Iron-[S,S']-EDDS (FeEDDS) Chelate as an Iron Source for Horticultural Crop Production: Marigold Growth and Nutrition, Spectral Properties, and Photodegradation

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Abstract. Aminopolycarboxylic acid (APCA) complexones, commonly referred to as ligands or chelating agents, like ethylenediaminetetraacetic acid (EDTA) and diethylenetriaminepentaacetic acid (DTPA), are commonly used in soluble fertilizers to supply copper (Cu), iron (Fe), manganese (Mn), and/or zinc (Zn) to plants. Offsite runoff and contamination of surface waters with these chelating agents is of increasing concern as a result of their reported ability to remobilize heavy metals in sediments and their low susceptibility to biodegradation. The APCA ethylenediaminedisuccinic acid (EDDS) is a structural isomer of EDTA with the [S,S'] stereoisomer of the complexone, a compound naturally produced by actinomycetes, and is biodegradable. Information on the use of [S,S']-EDDS as a chelating agent in formulating soluble fertilizers for the production of horticultural crops is limited. Therefore, a series of studies were conducted with the objectives of evaluating Fe[S,S']-EDDS as an Fe-chelate fertilizer agent in the production of marigold and [S,S']-EDDS (free ligand) and/or Fe[S,S']-EDDS spectral properties and vulnerability to photodegradation. Marigold grown in peat-based media were fertilized with complete nutrient solution containing 1 mg·L⁻¹ Fe from FeEDDS, FeEDTA, or FeDTPA. There was no significant difference in foliar Fe or Mn between Fe-chelate treatments, averaging 140 µg·g⁻¹ and 88 µg·g⁻¹, respectively, nor were there significant differences in leaf dry weight (2.30 g) between Fe treatments. Spectra of [S,S']-EDDS and Fe[S,S']-EDDS produced from ferrous or ferric sources of Fe absorbed maximally in the 210 to 230 nm and 238 to 240-nm range, respectively. The [S,S']-EDDS complexone used in the current study, a 30% assay solution, had chromaphoric properties, appearing light yellow in color. When exposed to light, Fe[S,S']-EDDS quickly degraded at a rate at least twice that of FeEDTA.

Aminopolycarboxylic acids like EDTA, diethylenetriaminetetraacetic acid (DTPA), and ethylenediamine-N,N'-bis(2-hydroxyphenylacetic) acid (EDDHA) are synthetically produced organic compounds known as complexones but commonly referred to in the trade as ligands or chelating agents. These com-

pounds, especially EDTA, are widely used in an array of domestic, medical, industrial, and agricultural purposes where complexation of multivalent metals in a system is desired. The primary drawback of synthetic APCAs is that they are not readily biodegradable, allowing them to persist and function in the environment beyond their intended use (i.e., target) (Egli, 2001). In Europe, EDTA is one of the most abundant anthropogenic compounds found in many surface waters (Oviedo and Rodriguez, 2003). It is largely accepted that EDTA in such water bodies may be contributing to elevated levels of heavy metals within the water column (Egli, 2001; Norwack and VanBriesen, 2005; Schmidt and Brauch, 2004). This is the result of EDTA's ability to extract and solubilize metals from sediments. The problem is of such concern in Europe that EDTA was subject to "priority substance for extensive evaluation" by European Union member states under European Regulation 793/93, which concluded in 2003 (Grundler et al., 2005). As a result of EDTA persistence in the environment, its extensive use, and potential

to degrade water quality by mobilizing metals, its use in Europe is being phased out and replaced with EDDS (Metsärinne et al., 2001).

A structural isomer of EDTA, EDDS has two chiral centers and three stereoisomer configurations: [S,S'], [R,R'], and [S,R'/R,S']. Unlike EDTA, a synthetic compound, the [S,S']-EDDS stereoisomer is produced by actinomycetes (Egli, 2001; Nörtemann, 2005). The naturally produced [S,S'] stereoisomer is readily biodegradable, whereas the [R,R'] and [S,R'/R,S'] stereoisomers of EDDS are not or only partially biodegradable, respectively (Schowanek et al., 1997; Tandy et al., 2006). The biodegradability of EDDS is of importance because its environmental signature, relative to EDTA and other synthetically produced APCA complexones, is short in duration, broken down microbially or by photooxidation (i.e., photodegradation) when complexed with Fe. Iron chelates of EDTA and DTPA are also vulnerable to photodegradation.

Photodegradation of FeDTPA or FeEDTA occurs in fertilizers, resulting in the loss of soluble (i.e., plant available) Fe. Photodegradation of FeEDTA [maximum absorbance (λ_{max}) = 258 nm] and FeDTPA (λ_{max} = 260 nm) were found to occur in fertilizers when exposed to spectral energy primarily in the ultraviolet (UV) A and UVB portions of the spectrum (Albano and Miller, 2001a, 2003). Use of photodegraded fertilizers in the production of horticultural crops was found to have a negative impact on plant growth and physiology. Marigold grown hydroponically (Albano and Miller, 2001b), or tomato grown in peat-based media (Albano and Miller, 2003) supplied with photodegraded Fe-chelate-containing fertilizer solution, expressed root physiology or nutrition associated with Fe deficiency induced Strategy I Fe efficiency. These plants had enhanced root ferric reductase activity (marigold) and higher levels of foliar Mn (marigold and tomato) than in control treatments (i.e., Fe-chelate containing fertilizer that was not irradiated) indicating that plants were responding to the loss of soluble Fe as a result of photodegradation of Fe-chelates (Albano and Miller, 2001b, 2003).

Iron-EDDS has been reported to degrade when exposed to UV radiation (Gorokhovatskaya et al., 1990; Metsärinne et al., 2001). These studies, however, were conducted on mixed stereoisomer EDDS solutions. Information could not be found on the absorbance spectra or vulnerability to photodegradation of pure [S,S']-EDDS as a free ligand or Fe-complexed compound. Such information is important for developing formulations and handling protocols for [S,S']-EDDS-containing fertilizers because this stereoisomer is biodegradable and will most likely be used as a replacement for nonbiodegradable APCAs (e.g., EDTA, DTPA, EDDHA) in fertilizers. Therefore, the objectives of this study were: 1) to determine the performance of Fe[S,S']-EDDS as a fertilizer agent for the production of marigold; 2) to determine the absorbance spectra for free-ligand and Fe-chelated [S,S']-EDDS; and 3) to assess free-ligand and Fe-chelated [S,S']-EDDS vulnerability to photodegradation.

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I dedicate this article to the memory of Donald "Andy" Hamm (1967–2008), a good technician and a great friend. You are sorely missed.

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Materials and Methods

Growing conditions. Marigold (*Tagetes erecta*, 'First Lady') seeds were sown in six-cell grow-packs (40 cm³ per cell) containing a moistened soilless peat-based medium (Fafard 4P; Conrad Fafard, Inc., Agawam, MA). Seeds germinated 2 to 3 d after sowing (DAS). Treatments were initiated on 12 DAS when the first true leaf pairs (TLP) were fully expanded and subsequently applied on 19, 24, 26, 28, 30, 32, and 34 DAS. Tissue samples were collected 35 DAS when TLP 5 was fully expanded. The experiment used a completely randomized design with three treatments (FeEDTA, FeEDDS, and FeDTPA) and four replications per treatment with a replication consisting of six plants. The study was conducted in a double-walled polycarbonate-glazed greenhouse located in Fort Pierce, FL (lat. 27.41° N, long. 80.35° W), 13 July (sowing) to 17 Aug. (harvest) 2006. Growing temperatures over the course of the experiment were 31/27 °C day/night, respectively. Treatment application (300 mL) was evenly distributed among cells of a grow-pack, and leaching fractions over the course of the study averaged 40% ± 5%.

Fe[S,S']-EDDS preparation. Equal molar concentrations of Fe from ferrous [Fe(II)] FeSO₄·7 H₂O (Fisher Scientific, Fair Lawn, NJ) or ferric [Fe(III)] Fe₂(SO₄)₃·H₂O (Sigma-Aldrich, Inc., St. Louis, MO) and [S,S']-EDDS trisodium salt (Fluka Analytical, Steinheim, Germany) solutions were placed on a stir plate and allowed to react for a minimum of 12 h in the dark before use. Formation of FeEDDS was confirmed by direct infusion liquid chromatography-mass spectroscopy (Thermo Finnigan LCQ-DECA; ThermoQuest, San Jose, CA) (data not shown). Iron concentration, 17.9 mmol·L⁻¹ (1000 mg·L⁻¹) Fe from FeEDDS was confirmed by inductively coupled plasma-optical emission spectrometry (ICP-OES) (IRIS 1000 HR Duo; ThermoElemental, Franklin, MA; or iCAP 6500; Thermo Scientific, Waltham, MA) (data not shown). Iron-EDDS prepared from Fe(II) sulfate (SO₄) was used in the marigold production study, whereas FeEDDS prepared from Fe(II)SO₄ and Fe(III)SO₄ were used in spectral and photo-degradation studies. All solutions were prepared with distilled-deionized water (DDI).

Nutrient solution treatments. A base nutrient solution (BNS) was laboratory prepared and contained the following concentrations (mg·L⁻¹) of essential plant nutrients: 200 nitrogen, 44 phosphorus, 164 potassium, 113 calcium, 49 magnesium, 64 sulfur, 1 Fe, 0.5 boron, 0.5 Mn, 0.05 Zn, 0.02 Cu, and 0.05 molybdenum. Source reagents for preparing BNS were: KNO₃, KH₂PO₄, MgSO₄, Ca(NO₃)₂, NH₄NO₃, (NH₄)₂H₂PO₄, CaHPO₄, H₃BO₃, and H₂MoO₄. Treatments consisted of FeEDDS, FeEDTA (Sigma-Aldrich), or FeDTPA (Sigma-Aldrich) added to BNS at 1 mg·L⁻¹ Fe final concentration. Manganese, Cu, and Zn were supplied as EDTA chelates. The BNS and Fe-chelates were prepared with DDI water. Treatment solutions were adjusted to pH 5.8 with HCl or KOH (0.1 N solutions) before applica-

tion. This treatment solution pH ensured that EDDS, EDTA, and DTPA remained as Fe chelates, eliminating the possibility for lower chelate affinity metals, Cu, Mn, or Zn, from displacing Fe.

Leaf sampling and analysis. Primary and axial leaf tissue was collected 35 DAS and washed in sequence for ≈10 to 15 s in each of the following solutions: DDI, 0.1 N HCl/0.01% detergent (Tween-80), and 3× DDI rinses. Washed leaf tissue was dried in a forced-air oven at 80 °C, weighed, and milled to pass a 20-mesh screen. Milled plant tissue was digested using a closed-vessel microwave-assisted procedure according to U.S. EPA Method 3052 (1997). Briefly, 500 mg of leaf tissue was combined with 10 mL concentrated HNO₃ (trace metal grade) in a Teflon digestion vessel and processed in a microwave digestion oven (MARS Express; CEM Corp., Matthews, NC). Digestion conditions (internal) were 170 °C and 2068 kPa (300 psi) held for 10 min after a 15-min ramp to these conditions. Digestates were transferred quantitatively to 100-mL volumetric flasks, filtered through Whatman 541 (Whatman Int., Kent, U.K.), and analyzed for Fe and Mn by ICP-OES (IRIS 1000 HR DUO) according to U.S. EPA Method 6010B (1997).

Ferric and ferrous FeEDDS and free-ligand EDDS spectral properties. All absorption spectra were determined using a scanning ultraviolet/visible spectrophotometer (Beckman DU 800; Beckman Coulter, Inc., Brea, CA). Spectra of FeEDDS solutions [17.9 (1), 89.5 (5), 179 (10), 268.5 (15), and 358 (20) μmol·L⁻¹ (mg·L⁻¹ Fe)] were determined from both an Fe(II)SO₄ and Fe(III)SO₄ Fe source by scanning from 200 to 800 nm at 1-nm intervals at 1200 nm/min using equal molar solutions of EDDS as a blank. Maximum absorbance for FeEDDS was determined by summing absorbance units (SAU) and running regression analysis (*r*²) for each nanometer across FeEDDS concentrations for both the Fe(II) and Fe(III) sources of the chelate. Spectra were determined for the free EDDS ligand by scanning as described previously for FeEDDS using DDI as a blank. Two separate sources (same product from same the manufacturer) of the EDDS complexone were used for determining spectra of the free-ligand: 2006 acquisition used in marigold production study (2006 source) and 2009 acquisition used in photochemistry studies (2009 source). For comparison, as described for FeEDDS and free EDDS ligand, spectra were also determined on FeEDTA, free EDTA ligand,

Table 1. Leaf Fe, Mn, and dry weight (DW) for marigold grown in peat-based media in six-celled grow packs supplied with a complete fertilizer solution (200 mg·L⁻¹ N) containing FeEDDS, FeEDTA, or FeDTPA (1 mg·L⁻¹ Fe).^z

Fe Chelate Source	Fe (μg·g ⁻¹)	Mn (μg·g ⁻¹)	DW (g)
FeEDDS	150.35 ± 9.75	95.50 ± 9.09	2.42 ± 0.40
FeEDTA	133.13 ± 5.85	85.21 ± 5.90	2.27 ± 0.50
FeDTPA	137.68 ± 7.43	82.95 ± 7.43	2.22 ± 0.29
Significance (<i>P</i> ≤ 0.05)	0.3203	0.4998	0.7761

^zValues are the mean of four replications.

Fe = iron; Mn = manganese; EDDS = ethylenediaminedisuccinic acid; EDTA = ethylenediaminetetraacetic acid; DTPA = diethylenetriaminepentaacetic acid.

Fig. 1. Absorbance spectra of 35.8 μmol·L⁻¹ Fe-[S,S']-EDDS produced ferrous sulfate (—) or ferric sulfate (---) solutions blanked against 35.8 μmol·L⁻¹ free [S,S']-EDDS, 35.8 μmol·L⁻¹ Fe(III)EDTA (···), and Fe(III)DTPA (- - -) solutions blanked against distilled-deionized water. Scans are the mean of three discrete samples.

FeDTPA, and free DTPA ligand. The mean of three discrete samples was used for analysis and studies were repeated.

FeEDDS photodegradation. Solutions (1 L) of Fe(III)EDDS, Fe(II)EDDS, free EDDS ligand, or FeEDTA ($179 \mu\text{mol}\cdot\text{L}^{-1}$) were contained in translucent 1-L low-density polyethylene (LDPE) bottles (Nalgene Co., Rochester, NY). Containers made of PE were selected because this material transmits nearly 100% ultraviolet radiation (200 to 400 nm) (Yang and Ranby, 1996). Treatment solutions were irradiated with $2772 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ portioned as follows: $862 \pm 32 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ [250 to 400 nm ($188 \pm 15 \text{ W}\cdot\text{m}^{-2}$)] and $1910 \pm 190 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (400 to 700 nm) measured at the external container surface using an Apogee Instruments, Model UVM, ultraviolet meter (Logan, UT) and a LI-COR, Model LI-250 light meter paired with a LI-COR quantum sensor (Lincoln, NE), respectively. Containers were placed on their sides for irradiation and control solutions were nonirradiated by covering with aluminum foil. Irradiance source was two 1000-W metal halide lamps (Multi-Vapor R1000 MVR1000/U; GE Co., Fairfield, CT) with a distance between the container surface and lamp at 25 cm. The lamp reflector box (2) angled out to a base dimension of 52×52 cm. Solution temperature during irradiation was 32.6 ± 1.1 °C. At 0, 6, and 12 h irradiation, 100-mL aliquots of sample solution were collected; 50 mL of each aliquot was centrifuged at $2000 g_n$ for 1 h in a Sorvall H1000B swinging-bucket rotor (DuPont Instruments, Wilmington, DE) at room temperature. The supernatant was reserved and absorbance determined at 238 and 258 nm on a spectrophotometer (previously described) for FeEDDS and FeEDTA, respectively. Blanks for FeEDDS samples were corresponding, in time, 0, 6, and 12 h irradiated free EDDS ligand samples (i.e., blanks that had received the same exposure) and DDI for FeEDTA. The supernatant for FeEDDS and FeEDTA samples was also analyzed for Fe by ICP-OES (iCAP 6500). There were four replications per treatment and the study was repeated.

Statistics. Data in the marigold production study, leaf Fe, Mn, and dry weight (DW), were analyzed by analysis of variance to determine the main effect of Fe-chelate treatment. Calculations were performed by the general linear model procedure of SAS (SAS Institute, Cary, NC). For the spectral property scans and photodegradation work, primary and repeated photochemistry reactions were not different; therefore, means from the primary studies are presented. For spectral property studies, data were generated from the mean of three discrete samples per treatment. For the photodegradation work, data were generated from the mean of four replications per treatment.

Results and Discussion

Plant nutrition. There were no visual differences in plant color, size, or shape between treatments. Means were not separated for Fe, Mn, or leaf DW because no main effect

generated a $P \leq 0.05$ (Table 1). Mean foliar levels of Fe and Mn were 140 and $88 \mu\text{g}\cdot\text{g}^{-1}$, respectively. These levels are considered sufficient for normal bedding plant growth (Vetanovetz, 1996). As a mean of Fe treatment, the foliar Fe:Mn ratio (1.7 Fe:1 Mn) was close to that supplied (2 Fe:1 Mn). Based on these data, FeEDDS is a suitable Fe source for producing marigold.

Manganese in the current study was supplied as an EDTA chelate as was Cu and Zn. The suitability of EDDS as a chelant for Cu, Mn, or Zn for fertilizers used in the pro-

duction of horticultural crops is unknown but appears to be influenced by pH. According to Orama et al. (2002), EDDS chelation pH ranges for Cu(II), Fe(III), Mn(II), and Zn(II) are 3 to 12, 3 to 9, 8 to 12, and 5 to 12, respectively. For Cu, Fe, and Zn, the reported pH chelation ranges for EDDS fall within the generally recommended pH range for growing most greenhouse bedding crops, 5.4 to 6.8 (Nelson, 1999). For Mn, however, the reported chelation pH range falls outside of that recommended for bedding plant production. This is something that requires further

Fig. 2. Visual color differences between solutions ($17.9 \text{ mmol}\cdot\text{L}^{-1}$) of a 2006 (A) and 2009 (B) source of [S,S']-EDDS, Fe-[S,S']-EDDS produced ferrous sulfate (C) or ferric sulfate (D) using the 2009 [S,S']-EDDS source, and FeEDTA (E).

Fig. 3. Absorbance spectra of Fe-[S,S']-EDDS ($35.8 \mu\text{mol}\cdot\text{L}^{-1}$) produced ferrous sulfate (—) or ferric sulfate (---) in the photosynthetically active radiation region of the spectrum blanked against $35.8 \mu\text{mol}\cdot\text{L}^{-1}$ [S,S']-EDDS (free ligand). Scans are the mean of three discrete samples.

investigation. Regardless, EDDS does share with EDTA and DTPA the same metal binding affinity profile, $\text{Fe} > \text{Cu} > \text{Zn} > \text{Mn}$ (Bucheli-Witschel and Egli, 2001; Jones and Williams, 2001).

Spectral properties of FeEDDS and EDDS. Iron-EDDS solutions were initially scanned using DDI water and EDDS as blanks. As a result of EDDS chromaphoric properties and where FeEDDS absorbs in the UV spectrum, it was difficult to discern peak absorbance of FeEDDS from absorbance of free EDDS ligand when DDI water was used as blank. Therefore, equal molar concentrations of EDDS were used as a blank for FeEDDS data reported here. Freshly prepared (nonirradiated) solutions of Fe(II)EDDS and Fe(III)EDDS ($89.5 \mu\text{mol}\cdot\text{L}^{-1}$) absorbed strongly in the UV regions of the spectrum, peaking in the 238 to 240-nm range with λ_{max} at 238 nm used for determining AU (Fig. 1). Iron-EDDS sources were reddish and yellow color in appearance for Fe(II) and Fe(III) forms of the chelate, respectively (Fig. 2). Absorbance of spectral energy (≥ 0.01 AU) for solutions of Fe(II)EDDS and Fe(III)EDDS began at 435 and 402 nm, respectively. The SAU for Fe(II)EDDS (238 to 435 nm) and Fe(III)EDDS (238 to 402 nm) were 45.56 and 48.35, respectively. In the photosynthetically active radiation region of the spectrum (400 to 700 nm), Fe(II)EDDS had greater absorbance (0.71 SAU) than Fe(III)EDDS (0.12 SAU), possibly contributing to the observed color differences between these Fe forms of the EDDS chelate complex (Fig. 3). These solutions also varied significantly in pH with Fe(II)EDDS and Fe(III)EDDS being basic (pH 7.8) and acidic (pH 3.5), respectively.

The free EDDS ligand ($17.9 \text{ mmol}\cdot\text{L}^{-1}$) had absorbance in the visible spectrum (400 to 550 nm) and therefore had color (Figs. 2 and 4) but absorbed maximally in the 210 to 230-nm range (Fig. 5), which was confirmed with two separate sources of the complexone (Figs. 2, 4, and 5). This is consistent with work by Gorokhovatskaya et al. (1990) in which free EDDS ligand ($100 \mu\text{mol}\cdot\text{L}^{-1}$) was reported to maximally absorb at 220 nm. The pH of EDDS solutions was 9.5. Personal communication with the manufacturer of EDDS used in the current studies confirmed the chromaphoric properties of the complexone (i.e., the light yellow color that was observed in fresh product). The 2006 EDDS source's color shifted from light yellow to reddish in color over time. Unlike the 2009 EDDS source, which was protected from light from time of acquisition, the 2006 source was exposed to ambient fluorescent lighting in the laboratory. Residual Fe levels (contaminant) of laboratory-prepared $17.9 \text{ mmol}\cdot\text{L}^{-1}$ EDDS stock solution, determined by ICP-OES (iCAP 6500), were low at $0.059 \pm 0.01 \text{ mg}\cdot\text{L}^{-1}$ but possibly sufficient enough to contribute to the complexones observed yellow to reddish color. Regardless, the effect of irradiation on EDDS is discussed in the next section on photodegradation. The chromaphoric character of EDDS is significantly different from that of free EDTA or DTPA ligands, which are

Fig. 4. Absorbance spectra (400 to 800 nm) of a 2006 (---) and 2009 (—) [S,S']-EDDS ($17.9 \text{ mmol}\cdot\text{L}^{-1}$) sources blanked against distilled-deionized water. Scans are the mean of three discrete samples.

Fig. 5. Absorbance spectra (200 to 400 nm) of a 2006 (---) and 2009 (—) [S,S']-EDDS ($17.9 \text{ mmol}\cdot\text{L}^{-1}$) sources blanked against distilled-deionized water. Scans are the mean of three discrete samples.

colorless solutions. Spectral scans of free EDTA and DTPA ligands ($35.8 \mu\text{mol}\cdot\text{L}^{-1}$) began to absorb at 258 nm with absorbance increasing sharply to 200 nm (data not shown).

Photodegradation of Fe-[S,S']-EDDS. There was no difference between Fe(II)EDDS and Fe(III)EDDS ($179 \mu\text{mol}\cdot\text{L}^{-1}$) response to irradiation; therefore, the term FeEDDS will represent both Fe forms. Iron-EDDS degraded when exposed to light and it degraded more rapidly when illuminated than FeEDTA (Fig. 6A). Complete degradation of FeEDDS and FeEDTA occurred within 6 and 12 h, respectively, for $179 \mu\text{mol}\cdot\text{L}^{-1}$ solutions of the Fe-

chelates. The loss in absorbance at 238 and 258 nm for FeEDDS and FeEDTA, respectively, corresponded with the loss in soluble Fe (Fig. 6B). Irradiated EDDS (free ligand, not chelated with Fe) ($179 \mu\text{mol}\cdot\text{L}^{-1}$) was affected by irradiation. Irradiated EDDS absorbance increased over time with SAU for $T = 0, 6,$ and 12 h irradiation of 19.82, 22.02, and 28.36, respectively (Fig. 7). The absorbance spectra for free ligand EDDS in Figures 5 and 7 are different. This is the result of EDDS concentration: $17.9 \text{ mmol}\cdot\text{L}^{-1}$ (Fig. 5) versus $179 \mu\text{mol}\cdot\text{L}^{-1}$ (Fig. 7). No change in absorbance spectra was observed for nonirradiated EDDS,

Fig. 6. Photodegradation of FeEDDS and FeEDTA: (A) FeEDTA and FeEDDS [Fe(II)EDDS and Fe(III)EDDS] determined spectrophotometrically at 258 and 238 nm, respectively; and (B) Fe determined by inductively coupled plasma for $179 \mu\text{mol}\cdot\text{L}^{-1}$ Fe-chelate solutions. Blanks used for determining absorbance (A) for FeEDDS and FeEDTA chelates were [S,S']-EDDS (free ligand) and distilled-deionized water, respectively. Solutions were irradiated with a HID light source providing $2772 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (200 to 800 nm) measured at the surface of 1-L low-density polyethylene containers. Scans are the mean of four replications.

FeEDDS, and FeEDTA solutions over the course of the study (data not shown). These data are consistent with work by Metsärinne et al. (2001) who found that FeEDDS photodegraded more rapidly than FeEDTA. Differences between the cited work (Metsärinne et al., 2001) and the current study include: 1) in the cited work, an isomeric mixture of EDDS containing 25% [S,S'], 25% [R,R'], and 50% [S,R'/R,S'] was used, whereas in the current study, a 100% [S,S']-EDDS solution was used for photochemistry; and 2) in the cited work, loss of the Fe-chelate complex was measured only by absorbance whereas in the current study, loss of soluble Fe was directly measured (by ICP-OES) in addition to loss of the Fe-chelate complex by absorbance. Previous work by the author showed that FeEDTA degrades faster than FeDTPA when irradiated (Albano and Miller, 2001a). Therefore, vulnerability to photodegradation would follow the profile: FeEDDS > FeEDTA > FeDTPA.

Conclusions

Results of this study demonstrated that FeEDDS performance as a fertilizer Fe source is comparable to that of FeEDTA or FeDTPA in the production of marigold with no significant differences in Fe or Mn nutrition or plant growth as represented by total leaf DW. Iron-EDDS, however, is more vulnerable to photodegradation than either FeEDTA or FeDTPA when exposed to light, meaning that fertilizer stock solutions formulated with FeEDDS will need to be protected from light to prevent the rapid photolysis of the Fe-chelate complex. Even the free EDDS complexone's absorbance shifted when exposed to light indicating that EDDS solutions will also need to be protected from illumination. The fundamental difference between EDDS and EDTA or DTPA for purposes as a fertilizer component appears to be that [S,S']-EDDS readily biodegrades. This difference has water-quality implications because the persistence of EDDS in the environment is reported to be less than that of EDTA or DTPA. In other words, offsite discharge of EDDS may pose a lower risk for (re)solubilizing sediment-bound heavy metals and subsequently transporting them into the water column where degradation to irrigation, environmental, and/or drinking water resources may result.

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Fig. 7. Absorbance spectra of [S,S']-EDDS complexone ($179 \mu\text{mol}\cdot\text{L}^{-1}$) irradiated with a HID light source providing $2772 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (200 to 800 nm) measured at the surface of 1-L low-density polyethylene containers. Scans are the mean of four replications ($n = 4$) at time (T) 0 (—), 6 (···), and 12 (---) h.

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