

Effective Strategies to Correct Iron Deficiency in Florida Vegetable Crops

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SUMMARY. Iron (Fe) deficiency is a frequent nutritional problem in Florida vegetable crops because of leaching of Fe fertilizer from the soil, poor soil aeration, low soil organic matter (SOM), temperature, high soil pH and/or water bicarbonate content, and interactions with high levels of manganese (Mn) and calcium (Ca). Most Fe-deficient plants are yellow and stunted, with symptoms on younger leaves near the top of the plant because of Fe immobility and poor translocation resulting in interveinal chlorosis. Iron deficiency in tomato (*Solanum lycopersicum*) is characterized by a drastic reduction of leaf chlorophyll content at first at the base of the leaves (bleached leaf) ending in necrotic spots. Iron deficiency can have a significant economic impact depending on the timing of the deficiency during the crop production cycle. Furthermore, crop genotypic variations influence the ability of root systems to acquire Fe. The objective of this article was to describe current methods used by vegetable growers to correct Fe deficiency and to evaluate their effectiveness in tomato, pepper (*Capsicum annuum*), bean (*Phaseolus vulgaris*), and eggplant (*Solanum melongena*) production in Florida. A survey was conducted in the major vegetable production areas in Florida during 2012. Results from the survey indicated that since Fe availability depends on complex soil and environmental factors, there was no reliable soil test method that can predict Fe deficiency on vegetable crops in Florida. Production areas surveyed with calcareous or alkaline soils that are often due to over-liming, Fe becomes unavailable because of significant reduction of Fe. Production practices for those areas were not to use calcitic lime to raise Ca levels, especially if the pH is adequate (6.5). Instead, gypsum or calcium nitrate was recommended for soil Ca. The survey indicated that Fe sulfate (inorganic form) is the most commonly used Fe fertilizer in Florida. However, chelates of Fe were effective but expensive Fe alternative. Among chelate sources, ferric ethylenediaminediaminedi-*o*-hydroxyphenylacetic acid was frequently the preferred chelate fertilizer for soil application, but it is an expensive option. Soil acidification to lower the soil pH was also used to improve soil Fe availability. Organic matter in animal manures and composts was used as an effective alternative to increase Fe with positive results in Florida tomato production. However, the survey indicated that Fe applied to the soil was converted into unavailable forms especially under high soil pH, thus foliar application was used if Fe deficiency symptoms were observed early in the production cycle.

Iron, a micronutrient essential for vegetable production, is required in low quantities between 1 and 1.5 lb/acre (Liu et al., 2012). Iron is the fourth most abundant element in the soil; however, Fe in the soil is in the form of ferric oxides [Fe₂O₃ (reddish and yellowish soil color)], which is not available to plants (Hochmuth, 2011; Schulte, 2004). Iron plays a significant role in protein (including chlorophyll and enzyme) biosynthesis, energy transfer, plant metabolism, and biological nitrogen (N) fixation (Hochmuth, 2011; Nenova, 2006). The lack of adequate Fe available for

the plant can lead to Fe deficiency (Broschat and Elliott, 2005; Koenig and Kuhns, 2010; Walworth, 2013). The primary symptom of Fe deficiency is interveinal chlorosis with a yellowing of the leaf tissue in the interveinal region while the veins remain green. Due to poor mobility within the plant, Fe deficiency symptoms are common in the youngest leaves first, especially at the base of the leaves. Under prolonged adverse conditions, leaf chlorophyll content declines significantly

with whitening of the leaf blade known as “bleached leaf” (Broschat and Elliott, 2005; Koenig and Kuhns, 2010; Walworth, 2013). Iron chlorosis during early growth stages affects mineral composition of leaves and flowers and hence causes significant decrease in yield and quality (Tagliavini et al., 2000, 2001).

Causes of Fe deficiency in Florida

Even though most Florida soils are rich in total nutrients, phytoavailability of specific nutrients such as Fe is often inadequate due to several factors. However, pedological and crop genetic factors are responsible for low Fe bioavailability resulting in crop Fe deficiency. Soil pH, nutrient interactions, soil aeration, SOM content, and crop mobilization capacity influence Fe solubility and availability to plants (Schulte, 2004). Ferrous (Fe²⁺) forms of iron are available for plant uptake only within an acceptable soil pH range (5.3–6.5) whereas ferric (Fe³⁺) forms are insoluble. Immobility of Fe at high soil pH (7.4–8.5) may be the main factor responsible for Fe and other micronutrient deficiency in vegetable crops (Fisher et al., 2003; Schulte, 2004). As pH increases, Fe solubility decreases. At high pH, various Fe compounds such as Fe₂O₃, carbonates, phosphates, and ferric hydroxides [Fe(OH)₂] exist that are not taken up efficiently by plants. There is a strong antagonism between Fe and calcium. High concentration of Ca reduces Fe bioavailability (Fisher et al., 2003; Melendez and Infante-Casella, 2011). Similarly, high levels of micronutrients such Mn, zinc (Zn), or copper (Cu) can interfere with Fe availability and uptake. Waterlogged/hypoxic soil conditions can increase carbon dioxide (CO₂) production leading to higher bicarbonate formation and ultimately Fe fixation. Soluble organic complexes from organic matter such as cover crops, compost, or animal manure application react with Fe in the soil solution, creating natural chelates

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
3.7854	gal	L	0.2642
1.1209	lb/acre	kg·ha ⁻¹	0.8922
2.2417	ton/acre	Mg·ha ⁻¹	0.4461

resulting in available Fe in the soil. The ability of root systems to solubilize, absorb, and effectively use soil Fe differs among crop genotypes (Table 1). Genotypes with greater ability for Fe absorption and translocation in plants are Fe-efficient plants. Iron-efficient genotypes have specific mechanisms to effectively reduce Fe³⁺ to Fe²⁺ in the root system. In these plants genotypes the bioavailability of phosphorous (P), Ca, Cu, Zn, and molybdenum (Mo) has a low influence on Fe absorption or is capable of secreting Fe-chelating molecules by the roots such as phytosiderophores that regulate Fe absorption and use (Clark, 1983).

The objective of this article was to summarize the current methods used by growers to correct Fe deficiency and ineffectiveness based on a survey conducted in the major tomato, pepper, bean, and eggplant production areas of Florida.

Materials and methods

A formal survey was conducted in the major tomato, pepper, bean, and eggplant production areas in Florida (Collier, Hendry, Lee, Glades, Charlotte, Palm Beach, and Miami-Dade counties) (Table 2). The survey included questions such as “do you use Fe soil test and interpretation?”, “do you get Fe deficiency?”, “if yes, in what season?”, “when during the season?”, “how do you diagnose Fe deficiency?”, “do you modify soil pH to prevent Fe deficiency?”, and “what products do you use in the soil and foliar?” The

Table 1. Florida vegetable crop relative susceptibility to iron (Fe) deficiency (Liu et al., 2012).

Crop/Scientific name	Susceptibility ^z
Bean (<i>Phaseolus vulgaris</i>)	High
Broccoli (<i>Brassica oleracea</i> var. <i>italica</i>)	High
Cabbage (<i>B. oleracea</i> var. <i>capitata</i>)	Medium
Potato (<i>Solanum tuberosum</i>)	Low
Sweet corn (<i>Zea mays</i>)	Medium
Strawberry (<i>Fragaria × ananassa</i>)	High
Tomato (<i>Solanum lycopersicum</i>)	High

^zHigh = needs Fe fertilization, medium = probably needs Fe fertilization, low = needs no Fe fertilization.

survey was conducted during 2012 through grower visits, phone calls, and e-mail. At least 59% of the 73,796 acres of the vegetables grown in these counties were covered in the survey and 67% percent of the acreage surveyed responded.

Results and discussion

IRON SOIL TEST AND INTERPRETATION IN FLORIDA. Eighty-five percent of vegetable growers surveyed indicated that they used routine soil tests for Fe and other micronutrients yearly (Table 3). However, the soil test results were not used for interpretation or as an Fe fertilization guideline. The major reason is that there is no reliable soil test method to predict Fe deficiency due to the influence of several factors such as soil

pH and bicarbonate concentration that influence soil Fe availability and mobility (Hochmuth, 2011).

IRON DEFICIENCY ON VEGETABLE CROPS IN FLORIDA. Ninety-five percent of the growers in calcareous and alkaline soils (man-made or natural), or with irrigation water sources with high pH (≥7.5), experienced Fe chlorosis (Table 3). Seventy percent and 30% of those growers experienced Fe deficiency near the end of the growing season for spring (December to February) and fall/winter (October to December) plantings, respectively. Eighty-five percent of vegetable growers used visual plant and leaf symptoms as a diagnostic tool for Fe deficiency, since plant and leaf symptoms are simple to recognize (Chaney, 1984). Only 15% of the vegetable growers

Table 2. Survey of vegetable crops, total acreage, acreage surveyed, acreage responded, growers surveyed, and average size farm surveyed by county for iron deficiency survey in Florida.

Crop	Total	Surveyed	Responded	Growers surveyed (no.)	Avg size of farms surveyed (acres)
		(acres) ^z			
<i>Collier, Hendry, Lee, Charlotte, Glades counties</i>					
Tomato, round	20,000	12,800	8,400	8	1,600
Bell pepper	7,000	4,200	1,890	10	420
Hot pepper	3,500	1,920	760	4	480
Bush bean	13,000	7,200	6,000	12	600
Eggplant	1,200	800	650	3	267
<i>Miami-Dade County</i>					
Tomato, round	2,267	2,267	1800	3	756
Tomato, grape/cherry	1,133	780	540	2	390
Bush and pole bean	18,696	7,800	6,000	12	650
<i>Palm Beach County</i>					
Bell pepper	5,000	3,800	2,200	7	543
Tomato, round	2,000	2,000	1,100	3	667
Total	73,796	43,567	29,340	64	637
Percentage	—	59	67	—	—

^z1 acre = 0.4047 ha.

Table 3. Survey questions and grower response to iron (Fe) deficiency survey in Florida.

Survey questions	Grower response (%)
Do you use Fe soil tests and interpretation?	85
Do you get Fe deficiency in high pH soils?	95
If you do get Fe deficiency in high pH soils, what season and when during the season?	70 (Spring) and 30 (Fall)
Do you use visual plant and leaf symptoms to diagnose Fe deficiency?	85
Do you use leaf tissue analysis and interpretation to diagnose Fe deficiency?	15
Do you modify soil pH to prevent Fe deficiency?	95

used leaf tissue analysis and interpretation as a diagnostic tool.

FLORIDA MANAGEMENT PRACTICES FOR SOIL FE APPLICATION. Several management practices are being applied for preventing Fe deficiency in Florida sandy soils. On the basis of the survey, 95% of the vegetable growers modified soil pH to 6.5 (Table 3). However, higher soil pH during the crop season, because of alkaline irrigation water, often causes vegetable crop Fe deficiency (Bailey, 1996; Liu et al., 2012). High soil pH can lower Fe bioavailability, therefore lowering the soil pH in vegetable crops can correct Fe deficiency disorders by increasing the solubility and uptake of Fe by plant roots (Walworth, 2013). Therefore, calcitic lime applications are not recommended if soil pH is adequate (5.5–6.5). Instead, gypsum or calcium nitrate can be applied to increase soil Ca content. In addition to correcting soil pH, several soil Fe sources have been used to correct Fe deficiency in vegetable production (Table 4). The most common inexpensive strategy used by 90% of the vegetable growers to correct Fe deficiency was incorporation of Fe fertilizer at bedding (plasticulture and open-beds). The most popular form of fertilizer was Fe sulfate (FeSO_4) at an average of 14 to 20 lb/acre for tomato, pepper, and eggplant. Only 10% of the vegetable growers were using chelated Fe fertilizers such as ferric ethylenediaminediaminedi-*o*-hydroxyphenylacetic acid (Fe-EDDHA), ethylenediamine di [(2-hydroxy-4-methylphenylacetic) acid Fe-EDDHMA], and ferric ethylenediaminetetraacetic

acid (Fe-EDTA). A chelated fertilizer is a metal nutrient ion encircled by an organic molecule, which may be a natural or synthetic ligand (Liu et al., 2012). Recommendations for chelated fertilizer applications are based on soil pH for vegetable production in Florida. At soil pH lower than 5.3, no chelated fertilizers are needed; at pH 5.3 to 6.5 in highly susceptible crops, chelated fertilizer may be needed (Table 1); and pH higher than 6.5, chelated fertilizers are needed (Liu et al., 2012). Soil applied Fe chelates such as Fe-EDDHA, Fe-EDTA, ferric hydroxyethylenediaminetriacetic acid (Fe-HEDTA), and ferric ethylenediaminetetraacetic acid (Fe-DTPA), or combinations have shown a very effective reduction in chlorosis compared with plants receiving other soil fertilizers such as ferric citrate, ferrous ammonium sulfate, FeSO_4 , and Fe glucoheptonate (Smith and Cheng, 2006). The most effective chelate fertilizer to control Fe deficiency symptoms at early plant developmental stages was Fe-EDDHA, since it is the most stable at soil pH higher than 7.0 (Broschat and Elliott, 2005; Liu et al., 2012).

Water and soil acidification treatments were used by 10% to 20% of the vegetable growers using drip irrigation to prevent Ca and magnesium (Mg) carbonates and Fe_2O_3 deposits in drip tubing together with FeSO_4 fertilization at bedding (Table 4). Since precipitation of these compounds occurs in water with a high pH (above 7.0), it can be prevented by continuously injecting small amounts of acid (phosphoric acid, hydrochloric acid,

and sulfuric acid) in irrigation water to maintain water pH below 7.0. The concentration of phosphoric acid, hydrochloric acid, and sulfuric acid will depend on the initial pH and the target pH. The recommended concentrations are determined by running a test in a 55-gal container before injecting the acids since only a small amount can change the pH by 3 units. An alternative strategy and more popular control method was periodic injection of a greater volume of acid for 45 to 60 min to reduce the water pH to 4.0 or 5.0.

Twenty-to-thirty percent of the vegetable growers were using compost or animal manures in vegetable production together with FeSO_4 fertilization at bedding. Compost and animal manures improve soil quality, enhance the use of fertilizer, and provide a source of macro- and micronutrients, thus improving the performance of vegetable crops (Ozores-Hampton et al., 1998, 2011; Ozores-Hampton and Peach, 2002). Increased SOM improves soil physical properties such as bulk density and increase available water-holding capacity. Chemical properties, cation exchange capacity, pH, and macro- and micronutrient supplies are also improved (Ozores-Hampton et al., 2011; Sikora and Szmids, 2001) and biological properties such as soil microbial activity have been reported to improve (Ozores-Hampton et al., 2011). Application of 12 tons/acre of yard trimming waste compost for 3 years on sandy soil in southern Florida with pH greater than 7.0 decreased Fe deficiency in tomato, as shown in Fig. 1. Disadvantages of manure

Table 4. Soil and foliar applied iron (Fe) fertilizer sources and survey response used in vegetable production in Florida.

Sources	Fe (%)	Survey response (%)	Comments
Iron or ferrous sulfate (FeSO_4)	20	90	Most commonly used Fe
Ferric hydroxyethylenediaminetriacetic acid (Fe-HEDTA)	12.8	10	The preferred chelate fertilizer sources for soil application, but the most expensive
Ferric ethylenediaminediaminedi- <i>o</i> -hydroxyphenylacetic acid (Fe-EDDHA)	6		
Ferric ethylenediaminetetraacetic acid (Fe-EDTA)	5–14		
Ferric diethylenetriaminepentaacetic acid (Fe-DTPA)	10		
Ethylenediamine di [(2-hydroxy-4-methylphenylacetic) acid Fe-EDDHMA]			
Water and soil acidification	6.5	10–20 ^z	Lower pH will allow soil Fe availability
Organic matter (compost and animal manures)	5–10	20–30 ^y	An effective alternative to decreased Fe deficiency with positive results on tomato in Florida

^zAcidification was used only by drip irrigation vegetable growers together with application of Fe fertilizers such as Fe sulfate at bedding.

^yCompost and animal manure were used combined with Fe fertilizers application at bedding.



Fig. 1. Typical iron deficiency symptoms (yellow and stunted plants) in tomato in soil pH above 7.5 (left) and no iron deficiency symptoms after compost application for 3 years at 12 tons/acre [$26.9 \text{ Mg}\cdot\text{ha}^{-1}$] (right) in Immokalee, FL.

application can be potential introduction of nematodes, excessive antagonism among minerals, cost, availability, and food safety.

MANAGEMENT PRACTICES FOR FE DEFICIENCY AS FOLIAR APPLICATION IN FLORIDA. Since Fe applied to the soil will be converted into unavailable forms in high pH soils, foliar applications are recommended when Fe deficiency symptoms occur in early growth stages, calcareous or alkaline soils of higher than pH 7.5, or when Fe chelates are not effective (Liu et al., 2012). Foliar Fe applications have a “re-greening” effect associated with increased chlorophyll and Fe contents. The most common sources of foliar Fe in Florida are shown in Table 4. Foliar application of chelated sources of Fe has been more effective than traditional sources such as FeSO_4 in correcting Fe deficiency in Florida (Cox, 2000; Liu et al., 2012; Neumann and Prinz, 1975). Bush bean production is highly susceptible to Fe deficiency in high pH soils of southern Florida (Table 1). To efficiently manage Fe deficiency and chlorosis, bean growers typically use one or two foliar Fe applications of chelated Fe fertilizers or more inexpensive alternatives such as FeSO_4 . Fisher et al. (2003) compared the efficacy of foliar applications of the Fe-EDTA vs. FeSO_4 and concluded that an organosilicon surfactant applied along with both products increased Fe uptake. However, Fe-EDTA was more effective compared with FeSO_4 , but Fe-EDTA was also a more expensive

Fe source to reduce Fe deficiency. Since Fe is required in relatively small amounts compared with macronutrients, foliar applications can be an effective supplement to soil-derived Fe in vegetable products. Further research and investigation is needed to fully understand Fe interaction in soil and vegetable production in Florida.

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