| | Blueberry | Ga sources | Quality, nutrient content | Ineffective | (Manzi and Lado 2019) |
| | Grape | Spray stages | Ca content, fruit quality | The young berries stage > 2 weeks before the harvest | (Guan et al. 2014) |
| | Peach | Spray stages | Ga content, quality | Coloring period > fruit enlargement period | (Yu et al. 2017) |
| | Honeydew fruit | Spray stages and frequency | Quality | Four applications > one or two applications | (Lester and Grusak 2004) |
| | Cantaloupe fruit | Spray stages and frequency | Quality | Did not benefit from applications | (Lester and Grusak 2004) |
| Zn | Potato | Zn sources | Zn absorption, and distribution | SA-Zn > $ZnSO_4$ | (Sun et al. 2015) |
| | Apple | Zn sources | Quality, nutrient content | SA-Zn ≥ $ZnSO_4$ | (Zhang et al. 2013) |
| | Rice | Zn sources | Seed enrichment, nutrient content, productivity | Sorbitol-stabilized Zn > nano-Zn > EDTA-Zn | (Alvarez et al. 2019) |
| | Apple | Spray stages | Quality, nutrient content | – | (Zhang et al. 2013) |
| | Apple | Spray stages | Quality, Zn content, enzymes activities | – | (Zhang et al. 2014) |
| | Rice | Spray concentration | Seed enrichment, nutrient content, productivity | – | (Alvarez et al. 2019) |
| B | Rapeseed seedlings | B sources | Morpho-physiological characters, B absorption and distribution | SA-B, glycerol-B > boric acid (BA) | (Yan et al. 2017a) |
| | Rapeseed seedlings | B sources | Mitigative effect on aluminum toxicity | BA > SAB | (Yan et al. 2017b) |
| | Eggplant | B sources | Growth, yield, quality | SA-B > organic B, BA | (Wang et al. 2017) |
| | Citrange rootstock | B sources | Growth, physiology characters | SA-B > BA | (Zhang et al. 2019) |
| Fe | Strawberry | Fe sources | Quality, Fe absorption | (AA+SA)-Fe > EDTA-Fe, $FeSO_4$ | (Yu et al. 2016) |
| Ga + B | Apple | Spray stages and frequency | The incidence of sunburn | – | (Lötze and Hoffman 2014) |

*AA*, amino acid; *SA*, sugar alcohol; *SA-Ga, AA-Ga, and (AA+SA)-Ga*, Ga chelated to sugar alcohol, Ga chelated to amino acid, and Ga chelated to amino acid and sugar alcohol (the same as other kind of elements)

nutritional effects on crops; few have focused on the effects of chelation on the utilization rate of nutrient elements, their absorption, migration, and transformation in crops, and the interactions among different nutrients with foliar spraying of different types of leaf fertilizer. More attention should be paid to the migration and transformation of nutrient elements chelated with different chelating agents in comparison to inorganic foliar fertilizer.

The main chelating agents currently in use are humic acid, amino acid, LS, sugar alcohol, and synthetic chelates. Sugar alcohols, as a kind of surfactant and primary products of photosynthesis, are a kind of promising chelator that can improve nutrient element uptake and transport. Due to the differences in physicochemical properties of chelating agents and the chelation conditions such as reaction temperature and reaction time, chelating leaf fertilizers vary in chelation rate and strength, which can have impact on their fertilizer efficiency. It is not clear which chelating agents and chelating conditions most contribute to nutrient absorption and release in plants. Therefore, further in-depth systematic studies are needed to evaluate the different types of chelating agents, and the effects of chelation technology on fertilizer efficiency, to guide the development of new foliar fertilizers.

Under conditions of deficiency in a particular nutrient element, the growth and development of crops cannot be improved, even if other nutrient elements are supplied in large quantities. However, excessive application of nutrient elements to the soil will result in an abnormal accumulation of elements. The combination of soil fertilization and foliar fertilization can reduce the use of chemical fertilizers and achieve good production and high yield; thus, use of this combination is an effective measure for alleviating secondary salinization and improving the soil environment. Nevertheless, the optimum quantity and nutrient element application method should be determined according to local conditions and comprehensive assessment of the fertility status of the soil to be cultivated. Systematic studies of the fertilization efficiency of different combinations of root and foliar fertilizers are needed, especially with respect to the interactions between foliar nutrients and soil nutrients, to establish a systematic and scientific fertilization model, promote widespread use of foliar fertilizer in agricultural production, and reduce the ecological impact of chemical fertilizer on the environment.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no competing interests.

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