AVAILABILITY OF ORGANIC AND INORGANIC Zn FERTILIZERS

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ABSTRACT

Zinc sulfate ($ZnSO_4$) has traditionally been the "reliable" source of Zn fertilizer but other sources of Zn are also available. Some are derived from industrial by-products, varying from flue dust reacted with sulfuric acid to organic compounds derived from the paper industry. The degree of Zn availability in Zn sources derived from these various by-products is related to the manufacturing process, the source of complexing or chelating agents (organic sources), and the original product used as the Zn source. Many claims are made regarding the relative efficiency of traditional inorganic Zn fertilizers and complexed Zn sources. The objective of this greenhouse study was to determine the availability coefficients of several commercial Zn fertilizer materials (organic and inorganic) which are commonly used to correct Zn deficiencies in soils. We evaluated the dry matter production, total Zn uptake, and Zn concentration in corn plants fertilized with six different commercial Zn fertilizers. The sources included three granular inorganic Zn sources, two granular organically complexed Zn sources, and liquid ZnEDTA. The soil was low in available Zn (AB-DTPA Zn = 0.48 mg kg^{-1}) and limed to a pH of 7.2. The Zn fertilizers were added to 5 kg pots at rates equivalent to 0, 0.5, 1, 2, 4, and 8 lb Zn A^{-1} (0, 0.21, 0.42, 0.84, 1.68, and 3.36 mg Zn kg^{-1} of soil). The ZnLignosulfonate, $ZnSO_4$, and ZnEDTA were always the most effective materials in supplying the plant's needs. The relative availability coefficients (RAC) of these three materials ranged from 70 to 100%, depending on plant parameter measured. The ZnOxysulfate, with 55% water solubility, also performed well with a RAC from 48 to 69%. The lower water soluble materials (ZnOxysulfate, 26% water soluble and ZnSucrate, 1% water soluble) were least effective with RAC values ranging from –12 to 25%. When comparing all sources, water solubility was the primary factor governing the performance of Zn fertilizers. High water solubility is required if a Zn fertilizer is going to be effective in meeting the plant's Zn needs. Zinc ions that are reacted with an organic complexing agent does not guarantee the resulting fertilizer will perform like a true chelate and have a high plant availability. If the end product is not highly water soluble, it will be very inefficient in supplying Zn to the plant. These results confirm our previous research where we concluded that a Zn fertilizer must be from 40-50% water soluble to be an effective Zn source.

INTRODUCTION

Zinc (Zn) is an essential micronutrient for normal crop growth and Zn deficiencies can severely impair crop growth and decrease yields. The potential for Zn deficiencies is greatest in soils with low organic matter contents and pH levels greater than 7.0. In these situations, Zn deficiencies are easily corrected by applying highly water-soluble granular Zn fertilizers (Amrani et al., 1997 and 1999). Zinc sulfate has traditionally been the "reliable" source of Zn fertilizer but other sources of Zn are also available. Some are derived from industrial by-products, varying from flue dust reacted with sulfuric acid to organic compounds derived from the paper industry. The degree of Zn availability in Zn sources made from these various by-products is related to the manufacturing process, the source of complexing or chelating agents (organic sources), and the original product used as the Zn source.

Many claims are made regarding the relative efficiency of organic vs. inorganic Zn sources. Producers of organic sources generally claim a 10:1 advantage of organic sources vs. inorganic sources (zinc sulfate) to satisfy the agronomic demand (i.e. 1 lb of Zn per acre from an organic source will give as much plant response as 10 lb of Zn A^{-1} from zinc sulfate). However, this claim is disputed by researchers as well as other fertilizer producers. Most research has found that there is approximately a 3:1 to 5:1 advantage for ZnEDTA, a “true” organic chelate (Hergert et al., 1984 and Mortvedt, 1979).

True chelates are compounds containing ligands that can combine with a single metal ion (e.g. Zn^{+2}) to form a well defined, relatively stable cyclic structure called a chelation complex (Mortvedt et al., 1999). These properties are particularly important and useful in agricultural regions with basic (i.e., high pH) and/or calcareous soils which routinely test low in plant-available Zn. In the chelated form, metal ions are less likely to react with and be immobilized by the soil and are more likely to be “delivered” to the plant root.

Some products are called “organic chelates” but are actually organically complexed Zn sources. Organic complexes, sometimes called “organic chelates”, are formed by reacting metallic salts with various organic, industrial by-products (e.g by-products of the wood pulp industry). In some cases, claims are made that organic complexes have greater Zn availability than inorganic Zn salts and require lower application rates to satisfy plant needs. The structure of these by-products is not well defined (hence the term complexes) and there is no evidence that the resulting product has true chelate structure or properties. Mortvedt et al. (1999) reported that these products may be less stable in the soil than true chelates. The agronomic effectiveness of these complexes varies greatly depending on source, manufacturing process, etc. The effectiveness of these complexed Zn sources relative to inorganic Zn sources has not been fully investigated.

Most solid Zn fertilizers now are applied to soil in granular form so they can be blended with other granular products and applied with todays equipment. Powdered Zn sources are dusty and will segregate from the other granular components of blends. Because granular fertilizer particles have a much lower specific surface than powdered products, the degree of water-solubility has a much greater effect on dissolution and plant availability of the applied Zn. Results by Amrani et al. (1997 and 1999) and Mortvedt (1992) showed that at least 40-50% of the total Zn in granular fertilizers should be in water-soluble form to be effective for the immediate crop.

Confusion exists in the marketplace and unsubstantiated claims are being made regarding the efficacy of various organic and complexed Zn fertilizer products. Therefore, it is important to evaluate the effectiveness of some classes of Zn fertilizers to correct Zn deficiencies. The objective of this greenhouse study was to determine the relative availability coefficients (RAC) of several granular, commercial Zn fertilizer materials (organic and inorganic) which are commonly used to correct Zn deficiencies in soils low in plant available Zn.

MATERIALS AND METHODS

Soil from the A horizon of a loamy sand soil classified as a loamy, mixed, mesic arenic Ustollic Haplargid was used in this study. Selected chemical and physical characteristics of this soil are presented in Table 1. The soil was chosen because it was naturally low in available Zn (AB-DTPA Zn = 0.48 mg kg^{-1}). The soil initially had a pH of 5.2 and was limed to a pH of 7.2 by adding 760 mg $CaCO_3$ kg $soil^{-1}$. Zinc fertilizer was added to each pot at rates equivalent to 0, 0.5, 1, 2, 4, and 8 lb Zn A^{-1} (0, 0.21, 0.42, 0.84, 1.68, and 3.36 mg Zn kg^{-1} of soil) in this greenhouse experiment. The experiment was arranged in a randomized block design with four replications. Each pot was lined with a clean plastic bag and contained 5 kg of soil.

The granular Zn materials were placed in the center of each pot 2.5 cm below the seed. We used the fertilizer sources in the physical condition found in fertilizer bags so the evaluation conditions were similar to those in commercial agriculture. Fertilizer materials were not ground or altered except at the two lowest Zn application rates in order to accurately weigh the minute quantities of fertilizer material. A liquid ZnEDTA source was included in this study to provide a “true” Zn chelate fertilizer comparison with organically complexed and inorganic Zn fertilizers.

We planted five corn seeds (*Zea mays*, L.; *cv* P3752) in each pot, and after 10 days we thinned the pots to 3 plants each. Supplemental plant nutrients were mixed with the soil as reagent grade materials prior to planting as follows: 283 mg N pot^{-1} and 625 mg P pot^{-1} (monoammonium phosphate), 625 mg K pot^{-1} (K_2SO_4), and 12 mg Fe pot^{-1} (FeEDDHA). We added three additional N applications of 130 mg N pot^{-1} each as NH_4NO_3 as a solution applied to the soil surface of each pot at 13, 24, and 33 days after planting. Pots were watered regularly with deionized water to bring the soil to approximately 90% of field capacity (15% water by weight).

Forty-four days after planting, we harvested the above-ground corn forage. All samples were dried at 60°C for 4 days. After weighing and grinding samples to pass 0.5 mm sieve, we digested a 1 g portion for Zn analysis by inductively-coupled plasma (ICP) using a modified nitric acid digestion by Ippolito and Barbarick (1999).

Table 1. Selected physical and chemical characteristics of the soil (before liming) used in this study.

Paste		AB-DTPA							
pH	EC	OM	P	NO_3-N	K	Zn	Fe	Mn	Cu
	mmhos cm^{-1}	---%---	mg kg^{-1}						
5.2*	0.5	0.8	8.3	8.4	210	0.48	26	15	1.3

***pH was adjusted to 7.2 before the start of the experiment.**

Description of Zinc Fertilizers

ZnEDTA:

ZnEDTA is a liquid Zn fertilizer (9% total Zn) which is often added to tanks during fluid fertilizer formulation. ZnEDTA is 100% water-soluble Zn.

$ZnSO_4$:

Zinc sulfate monohydrate is produced by adding sulfuric acid to ZnO (Zn oxide) followed by dehydration to form $ZnSO_4AH_2O$. Our source contained 35% total Zn and 98% water-soluble Zn.

ZnOx26 and ZnOx55:

Zinc oxysulfate is formed by adding H_2SO_4 to Zn feedstocks. These feedstocks are commonly ZnO industrial byproducts. The solubility of these fertilizer materials is variable and is related to the amount of H_2SO_4 added during the manufacturing process. Our two sources contained 38 and 27% total Zn and 26 and 55% of the total Zn as water-soluble Zn, respectively. The first zinc oxysulfate will be called ZnOx26 and the second ZnOx55 throughout this paper.

ZnSuc:

Zinc sucrate is a complexed organic Zn fertilizer which is formed by reacting sucrose-type materials (e.g. cane sugar molasses) with ZnO. Our source was 38% total Zn and <1% water-soluble Zn.

ZnLigno:

Zinc lignosulfonate is a complexed organic Zn fertilizer which is formed by reacting $ZnSO_4$ with lignin wastes produced by the paper industry. Our source contained 10% total Zn and 91% of the total Zn as water-soluble Zn.

RESULTS

Dry Matter Production

Zinc deficiency symptoms and visual differences in biomass production were apparent within 22 days of planting (Photos 1 and 2). Dry matter production at harvest as a function of Zn rate and source, is shown in Figure 1. Yield data for all sources and rates are given in Table 2 and the statistical analysis is shown in Table 3. Dry matter production was significantly different among the different fertilizer sources. Except for the ZnSuc source, the 2 lb Zn A^{-1} rate for all Zn sources increased dry matter production 4 to 23% over the control pots. At the highest Zn rate (8 lb Zn A^{-1}) dry matter production was increased 9 to 21% by all Zn sources, with the exception of ZnSuc, when compared with the control treatment.

Overall, $ZnSO_4$, ZnLigno, and ZnEDTA produced the largest increases in dry matter production (15-21%) when compared to the control. ZnOx26 and ZnOx55 performed marginally well and increased dry matter production by 9%. ZnSuc was the poorest performer and only increased dry matter production by 4% at the 8 lb Zn A^{-1} rate, which was not significantly different than the check.

Linear regression analysis was performed on dry matter production as a function of application rate (Figure 1). All regression equations were statistically significant, indicating significant increases in dry matter

Photo 1. Twenty-two days after planting all treatments that received 2 lb of Zn/acre, with the exception of $ZnSO_4$ and ZnEDTA(not shown), displayed Zn deficiency symptoms.

Photo 2. Zinc deficiency symptoms on corn 22 days after planting.

Photo 3. ZnEDTA (0.5 lb of Zn/acre), and Zn Lignosulfonate (0.5 lb of Zn/acre). Forty-one days after planting.

ZnEDTA **ZnLigno**

Photo 4. Zn Sucrate (8 lb of Zn/acre), and $ZnSO_4$ (4 lb of Zn/acre). Forty-one days after planting.

ZnSuc **$ZnSO_4$**

Photo 5. ZnEDTA (0.5 lb of Zn/acre), and $ZnSO_4$ (4 lb of Zn/acre). Forty-one days after planting.

ZnEDTA **$ZnSO_4$**

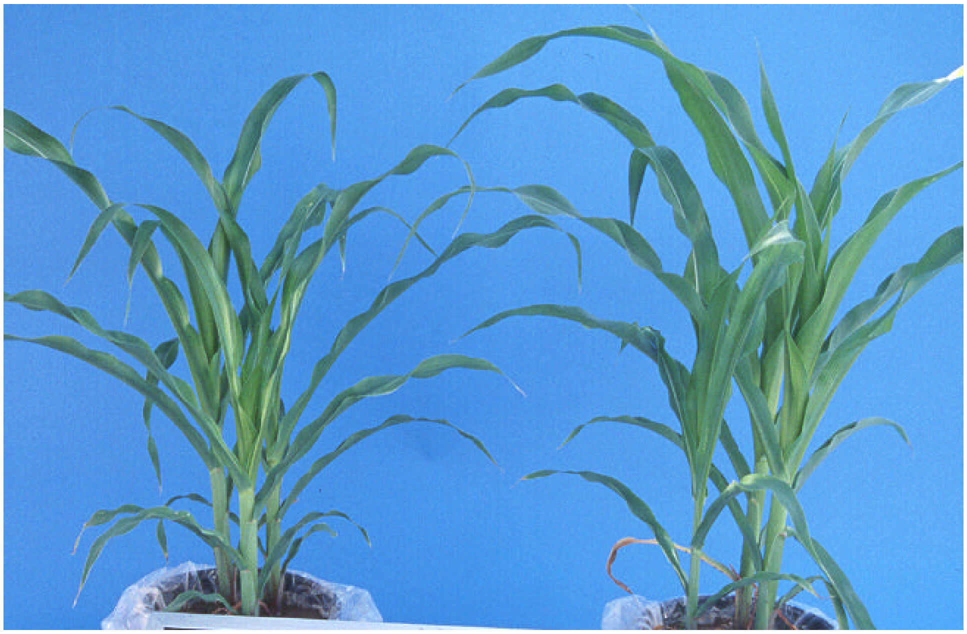

Photo 6. Zn Lignosulfonate (0.5 lb of Zn/acre) and $ZnSO_4$ (4 lb of Zn/acre). Forty-one days after planting.

ZnLigno **$ZnSO_4$**

Table 2. Corn dry matter production, Zn concentration, and Zn uptake as influenced by Zn rate and source.

Zn fertilizer	Dry matter production					Zn concentration					Zn uptake				
	Zn rate Lb/A														
	0.5	1	2	4	8	0.5	1	2	4	8	0.5	1	2	4	8
	----------g pot^{-1}----------					----------mg kg^{-1}----------					----------mg pot^{-1}----------				
ZnEDTA	16.1	15.0	15.4	16.2	16.1	10.2	13.9	17.8	25.4	37.6	0.164	0.207	0.274	0.411	0.606
$ZnSO_4$	14.4	14.9	14.8	15.0	16.7	9.1	8.9	9.9	11.3	15.1	0.132	0.132	0.146	0.168	0.251
ZnLigno	14.2	14.8	17.0	16.7	15.9	9.1	9.5	10.1	11.6	14.6	0.130	0.140	0.147	0.192	0.232
ZnOx26	14.6	14.3	14.3	14.8	15.1	11.6	9.5	10.0	9.5	8.7	0.171	0.135	0.143	0.140	0.131
ZnOx55	13.0	13.0	14.6	16.5	15.1	10.5	9.7	9.2	10.2	12.4	0.138	0.126	0.134	0.169	0.187
ZnSuc	13.1	13.0	13.6	13.6	14.4	9.7	8.8	8.3	10.6	10.6	0.127	0.114	0.113	0.144	0.152
$LSD_{0.1}$ (within sources)	2.2	1.2	1.8	1.8	1.7	1.3	1.4	0.9	1.8	2.5	0.035	0.021	0.032	0.024	0.052
Check (0 lb Zn/A)	13.8					9.3					0.129				

production as Zn application rate increased, with the exception of the ZnSuc treatments. The regression equation for ZnSuc was not significant indicating this material did not increase dry matter production at the rates evaluated as compared to the control treatment. Overall, ZnSuc and ZnOx26 showed a poor relationship between Zn rate and dry matter production. The remaining Zn materials significantly increased dry matter production relative to the control treatment.

Homogeneity of regression coefficients was analyzed using the technique described by Gomez and Gomez (1984) and results are presented in Table 4. This shows how the sources performed relative to each other for dry matter production. The ZnLigno, ZnEDTA, $ZnSO_4$, and ZnOx55 performed equally well. The ZnLigno performed better than ZnOx26. However, the ZnOx26 material performed as well as the remaining Zn sources. ZnSuc was outperformed by ZnLigno, $ZnSO_4$, and ZnEDTA, but did not differ from ZnOx26 and ZnOx55.

Zinc Concentration

Zinc concentrations in the corn tissue at harvest were significantly affected by Zn source and rate (Figure 2; Tables 2 and 3). At the Zn application rate of 2 lb Zn A^{-1}, plant concentrations of Zn ranged from 8-18 ppm with ZnSuc and ZnEDTA, respectively. The Zn concentration for the 8 lb Zn A^{-1} application rate ranged from 9 to 38 ppm

Table 3. Analysis of variance evaluating the interactions of Zn sources and rates.

Variable	Dry matter	Zn concentration	Zn uptake
	---------------Probability---------------		
Zn sources	<0.000	<0.000	<0.000
Rate	<0.000	<0.000	<0.000
Zn source x rate	0.499	<0.000	<0.000

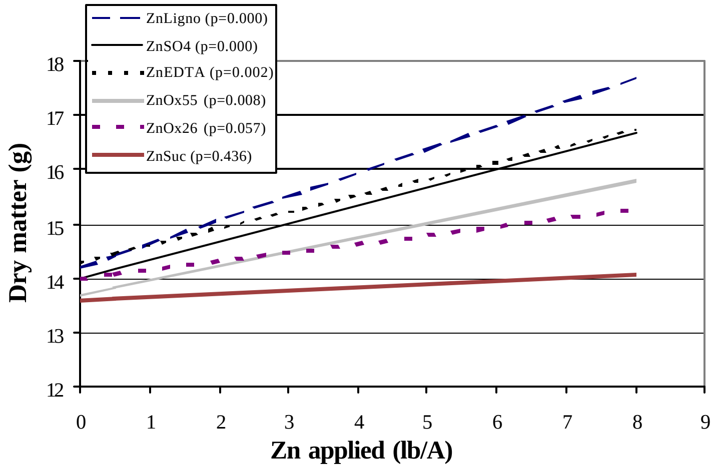

Figure 1. Regression of corn dry matter production, as affected by Zn source and rate.

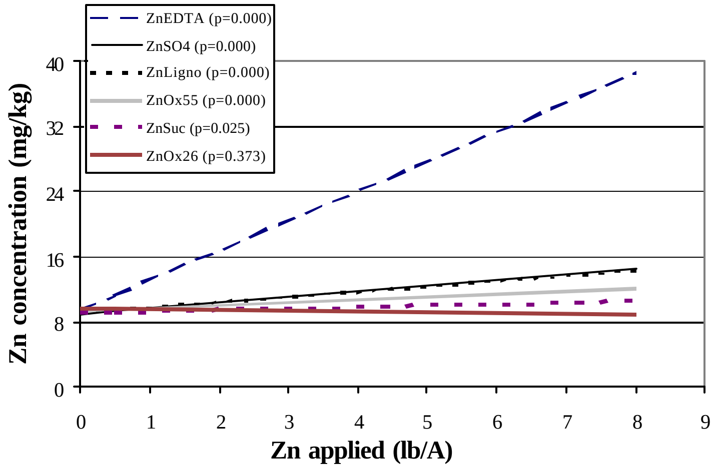

Figure 2. Regression of Zn concentration (mg/kg) in corn dry matter, as affected by Zn source and rate.

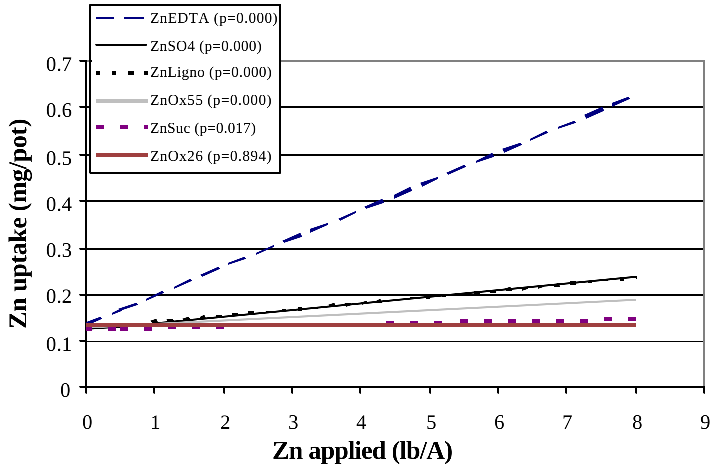

Figure 3. Regression of Zn uptake (mg/pot) by corn dry matter, as affected by Zn source and rate.

depending on Zn source. Overall, ZnEDTA was the most effective source of Zn when Zn concentration in plant tissue is used as the criteria. This is expected since ZnEDTA is a “true” metal chelate that is 100% water-soluble and whose behavior in the soil environment has been described and shown to be very effective at delivering Zn to the plant root.

Linear regression analysis on Zn concentration revealed that all equations were statistically significant, with the exception of the ZnOx26 source (Figure 2). Based on the analysis of the homogeneity of the regression coefficients we can place the fertilizer materials into 3 categories: (i) ZnEDTA application resulted in the largest concentrations of Zn in the plant material; (ii) $ZnSO_4$ and ZnLigno applications resulted in similar increases in plant Zn concentrations although both were lower than ZnEDTA; and (iii) the remaining materials which resulted in moderate to low increases in plant Zn concentration and the increases were significantly lower than those in categories i, and ii (Table 4).

Zinc Uptake

Zinc uptake results were very similar to those for Zn concentration (Figure 3; Table 3). ZnEDTA application resulted in the highest Zn uptake rates. The $ZnSO_4$ and ZnLigno performed similarly, but had uptake values lower than ZnEDTA. The remaining sources had Zn uptake values that were significantly lower than ZnEDTA, $ZnSO_4$, and ZnLigno. Similar conclusions were reported by Amrani et al. (1997 and 1999) and Mortvedt (1992). They concluded that Zn availability is dependent on water-solubility levels of Zn in granular fertilizer materials. Granular sources with low water-solubility do not supply enough Zn to the soil solution to meet the plant needs. The total Zn content of a granular Zn material is not an adequate estimate of its performance.

Relative Availability Coefficients (RAC)

The principles to determine the effective quantity or availability of a nutrient in a fertilizer source were established by Black and Scott (1956). Simply described, availability a, is a function of the quantity of the nutrient x, and the availability coefficient 8. This is represented as the equation:

Equation 1: $a=8(x)$

The numerical value of the availability coefficient cannot be determined, but the ratios among the relative availability coefficients of nutrient sources under similar conditions can be compared (i.e. the slopes of the regression lines can be compared). A similar technique was used by Boawn (1973) to compare zinc sulfate and zinc EDTA fertilizers.

Table 5 summarizes the relative availability coefficients (RAC) for each Zn source for dry matter production, Zn concentration, and Zn uptake. The RAC is calculated by equation 2:

Equation 2: $$\text{RAC\%} = \frac{\text{Slope of material in question}}{\text{Reference slope}} \times 100$$

Table 4. Analysis of homogeneity of regression coefficients (alpha=0.1). An equal sign (=) indicates there was no significant difference between the two regression coefficients. An x indicates the coefficients were significantly different.

Dry matter production

	ZnLigno	ZnEDTA	ZnSO$_4$	ZnOx55	ZnOx26	ZnSuc
ZnLigno		=	=	=	x	x
ZnEDTA			=	=	=	x
ZnSO$_4$				=	=	x
ZnOx55					=	=
ZnOx26						=
ZnSuc						

Zn concentration

	ZnLigno	ZnEDTA	ZnSO$_4$	ZnOx55	ZnOx26	ZnSuc
ZnLigno		x	=	x	x	x
ZnEDTA			x	x	x	x
ZnSO$_4$				x	x	x
ZnOx55					x	=
ZnOx26						x
ZnSuc						

Zn uptake

	ZnLigno	ZnEDTA	ZnSO$_4$	ZnOx55	ZnOx26	ZnSuc
ZnLigno		x	=	x	x	x
ZnEDTA			x	x	x	x
ZnSO$_4$				x	x	x
ZnOx55					x	x
ZnOx26						=
ZnSuc						

The following example will demonstrate how the Zn RAC values were determined for dry matter production:

1. When determining the RAC values, the material with the greatest slope will always have a RAC value of 100%.

2. Identify the reference slope. In this case, ZnLigno had a slope of 0.438.

3. Choose the Zn material in question and then insert the two slopes into Equation 2. For example, $ZnSO_4$ had a slope of 0.338. Therefore, the RAC of $ZnSO_4$ was $(0.338 \div 0.438) \times 100 = 77\%$.

Although the coefficients displayed in Table 5 are relative as determined in this experiment, the RAC calculation is a valuable tool to normalize the data and allow us to make meaningful comparisons among sources over the entire application range. The RAC values for ZnLigno, $ZnSO_4$, and ZnEDTA were 100, 77, and 70% for dry matter production (Table 5), and ZnOx55 had a RAC of 60%. This means that the $ZnSO_4$ and ZnEDTA were 77% and 70%, respectively, as effective as ZnLigno in producing dry matter. However, to determine if these values are significantly different, you must refer to Table 4. The homogeneity of regression analysis (Table 4) showed that ZnOx55 performed as well as the other three Zn sources cited above. These four sources all have water-solubilities >50% of the total Zn. The ZnOx26 and ZnSuc had RAC values of 37 and 14%, respectively, and did not perform as well as the other sources with respect to dry matter production. This is not surprising since both of these materials have low water-solubilities of Zn.

The RAC for ZnEDTA was much higher than the other Zn sources for concentration and uptake. Overall, the ZnEDTA treatments had Zn concentration or Zn uptake values approximately 5 times higher than the other treatments. Boawn (1973) found Zn uptake and concentration values 2 to 2.5 times higher in ZnEDTA treatments compared to $ZnSO_4$. Schulte and Walsh (1982) found ZnEDTA to be approximately five times more effective than $ZnSO_4$ in supplying Zn to the plant. Therefore, although the Zn concentrations in the plant material appear to be high, the literature is in

Table 5. Relative availability coefficients (RAC), as determined by the slope of the regression equation for dry matter production, Zn concentration, and uptake.

Zn Fertilizer	Dry matter		Zn concentration			Zn uptake		
	slope	RAC %	slope	RAC %	RAC%*	slope	RAC %	RAC%*
ZnEDTA	0.306	70	3.640	100	-	0.0615	100	-
$ZnSO_4$	0.338	77	0.687	19	100	0.0143	23	100
ZnLigno	0.438	100	0.646	18	94	0.0134	22	94
ZnOx26	0.160	37	-0.085	-2	-12	0.0002	0.5	1
ZnOx55	0.263	60	0.343	9	50	0.0077	12	48
ZnSuc	0.062	14	0.173	5	25	0.0030	5	21

*** RAC values in this column are based on $ZnSO_4$ as the reference slope.**

agreement with our observations. A possible explanation for the high Zn concentrations from the ZnEDTA source may be luxury consumption (i.e. the plant absorbs more Zn than is necessary at the current growth stage). Since ZnEDTA outperformed all other sources so greatly for Zn concentration and uptake, the next most effective material ($ZnSO_4$) was used as the "reference source" to calculate RAC values for concentration and uptake.

The RAC values for $ZnSO_4$ and ZnLigno were 100 and 94% respectively. Both sources were very effective in supplying Zn to the plant and supporting plant growth (Table 5). The ZnOx55 had a RAC of 48% and was significantly lower than $ZnSO_4$ and ZnLigno. The ZnOx26 and ZnSuc were not effective in supplying Zn to the plant and had RAC values of 1 and 21% respectively. These materials have low Zn water-solubility.

The RAC values for Zn uptake were similar to Zn concentration values. $ZnSO_4$ and ZnLigno had RAC values of 94 and 100%. The ZnOx55 was moderately effective at delivering Zn to the plant and had a RAC of 48% when compared to $ZnSO_4$ (Tables 4 and 5). Again, the low water-soluble materials, ZnOx26 and ZnSuc, were both ineffective.

CONCLUSIONS

Water-solubility is the primary factor that affects Zn uptake andavailability, not total Zn content or organic complexation in granular Zn fertilizers. Amrani et al. (1997 and 1999) concluded that a 50% water-soluble Zn source was required to be effective, and Mortvedt (1992) concluded that 40% is required. Plants fertilized with low water-soluble Zn sources (i.e. ZnSuc [<1% water-soluble], and ZnOx26 [26% water-soluble]) had reduced dry matter production, Zn concentration, and Zn uptake values, as compared with the higher water-soluble Zn sources (ZnEDTA, $ZnSO_4$, ZnLigno, and ZnOx55). The highly water-soluble Zn sources also had higher RAC values when compared to the low water-solubility materials (i.e. ZnOx26 and ZnSuc). The Zn uptake and concentration results followed similar trends except the plants were able to utilize substantially more Zn from ZnEDTA, relative to the other granular Zn sources, which was probably due to luxury consumption.

When considering all parameters measured and the visual symptoms observed, the Zn sources evaluated can be separated into three groups. The ZnEDTA, ZnLigno, and $ZnSO_4$ were always very efficient in supplying Zn to the plants. The ZnOx55 was less effective, but seemed to supply enough Zn to meet the crops needs, but Zn deficiency symptoms were visible at 22 days after planting (Photos 1 and 2). The ZnOx26 and ZnSuc were relatively ineffective in supplying Zn to the plant. These results confirm the need for high Zn water-solubility (>40-50%) of the Zn source to be an effective Zn fertilizer on alkaline soils.

Complexed Zn sources did not perform as well as a true Zn chelate (i.e. ZnEDTA) with respect to Zn concentration and uptake; although the highly water-soluble ZnLigno, $ZnSO_4$, and ZnEDTA were effective in producing dry matter (Photos 3 and 4; Table 4). Zinc uptake was greater for ZnEDTA compared to the complexed Zn sources (i.e. ZnSuc and ZnLigno; Table 4). Micronutrients can be complexed with other "complexing agents" than those described in this paper. However, regardless of the "complexing agent" the most important factor to consider is the resulting water-solubility of the micronutrient product. The results of this study have shown that just because a micronutrient is reacted with an organic complexing agent, it does not bestow chelate characteristics on the resulting product.

True chelates are typically more effective at delivering micronutrients to the plant root. The result of this increased effectiveness is reduced application rate requirements. Results from previous work, as well as those of the current study, suggest that ZnEDTA can be 2 to 5 times more effective at delivering Zn to the plant compared to the other water-soluble sources we studied. The organic complexes used in this experiment were not more effective than inorganic $ZnSO_4$. When RAC values of $ZnSO_4$ and ZnLigno are compared there is little evidence to suggest that any more than a 1:1 effectiveness ratio exists between these two sources (Tables 4 and 5). The other organic complex, ZnSuc, performed poorly compared to all other Zn sources. The ZnSuc source has a low Zn water-solubility (<0.5%) and its effectiveness was minimal.

Photo 5 is a visual comparison of ZnEDTA 0.5 lb A^{-1} and $ZnSO_4$ 4 lb A^{-1} (i.e. 1:8 Zn ratio). Based on this photo and the results presented in this study it is clear that ZnEDTA, a true metal chelate, is more effective at delivering Zn to the plant. Photo 6 compares ZnLigno with $ZnSO_4$ at a 1:8 ratio. Visual observation, statistical analysis, and RAC estimation confirm that the complexed Zn sources do not perform similarly to chelates and ZnLigno is equally as effective as $ZnSO_4$.

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