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Solubility of Iron, Manganese, and Magnesium Sulfates and Glucoheptonates in Two Alkaline Soils

Travis W. Shaddox*
UF/IFAS
Fort Lauderdale Research and Education Center
Univ. of Florida
3205 College Ave.
Ft. Lauderdale, FL 33314

J. Bryan Unruh
West Florida Research and Education Center
Univ. of Florida
4235 Experiment Dr.
Jay, FL 32565

Jason K. Kruse
Natasha G. Restuccia
Dep. of Environmental Horticulture
Univ. of Florida
PO Box 110670
Gainesville, FL 32611

Sulfate and glucoheptonate forms of Fe, Mn, and Mg are commonly applied to horticultural and agricultural crops. Once these metals enter the soil solution, their solubility may be limited. Glucoheptonate may prolong soil solubility, but its influence in alkaline soils has not been documented. The objective of this study was to determine the solubility of Fe, Mn, and Mg sulfates and glucoheptonates in two alkaline soils. A Tavares sand (a hyperthermic, uncoated Typic Quartzipsamment) and a Fuquay loamy sand (a loamy, kaolinitic, thermic Arenic Plinthic Kandiudult) were incubated with soluble Fe, Mn, or Mg applied as either the sulfate or the glucoheptonate. At 1 h, 4 h, 1 d, and 1, 2, and 3 wk, soils were extracted with 0.01 mol L^{-1} $CaCl_2$ and analyzed for Fe, Mn, or Mg. At 1 h, approximately 98 and 93% of applied Fe was insoluble in the Tavares sand and Fuquay loamy sand, respectively. The greatest differences between soils occurred with Mn solubility, with 54 and 20% rendered insoluble in Tavares sand and Fuquay loamy sand, respectively, at 1 h. Soluble Mg declined at 1 h by 10%, with no further reductions throughout the 3-wk incubation. Soil applications of Fe as sulfate or glucoheptonate should be avoided. Applications of Mn sulfate or glucoheptonate may lead to increased soil solubility immediately following the application but may rapidly decline. Magnesium, however, remains soluble for as much as 3 wks. Glucoheptonate did not increase the solubility of Fe, Mn, or Mg compared with sulfate in either soil.

Abbreviations: EDDHA, ethylenediaminedi-*o*-hydroxyphenlyacetic acid; EDTA, ethylenediaminetetraacetic acid.

Core Ideas

- **Iron, Mn, and Mg solubility decreased in as short a time as 1 h.**
- **Mg declined only by 10% in 3 wk, but Fe was 93% or more insoluble in 1 h.**
- **Glucoheptonate did not increase solubility compared with sulfate in alkaline soils.**

Iron, Mn, and Mg are common components of both granular and foliar agricultural nutrient programs. In granular form, these elements are commonly applied as soluble salts (sulfates) blended with other components such as N, P, or K. In sulfate form, Fe and Mn may rapidly convert to insoluble compounds, which reduces plant uptake, leading to deficiency symptoms, particularly in high-pH soils (Petrie and Jackson, 1984; Snyder et al., 1979). Thus, metals are often applied in chelated forms that are designed to maintain solubility, especially in high-pH soils (Sommers and Lindsay, 1979). Glucoheptonate (Fig. 1) (National Center for Biotechnology Information, 2016) is a chelate relatively new to agricultural use. Glucoheptonate is typically recommended as a foliar spray. However, some applicators use glucoheptonate as a soil application or soil drench despite any evidence confirming the ability of glucoheptonate to sustain metal solubility in alkaline soils.

The solubility of Fe, Mn, and Mg in soils is strongly influenced by soil pH and moisture. As transitional heavy metals, Fe and Mn respond similarly to soil pH and moisture, with both exhibiting reduced solubility as pH increases and moisture decreases (Lucena et al., 1987; Mortvedt, 1986; Petrie and Jackson, 1984; Sommers and Lindsay, 1979). For every unit increase in pH, Fe^{3+}, Fe^{2+}, and Mn^{2+}

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*Corresponding author (shaddox@ufl.edu).

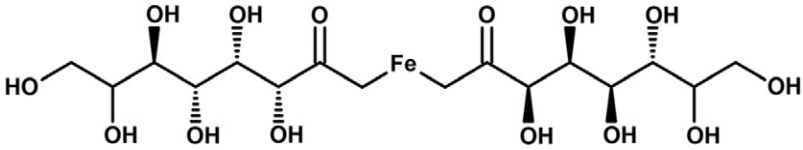

Fig. 1. Molecular structure of iron glucoheptonate (National Center for Biotechnology Information, 2016).

concentrations decrease 1000-, 100-, and 100-fold, respectively (Lindsay, 1981). At normal pH ranges for crop production (4.0–8.0), soluble Fe in solution precipitates out as an oxide species (Lindsay, 2001), often rendering soil solution Fe insufficient to meet crop demand. Soluble Fe and Mn may increase in soils subjected to elevated moisture levels via reduction in the presence of reduced O_2 (Carrow et al., 2001, p. 245–267). Sharpley (1991) documented the reduction in Mg solubility as soil pH increased from 3.0 to 8.0 and noted that the slope of the relationship between water-soluble cation and pH was most closely related to the clay content and cation exchange capacity. In agricultural production, Mg chelates are less common than other metal chelates due to Mg remaining more soluble than Fe or Mn in high-pH soils (Ulrich and Sumner, 1991).

Glucoheptonates are biodegradable chelating agents composed of carbohydrates most commonly manufactured from corn sugars (Zak, 1972). Glucoheptonate metals for use in agriculture are produced by blending glucoheptonate with a metal salt, typically a sulfate, carbonate, or nitrate (Whitehurst et al., 1989). However, information regarding the chelation ability of glucoheptonate in high-pH soils is limited. Moreover, glucoheptonate is highly degradable, with as much as 98% degradation occurring within 2 d (Maxwell, 2004, p. 325–331). With such rapid degradation, the influence of glucoheptonate on maintaining metal solubility is suspect. Goos and Germain (2001) incubated soils with 12 Fe fertilizers and found that Fe remained soluble for at least 8 wk when applied as ethylenediaminetetraacetic acid (EDTA), diethylenetriaminepentaacetic acid (DTPA), and ethylenediaminedi-*o*-hydroxyphenlyacetic acid (EDDHA), with little to no Fe solubility observed from either lignosulfate, gluconate, or glucoheptonate. Furthermore, they noted that soluble Fe applied as $FeSO_4$ was equivalent to the untreated control after 1 d of incubation, an observation that was confirmed by Garcia-Mina et al. (2003). Moreover, Broschat (2003) applied several Fe sources to dwarf ixoras (*Ixora* spp.) and reported that the chlorosis index was unaffected by Fe glucoheptonate at 2 and 6 mo after application. Broschat (2003) did observe a chlorosis reduction at 4 mo after application compared with the untreated control but not compared with $FeSO_4$. Clearly Fe glucoheptonate may result in a plant response, but its ability to influence Fe solubility in the soil solution is questionable.

We are unaware of any study that has investigated the solubility of Mn and Mg glucoheptonates in soils. However, Norvell and Lindsay (1969) investigated the solubility of Mn-EDTA in five soils and reported a more rapid reduction in soluble Mn than either Fe, Zn, or Cu. At pH 6.1, approximately 10% of applied Mn remained soluble after 6 h of incubation, with Mn applied as EDTA being rendered insoluble as rapidly as soluble inorganic Mn salt. Snyder et al. (1979) investigated the response of 'Tifgreen' bermudagrass (*Cynodon* × *magenissii* Hurcombe) to $MnSO_4$, Mn chelate, Mn oxide, and $(NH_4)_2SO_4$ and concluded that the dominating factor influencing the Mn response was the pH reduction by the $(NH_4)_2SO_4$ treatment, which presumably solubilized existing soil Mn. Furthermore, they noted that Mn applications were unnecessary to correct pH-induced Mn deficiency because $(NH_4)_2SO_4$ applied alone supplied sufficient Mn through the reduction in pH and $(NH_4)_2SO_4$ is a commonly applied N source. Other researchers have also documented the influence of pH on Mn (Mousavi et al., 2011; Petrie and Jackson, 1984; Sommers and Lindsay, 1979).

In most soils of agronomic importance, Mg remains soluble and available for plant uptake for several weeks after application (Härdter et al., 2004). However, numerous fertilizer manufacturers have included glucoheptonate as a component of Mg nutrient solutions and positioned the end product (Mg glucoheptonate) as being able to increase Mg availability via either foliar or soil applications. While the addition of glucoheptonate may enhance the blending process by increasing solution stability, the addition also increases application costs. The increase in cost should coincide with an increase in value to the applicator. However, the value, if any, as a soil chelate has not been documented.

Information regarding Fe, Mn, and Mg glucoheptonates in soils is limited, and while their use as chelates has been investigated (Broschat and Elliott, 2005; Guertal, 2010), the stability of glucoheptonates and their influence on metal solubility in alkaline soils would be valuable information and may lead to reduced applicator costs. Therefore, the objective of this research was to determine the solubility of Fe, Mn, and Mg sulfates and glucoheptonates in two alkaline soils.

MATERIALS AND METHODS

Two soils representative of native soils in North Florida were incubated with solubilized Fe, Mn, or Mg for 1 h, 4 h, 1 d, and 1, 2, and 3 wk at 25°C. Tavares sand (a hyperthermic, uncoated Typic Quartzipsamment) was collected from the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Plant Science Research and Education Unit in Citra, FL (Table 1). Fuquay loamy sand (a loamy, kaolinitic, thermic Arenic Plinthic Kandiudult) was collected from the West Florida Research and Education Center in Jay, FL. Each soil was collected from research plots on which 'Palmetto' St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze.] had been established for >5 yr. The soils were air dried and crushed to pass a 2-mm sieve. Ten-gram subsamples of soil were weighed into plastic cups and treated with 500 μg of either Fe, Mn, or Mg, providing an initial loading rate of 50 mg kg^{-1}. Five replications were used. Treatments were arranged in a randomized complete block design and included an untreated control, Fe sulfate (6%),

Fe glucoheptonate (6%), Mn sulfate (5%), Mn glucoheptonate (5%), Mg sulfate (4%) and Mg glucoheptonate (4%). All products were procured directly from the manufacturer (Hocking International Laboratories) by taking a 4-L sample following a batch production of each product. Manganese and Mg glucoheptonate were manufactured as Harrell's Max Manganese 5% and Harrell's Max Magnesium 4%, respectively. Because Fe glucoheptonate, Fe sulfate, Mn sulfate, and Mg sulfate are commonly blended with other elements, these treatments were custom manufactured to allow the investigation of individual metals. Treatments were applied in 2 mL (200 mL kg^{-1}) of deionized water to bring each soil moisture level to approximate field capacity. Plastic wrap was used to seal the top of each cup. A 1-cm hole was cut in the wrap for aeration. Cups were then immediately weighed. The cups were weighed weekly, and the water lost by evaporation was replenished with deionized water. At each incubation time, 50 mL of 0.01 mol L^{-1} $CaCl_2$ was added to each sample. The samples were then shaken for 2 h, filtered, acidified with HCl to 2.0 pH, and stored at 4°C. Filtrates were analyzed for Fe, Mn, and Mg at the University of Florida Analytical Research Laboratory, Gainesville, using an inductively coupled plasma spectrometer (USEPA, 2001). The minimum detection limits (MDLs) for Fe, Mn, and Mg were 0.05, 0.10, and 0.05 mg L^{-1}, respectively. Concentrations that were lower than the MDL were corrected to the MDL value.

Model residuals were analyzed for normality both graphically and numerically with the Shapiro–Wilk *W* test. Data were also checked graphically for homogeneity of variance. These tests determined that the data residuals of each soil were normally distributed. Soil, time, and treatment levels were analyzed as fixed effects.

Table 1. Chemical properties and particle size distribution of Tavares sand and Fuquay loamy sand.

Parameter	Tavares sand	Fuquay loamy sand
Mehlich III content, mg kg^{-1}		
P	64.9	46.5
K	41.5	57.8
Ca	754.9	372.1
Mg	26.9	34.7
Fe	69.9	161.9
Mn	8.0	24.4
Al	149.2	961.1
Na	15.9	8.4
pH	7.2	7.3
OM†, %	1.6	4.6
CEC‡, cmol kg^{-1}	5.5	2.9
Particle size diameter§		
mm	%	
2.0–1.0	0.3	0.2
1.0–0.5	6.4	10.8
0.5–0.25	47.3	30.2
0.25–0.15	30.3	23.4
0.15–0.05	14.5	25.8
<0.05	1.2	9.6

† Organic matter by weight loss on ignition.
‡ Cation exchange capacity by NH_4OAc.
§ Determined by ASTM (2001).

The GLIMMIX procedure in SAS (SAS Institute) was used to analyze the data, and mean separations were conducted using the Tukey–Kramer procedure for multiple comparisons ($P \leq 0.05$).

RESULTS AND DISCUSSION

The solubility of Fe and Mn was influenced by each main effect and their interactions (Table 2), whereas the solubility of Mg was influenced by each main effect and the time × treatment interaction. Because our objective was to determine differences among treatments within soils and time and because the soil × time × treatment interaction was often significant, treatment means are presented within each soil and time.

Iron

The addition of Fe sulfate and Fe glucoheptonate increased Fe in solution after 1 and 4 h of incubation in Tavares sand and after 1 h in Fuquay loamy sand but provided no additional Fe following 1 d of incubation (Tables 3 and 4). Our findings support those of Goos and Germain (2001), who investigated the solubility of 12 soluble Fe sources in soils from North Dakota and Italy. They reported that Fe sulfate and Fe glucoheptonate resulted in no soluble Fe after 1 d of incubation, which was similar to the control during their 8-wk incubation. However, the first extraction time in the Goos and Germain (2001) study was 1 d, whereas we extracted soluble Fe at 1 and 4 h. The 1- and 4-h extraction times indicate that the application of Fe may result in 98% insolubility of applied Fe within 1 h of entering the soil solution. Our observation that soluble Fe becomes rapidly insoluble is supported by prior studies, which have reported that Fe^{2+} remains soluble for no more than a few minutes in aerated soil solutions of pH ≥7 (McBride, 1994, p. 240–272).

Iron glucoheptonate resulted in similar amounts of soluble Fe during each extraction time as Fe sulfate in both soils. This differs from prior research, which has shown that the addition of Fe chelates increases soluble Fe compared with non-chelated forms. O'Connor et al. (1971) investigated the diffusion of Fe in soils and Fe uptake by sorghum (*Sorghum vulgare* Pers.) roots. They determined that most of the applied ^{59}Fe-EDDHA remained chelated and in solution, while the non-chelated ^{59}Fe was lost from solution, presumably as amorphous Fe oxides. In their plant uptake study, O'Connor et al. (1971) observed that

Table 2. Type III tests for fixed effects of Fe, Mn, and Mg sulfates and glucoheptonates soluble in 0.01 mol L^{-1} $CaCl_2$ in Tavares sand and Fuquay loamy sand 1 h, 4 h, 1 d, and 1, 2, and 3 wk after initiation.

Source of variation	df	Fe	Mn	Mg
Soil (S)	1	***	***	***
Time (T)	5	***	***	*
Treatment (TR)	2	***	***	***
S × T	5	***	***	NS
S × TR	2	***	***	NS
T × TR	10	***	***	***
S × T × TR	10	***	*	NS

* Significant at the 0.05 probability level; NS, not significant.
*** Significant at the 0.001 probability level.

Table 3. Iron, Mn, and Mg soluble in 0.01 mol L^{-1} $CaCl_2$ as influenced by product and length of incubation from 1 h to 21 d in Tavares sand.

Treatment	1 h	4 h	1 d	7 d	14 d	21 d
Fe	mg kg^{-1} soil (% of applied)					
Control	0.36 b†	0.32 b	0.28 a	0.22 a	0.20 a	0.20 a
Sulfate	0.60 a (0.48)	0.40 a (0.16)	0.32 a (0.08)	0.28 a (0.12)	0.26 a (0.12)	0.20 a (0.00)
Glucoheptonate	0.52 a (0.32)	0.38 ab (0.12)	0.32 a (0.08)	0.32 a (0.20)	0.24 a (0.08)	0.20 a (0.00)
Mn						
Control	0.20 b	0.20 b	0.20 b	0.20 b	0.20 b	0.20 b
Sulfate	23.50 a (46.6)	21.16 a (41.9)	19.64 a (38.8)	13.02 a (25.6)	10.20 a (20.0)	1.82 a (3.2)
Glucoheptonate	21.70 a (43.0)	19.60 a (38.8)	18.10 a (35.8)	12.98 a (25.5)	6.60 a (12.8)	1.64 a (2.8)
Mg						
Control	18.02 b	18.80 b	21.26 b	20.44 b	21.24 b	20.54 b
Sulfate	63.58 a (91.1)	58.98 a (80.3)	60.64 a (78.7)	57.72 a (74.5)	61.50 a (80.2)	60.36 a (79.6)
Glucoheptonate	64.10 a (92.1)	59.88 a (82.1)	61.80 a (81.1)	59.02 a (77.1)	61.60 a (80.7)	61.54 a (82.0)

† Within a column, treatment means followed by the same letter are not different according to Tukey–Kramer at $P < 0.05$.

Table 4. Iron, Mn, and Mg soluble in 0.01 mol L^{-1} $CaCl_2$ as influenced by product and length of incubation from 1 h to 21 d in Fuquay loamy sand.

Treatment	1 h	4 h	1 d	7 d	14 d	21 d
Iron	mg kg^{-1} soil (% of applied)					
Control	0.40 b†	0.42 b	0.44 a	0.28 a	0.30 a	0.22 a
Sulfate	4.20 a (7.60)	1.98 a (3.12)	0.50 a (0.12)	0.32 a (0.08)	0.34 a (0.08)	0.24 a (0.04)
Glucoheptonate	4.10 a (7.40)	1.88 a (2.92)	0.52 a (0.16)	0.30 a (0.04)	0.28 a (–0.04)	0.24 a (0.04)
Manganese						
Control	6.62 b	5.58 b	7.70 b	7.26 b	4.52 b	2.16 b
Sulfate	48.82 a (84.4)	49.42 a (87.6)	44.16 a (72.9)	38.44 a (62.4)	29.14 a (49.2)	22.32 a (40.3)
Glucoheptonate	46.02 a (78.8)	44.12 a (77.1)	41.34 a (67.3)	36.88 a (59.2)	25.70 a (42.4)	17.28 a (30.2)
Magnesium						
Control	27.70 b	29.08 b	30.44 b	31.42 b	32.42 b	29.98 b
Sulfate	73.38 a (91.3)	72.62 a (87.1)	71.72 a (82.5)	72.06 a (81.3)	71.74 a (78.6)	69.66 a (79.4)
Glucoheptonate	73.40 a (91.4)	70.74 a (83.3)	73.52 a (86.2)	71.38 a (79.9)	71.76 a (78.7)	69.62 a (79.3)

† Within a column, treatment means followed by the same letter are not different according to Tukey–Kramer at $P < 0.05$.

^{59}Fe-EDDHA led to increased plant uptake, while the non-chelated ^{59}Fe was not found in the plant at the two highest soil solution concentrations (0.4 and 0.8 mg kg^{-1} Fe). Thus, the use of an appropriate Fe-specific chelate can result in increases in solution concentration. While glucoheptonate has been suggested to be an Fe chelate (Clemens et al., 1990), these results indicate that glucoheptonate has no apparent chelation ability in these soils. The stability constants of Fe glucoheptonate and Fe-EDTA are 1.1 and 15.3 (log *K*), respectively (Martell and Smith, 1974). The low stability of Fe glucoheptonate explains our finding that glucoheptonate was unable to increase Fe solubility in these soils.

While our results indicate that soil-applied Fe becomes rapidly insoluble regardless of the addition of glucoheptonate, other investigators have determined that Fe may remain soluble under certain conditions. Matocha and Pennington (1982) investigated the response of grain sorghum [*Sorghum bicolor* (L.) Monech] to various Fe sources including an experimental treatment that was created by blending Fe sulfate with plant metabolites from Johnsongrass [*S. halepense* (L.) Pers.]. They reported that sorghum tissue was as effective as Fe-EDDHA at maintaining Fe solubility and increasing plant uptake of Fe in calcareous soils. Godsey et al. (2003) investigated corn (*Zea mays* L.) response to seed-row-applied or foliar-applied Fe sulfate. Although increased yields were not consistent among locations or years, they did observe an average grain yield of 1.6 Mg ha^{-1} when Fe sulfate was seed-row-applied at 81 kg ha^{-1} to responsive sites (four out of seven site-years). Rather than applying Fe as a sulfate, Mostaghimi et al. (1988) applied Fe via increasing rates of sewage sludge and observed that the Fe concentration in sorghum [*S. bicolor* (L.) Monech] shoot tissue increased from 80.4 to 113.5 mg kg^{-1} as sludge rates increased from 0.0 to 20.0 g kg^{-1}, respectively. However, their results were not consistent among soil types. Clearly, previous investigations have indicated that a plant response to soil-applied Fe may occur under certain conditions. Nevertheless, our results indicate that the use of granular Fe sulfate would be of little value in terms of plant response under our study conditions.

Manganese

In Tavares sand, Mn sulfate and Mn glucoheptonate resulted in increased Mn in solution compared with the control during each incubation time (Table 3). Approximately 46% of the applied Mn remained soluble after 1 h of incubation, but this declined to 3% by the end of the study. In Fuquay loamy sand, both Mn sulfate and Mn glucoheptonate resulted in greater soluble Mn than the control during the entire incubation (Table

4). Additionally, after 1 h of incubation, soluble Mn from both sources was approximately 80% of that applied, declining to about 30% after 21 d. The greater amount of soluble Mn observed in Fuquay loamy sand was the result of greater Mehlich III extractable Mn found in Fuquay loamy sand compared with Tavares sand (Table 1). The rapid decline of soluble Mn in both soils is consistent with prior studies conducted on soils with a pH ≥7. Petrie and Jackson (1984) incubated a soil from southern Oregon with 5.6 kg ha^{-1} of Mn from $MnSO_4$ with either $(NH_4)_2SO_4$ or urea for 7, 14, and 28 d. After 7 and 28 d of incubation, soluble Mn from $(NH_4)_2SO_4$ + $MnSO_4$ was 400 and 285 μmol L^{-1} (30% reduction), while soluble Mn from urea + $MnSO_4$ was 480 and 90 μmol L^{-1} (90% reduction). The soil pH of the $(NH_4)_2SO_4$ + $MnSO_4$ and urea + $MnSO_4$ treatments was 6.3 and 6.6 after 7 d of incubation and 6.7 and 7.4 after 28 d of incubation, respectively. They concluded that the increase in pH resulting from the urea + $MnSO_4$ treatment led to the reduction in soluble Mn. Similar results have also been reported in field studies. Snyder et al. (1979) investigated the influence of Mn fertilization on 'Tifgreen' bermudagrass and reported that Mn sulfate and Mn chelate provided short-term corrections of Mn deficiency while $(NH_4)_2SO_4$ applied without Mn resulted in adequate Mn nutrition throughout the 3-yr study. After soil analysis, they concluded that when the pH was <7, sufficient Mn was available for normal turfgrass growth, but as the pH increased above 7, Mn deficiency limited turfgrass growth. Plants absorb Mn as Mn^{2+}, which is also the principal species of Mn in soil solution (Havlin et al., 1999). The solubility of Mn in soil solution decreases 100-fold for each unit increase in pH (Sommers and Lindsay, 1979). The pH of Tavares sand and Fuquay loamy sand was 7.2 and 7.3, respectively (Table 1). Therefore, we postulate that the rapid reduction of soluble Mn in our study was probably the result of Mn precipitating out of solution as a Mn oxide. Our postulation is reinforced by prior results documenting that O_2 is the only sufficiently strong and common oxidant in soils capable of oxidizing Mn^{2+} (Patrick and Jugsujinda, 1992). While we postulate that Mn oxidation is primarily responsible for the reduced Mn solubility, microbial immobilization could have contributed to the reduction in soluble Mn. Broschat (1991) compared Mn binding in various potting media before and after autoclaving and reported that less Mn binding occurred in the autoclaved media (66% of that applied) than the raw media (71% of that applied). While these results were significant, the reduction in Mn solubility due to microbial activity was only observed in two of six media and accounted for <15% of the total Mn binding. Therefore, microbial immobilization may or may not have played a significant role in our study. Further investigation into the magnitude and causality of Mn immobilization in alkaline soils would be valuable.

Magnesium

In both soils, Mg sulfate and Mg glucoheptonate increased soluble Mg compared with the control at each incubation time (Tables 3 and 4). Additionally, no differences in soluble Mg were observed between Mg sulfate and Mg glucoheptonate regardless of incubation time. This result was probably due to the low stability of Mg glucoheptonate [0.78 (log *K*)] relative to other well-documented Mg chelates [Mg-EDTA 9.8 (log *K*)] (Martell and Smith, 1974). After 21 d of incubation, approximately 80% of the applied Mg remained soluble in both soils. Our findings that Mg remains soluble for extend periods of time are consistent with those of Sartain (1993), who applied Mg as granular $MgSO_4$ at 0 and 200 kg ha^{-1} every 60 d to 'Tifway' bermudagrass (*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy) in Gainesville, FL. Upon termination of the 3-yr study, Mehlich I extractable Mg from the 0 and 200 kg ha^{-1} every 60 d treatments were 20 and 122 mg kg^{-1}, respectively. The increase in extractable Mg led to increases in clipping yield and turfgrass quality.

Although our Mg results complement prior studies, the results from Härdter et al. (2004) indicate that larger portions of Mg may become insoluble. They compared Mg leaching from kieserite and Mg sulfate under high rainfall (20 mm d^{-1}) and reported that Mg sulfate leached 22% of the applied Mg after 16 d. They noted that the percentage lost was less than could be expected from a low cation exchange capacity, tropical soil under high rainfall but provided no explanation. Farina et al. (1980) observed a reduction in Mg solubility (0.01 mol L^{-1} $CaCl_2$) in several soils as pH increased from 4.5 to 7.0. The pH of the soils in the present study were 7.2 and 7.3 for Tavares sand and Fuquay loamy sand, respectively. Thus, a portion of the soluble Mg probably precipitated out of solution, which may explain the 10% reduction in soluble Mg within the first hour of incubation in both soils. Determining Mg speciation was not the intent of this study. Further investigations on Mg speciation would provide greater insight into the dynamics of Mg solubility under our experimental conditions.

In Tavares sand and Fuquay loamy sand, soluble Mg from Mg sulfate and Mg glucoheptonate remained relatively constant from 1 h to 21 d. This indicates that soil application of either Mg sulfate or glucoheptonate may provide plant-available Mg for at least 21 d after application in these soils. Furthermore, as an intended foliar application, Mg from these sources that may wash off the leaf surface either by rainfall or irrigation and move into the soil solution would remain soluble and may be taken up via root uptake. Of the three metals investigated (Fe, Mn, and Mg), only Mg remained soluble and stable throughout the 21-d incubation period. This was probably a result of the differences in the redox potentials of Fe^{2+}, Mn^{2+}, and Mg^{2+}, which are −0.44, −1.18, and −2.37 V, respectively (Bratsch, 1989).

CONCLUSIONS

Iron applied to these soils either as sulfate or glucoheptonate provided no increase in soluble Fe after 1 d of incubation. Additionally, 93% of the applied Fe was rendered insoluble within 1 h. Thus, soil-applied Fe sulfate and glucoheptonate is highly questionable and should be avoided. Soluble Mn declined rapidly after application but remained above 30% of that applied at 21 d in Fuquay loamy sand. The use of Mn sulfate or Mn glu-

coheptonate should take into account this rapid reduction in solubility, and plant responses, if any, would probably be greatly reduced beyond 21 d. Magnesium remained soluble from both Mg sources for the entire 21-d incubation period, indicating that Mg-deficient crops may benefit from soil-applied Mg sulfate or Mg glucoheptonate. Neither Fe, Mn, nor Mg glucoheptonates resulted in greater soil solubility than sulfates. Therefore, the use of glucoheptonates through soil-applied applications should be avoided if their use increases production costs. The value, if any, of glucoheptonates may be via foliar absorption or in the liquid nutrient manufacturing process, potentially allowing easier blending of metals in the raw material solution. This dynamic has not been fully reported and may warrant further investigation. The practical implications of this study are that Fe and Mn applied to these soils as sulfates or glucoheptonates become rapidly insoluble and, therefore, should be avoided if a plant response is desired. Magnesium may remain soluble for at least 21 d after application, but the use of glucoheptonate provides no additional soil solubility compared with sulfate.

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