EVALUATION OF SEVEN MATERIALS AS SOURCES OF ZINC FOR SOYBEANS [*Glycine max* (L)]

by

ENOCH ABIODUN SALAKO

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Approved by:

Larry Murphy
Major Professor

T Mader
Major Professor

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INTRODUCTION

Soybean, Glycine max (L) Merrill, is one of the most important cash crops in the United States. It has a relatively high yield potential and is a highly efficient producer of protein and oil for both man and animal. The importance of this crop as a source of protein for the formulation of low-cost, nutritionally balanced protein foods is widely recognized. Production figures for soybeans in Kansas show production of 8198 million kilograms from 412,000 hectares of land in 1974.

The United States produces a considerable amount of soybeans. For example, approximately 20,984,000 hectares of soybeans were prouuced in 1974. Soybean is also becoming an important cash crop in many of the developing countries of the world, e.g. Nigeria, other West African countries, Brazil, and India.

The need for increased production of soybeans for the provision of low-cost protein foods for man and livestock has necessitated an increasing amount of research. Many efforts have been expended on both the nutrient and environmental requirements of the soybean plant. From the point of nutritional research, most studies have been conducted on the macronutrient requirements. Evidence of the existence of possible interactions of some micronutrients with macronutrients has shown the need for a balance between nutrients. Use of high analysis fertilizers, without micronutrients, to increase yields may bring about consequent imbalances and micronutrient deficiencies. Zinc is frequently involved. Efficient fertilization programs must recognize this factor.

Soybean plant zinc deficiency has been occasionally reported. Environmental factors which favor the development of zinc deficiency include high soil pH; low cation exchange capacity (CEC); cool, wet soil conditions early in the growth cycle of plants; low soil organic matter content; high available phosphorus; soil compaction and land levelling for irrigation and conservation structures; and the type or nature of the crop.

The occurrence of these conditions favorable to zinc deficiencies and varying tolerance of crops to these conditions, has necessitated study of methods for their correction and prevention. Information needed for correction and prevention includes comparative efficiencies of zinc sources and evaluation of zinc application rates.

Preliminaty studies conducted by the Department of Agronomy at Kansas State University and work by other researchers in other parts of the world have shown that soybeans will respond to zinc fertilization, although the amount of information available is limited. With the need for more information on zinc fertilization of soybean, growth chamber, greenhouse, and field experiments were conducted with the following objectives:

1. To study morphological responses of soybean to zinc (Zn) fertilization.
2. To investigate the effects of Zn on yields of soybean.
3. To evaluate the comparative performance of several materials as sources of Zn for soybean as measured by Zn concentrations in plant tissue and by seed yields.
4. To compare residual effects of the Zn fertilization on the succeeding crop of soybean under controlled growth chamber and greenhouse conditions.

LITERATURE REVIEW

The importance of zinc [Zn] in the nutrition of plants has long been recognized. An inadequate Zn supply frequently results in the development of deficiency symptoms (5, 26, 35, 38) in the plant, low dry matter production (26, 35, 38), low Zn concentration in the plant (21, 27, 38, 40) and a delay in the synthesis of phenylalanine or tryptophan in the bean seeds (5) [*Phaseolus vulgaris*].

Plants may differ in either the Zn requirements of their tissues expressed on a dry-weight basis or in the capacities to absorb native or applied Zn from the soil. Viets et al. (38) investigated the response of 26 crops to soil and foliar applied Zn and grouped beans [*Phaseolus vulgaris*], soybeans [*Glycine max*] and corn [*Zea mays*] as the very sensitive crops to Zn deficiency. On the other hand, experimental results of the Department of Agronomy at Kansas State University show that corn is more susceptible to Zn deficiency conditions than grain sorghum [*Sorghum bicolor*].

Knowles (22) studied Zn toxicity in plants and reported mustard [*Brassica alba*] to be Zn sensitive while peas [*Pisum sativum*] were tolerant of active Zn in the presence of adequate water supply.

Factors Favoring Zinc Deficiency

Although there is a great variability among the crop species in their tolerance to Zn deficiency, certain conditions have been identified as the major contributing factors to Zn deficiency development. Judy and others (20) observed severe Zn deficiencies on alkaline [high pH] Michigan soils and also reported that high residual soil phosphorus levels reduced yields unless Zn was included with the starter fertilizer. Their findings typify the well-established phenomenon of P-induced Zn deficiency, the mechanism of which is still not understood.

Tisdale and Nelson (36) also cited reduction of Zn content of beans [Phaseolus vulgaris] by 20-30% due to high level soil phosphorus. Schrenk (30) observed high Zn content of alfalfa [Medicago sativa] in eastern Kansas soil with low pH.

Zinc has been found to be associated with the soil organic matter. Soil compaction and land levelling for irrigation or conservation structures reduces its availability due to the incorporation of the top soil [rich in organic matter] into the subsoil, and a reduction of oxygen supply. Viets et al. (38) identified low soil organic matter as one of the factors contributing to the occurrence of Zn deficiency in the soil.

Low cation exchange capacity [CEC] of soils also contributes to Zn deficiency due to possible losses through leaching. Wallace and Mueller (40) reported greater absorption of Zn from $ZnSO_4$ by soybeans grown on a non-alkaline loam soil than from Hacienda loam [with 32% $CaCO_3$].

A knowledge of conditions common to Zn deficiency is of vital importance in attempting to meet crops' requirement for this element. In many crops including soybeans, work has been conducted in four major areas. These include the Zn sources, methods of Zn application, application rates, and residual effects; all aimed at pin-pointing the most efficient Zn carrier, the most effective method of application and at the most economical rate of application with no unfavorable residual effects.

Effects of Zinc Carriers on Zinc Uptake

Preferential uptake of Zn by crops from some Zn sources has been observed. Both organic and inorganic sources have been used by many of the workers. However, crop response to any of the Zn sources is also influenced by soil factors, type of Zn carriers used, method of application, rates of application and other factors.

Holden and Brown (18) compared Zn-ethylenediaminetetraacetic acid [Zn-EDTA] with Zn sulphate [$ZnSO_4$] as Zn sources for alfalfa and observed that the increase in the Zn concentration in the plants using Zn-EDTA doubled that of $ZnSO_4$ on a neutral soil and up to 6 times more on a calcareous soil. Wallace and Mueller (40) also reported greater uptake of Zn by soybeans from Zn-HEEDTA than from $ZnSO_4$ in Hacienda loam [32% $CaCO_3$].

In a greenhouse study, Shukla and Morris (31) compared soil applications of $ZnSO_4$ and ZnO with treatments of Zn-polyflavonoid and Zn chelate and found $ZnSO_4$ and ZnO to be equal or superior to chelated and Zn-polyflavonoid in increasing the Zn concentration and uptake of corn.

Although Gallagher (15) in his study on ZnO and $ZnSO_4$ as Zn sources for Zea mays and Sorghum bicolor observed increase in Zn uptake with applications of Zn-EDTA, $ZnSO_4$ and Coop-Zn, comparison of these Zn carriers in terms of Zn uptake by the plants did not reveal any significant difference statistically.

The form in which the Zn carrier is applied is also influential with regards to crop response. Brown and Krantz (10) observed that granulation of $ZnSO_4$, $Zn(NH_4)PO_4$ and Zn-polyflavonoid greatly reduced their effectiveness. Brinkerhoff et al. (9) also found powdered or granular Zn-EDTA to be a more effective Zn source both when incorporated into fertilizer or mixed with fertilizer at planting time. They reported that the inorganic Zn carriers [$ZnSO_4$ and Zn frits] were more effective when mixed with the fertilizer than when incorporated into granules.

On their work on plant utilization of Zn from various types of Zn compounds and fertilizer materials, Boawn et al. (6) observed greater Zn uptake by beans [Phaseolus vulgaris] using Zn-EDTA than $ZnSO_4$. They also reported the chelated form of Zn to be 3.5 times better than $ZnSO_4$ in increasing the plant uptake of Zn in the absence of nitrogen. With nitrogen application, Zn-EDTA was found to be 2.4 times more efficient than $ZnSO_4$.

The superiority of Zn-EDTA over $ZnSO_4$ in increasing plant uptake of Zn was also confirmed by Vinande and others (39) who reported Zn-EDTA to be 5 times more efficient than $ZnSO_4$ or ZnO in increasing the Zn uptake of beans [Phaseolus vulgaris] while ZnO was found to be more effective on corn. Both $ZnSO_4$ and ZnO were rated equal. Judy et al. (20) also found the chelated Zn to be 5 times better than the inorganic form in correcting Zn deficiency in Zn deficient soils. Ganiron and others (16) found Zn-EDTA to produce slightly higher concentrations of Zn in corn tissue than did $ZnSO_4$ in their growth chamber solution culture studies.

In their literature review on the correction of micronutrient deficiencies with fertilizers, Murphy and Walson (27) found $ZnSO_4$ to be the most efficient among the inorganic Zn sources, and Zn-EDTA the most efficient among the organic sources.

Influence of Methods and Rates of Application of Zinc Carriers on Zinc Uptake by Plants

As reported by Sorensen et al. (33) Zn does not move appreciably in the soil and wider distribution of low analysis material aids in root fertilizer contact due to the increased number of particles. They emphasized the importance of vertical distribution of Zn and that it should not be placed above the plant roots to avoid positional unavailability. This relative immobility of Zn in the soil has necessitated research into the most suitable methods of application to enhance its availability to the plants. Consequently three main methods of application are employed. These include soil, foliar applications and seed treatments; but the most common and generally successful one (27) is the soil application. In the latter method [soil application], the Zn carriers may be applied broadcast, pre-plant [soil incorporated] or as a side dressing.

Brown and Krantz (10) observed equal response by sweet corn to broadcast soil applications of $ZnSO_4$, Zn-EDTA and Zn-polyflavonoid in a greenhouse study. Zn-EDTA was found to be more effective when banded.

On their work on plant uptake and fate of soil-applied Zn, Brown and others (11) established that surface applications of Zn have proven to be relatively ineffective for upland crops in several cases and concluded that immobility of Zn results in positional unavailability when applied to the soil surface.

Comparing band application of Zn [with the seed], with broadcast method, Martens and others (26) found the former to be more effective in correcting Zn deficiency in corn.

Ellis et al. (13) observed that incorporation of ZnO or $ZnSO_4$ into fertilizer reduced the water solubility and uptake of Zn, as well as yields as compared with hand-mixing of the Zn carrier with the fertilizer at planting time. Their study revealed that Zn-EDTA chelate remained water-soluble when coated on the fertilizer granule in conjunction with $MnSO_4$.

The effectiveness of band applications of Zn can be influenced by the relative position of the banded fertilizer to the seeds. Boehle and Lindsay (8) indicated the efficient use of band applications of Zn when placed beside and below the seed and suggested that banded chelates may be more effective than inorganic Zn sources because of greater mobility in the root zone. Pre-plant broadcast applications were found to be acceptable and that applications with mixed fertilizers or nitrogen materials may enhance Zn uptake. On the other hand, sidedressed applications of Zn fertilizers after crop emergence were reported to represent the least effective method. They also stressed that soil applications of Zn may last for several years.

Ganiron et al. (16) observed equal performance of Zn-EDTA and $ZnSO_4$ when applied as a band treatment at seeding.

Foliar application is one other method that is often practiced specifically for correcting temporary Zn deficiency in plants grown on Zn deficient soils or situations where Zn deficiency is present.

In their investigation on the behavior of $ZnSO_4$ as foliar and soil applications, Lyden and Toth (23) observed that $Zn^{65}SO_4$ was absorbed in both cases and to some extent distributed throughout soybeans growing in sand culture. $Zinc^{65}$ was noted to be absorbed from root applications than from similar applications to the leaves.

Thorne (35) obtained better performance of $ZnSO_4$ sprays over Zn chelates and suggested that the need for Zn chelates in sprays is not as critical as for Fe chelates.

Viets et al. (38) observed the disappearance of deficiency symptoms in sweet and field corn, soybeans, castor beans [Ricinus communis], field beans and lima beans with foliar application but were unable to collect yield information due to the design of the project.

Seed treatment with various Zn carriers may not serve as a satisfactory substitute for conventional Zn fertilization. Rasmussen and Boawn (28) treated bean seeds with $ZnSO_4$ powder as a source of Zn and concluded its ineffectiveness as a substitute for Zn fertilization. They observed the insufficiency of Zn uptake to meet plant needs beyond the 3-compound leaf stage, even though the amount of Zn applied to the seed exceeded the total Zn uptake by the crop. They succeeded in eliminating temporary scattered Zn deficiency when seed treatment was coupled with soil application of 11 kg Zn/ha.

Influence of Rates of Application on Zinc Uptake

Apart from the variability that exists among the crops in their ability to utilize or absorb soil Zn, crop response to Zn fertilization is often influenced by rates of application and soil type. Most of the workers have observed a positive correlation between the rates of application and Zn uptake by the crop.

Martens et al. (25) observed an increase in Zn concentration in soybeans with increased Zn application rates in Davidson clay loam and Malboro fine sandy loam soils. Increase in Zn concentration in soybeans seeds were noted on the clay loam soil and an application of as high as 11.1 kg Zn/ha to both soil types annually for 6 years, was found to have no effect on plant weight and seed yield.

Method of application often serves as a determining factor of the most practicable rate of application. Martens, Hawkins and Datt (26) reported that a lower Zn level [6.7 kg Zn/ha] banded with the seed was more effective in correcting Zn deficiency symptoms in corn than was a higher rate [26.9 kg Zn/ha].

Leyden and Toth (23) concluded from their studies on foliar application of $ZnSO_4$ that doubling the concentration of applied Zn did not affect root or foliar absorption of Zn by soybeans, tomato [Lycopersicum esculentum] and corn.

Judy et al. (20) suggested that the use of 3-4 lbs/acre Zn for pea beans in the inorganic form or about 1/5th as much chelated Zn should supply sufficient Zn on sites where deficiency is known or suspected.

Gallagher (15) observed greater Zn uptake by Zea mays and Sorghum bicolor with a higher [9.0 kg Zn/ha] rate than a lower [4.5 kg Zn/ha] rate of the Zn carriers used. He also noticed a greater Zn concentration in the leaves with a lower rate of application using Zn-EDTA as a Zn carrier.

Residual Effects of the Zinc Fertilization

It has been established (8) that soil applications may render Zn available for several years. Large soil applications of Zn can be successfully monitored by continued soil analysis.

Keefer and Singh (21) reported increased Zn concentrations in soybeans through application of $ZnSO_4$ on Wharton soil, initially high in available Zn.

Shaw et al. (32) reported the availability of residual soil Zn from previously applied $ZnSO_4$ and also noted that the percentage utilization of the Zn fertilizers was inversely related to the rate of application, but very low in all cases.

Boawn et al. (7) found that high percentages of Zn from 9 and 18 kg/ha Zn application rates were still acid extractable from a Ritzville fine sandy loam after 5 years.

Effects of Zn Application Rate on the Occurrence of Zn Toxicity

An excessive supply of any nutrient may result in luxury consumption by plants and represents a waste of that nutrient. It has also been established that an excessive supply of some nutrients may produce detrimental effects on plant metabolic activities with consequent poor yields.

In their work on plant Zn nutrition and toxicity, Berg and others (4) reported that Zn toxicity is a potential hazard when its concentrations are over 100 ppm on heavy humus-rich soils.

In an earlier work on Zn toxicity, Berg (3) found that excessive available Zn produced lowered yields in wheat [Triticum vulgare], oats [Avena sativa], barley [Hordeum spp], and rye [Secale cereale], and also produced a reddish violet color in leaves of rye.

High concentrations of heavy metals in soils have been found to induce deficiencies of micro-nutrients. Hewitt (17) observed Zn deficiency in sugar beets [Beta vulgaris] due to excessive amounts of Mn^{++} and Co^{++}.

Hunter and Vergano (19) found the toxic effects of Ni, Co, Cu, Zn, Mn and Mo in oats to be associated with high concentrations of the elements in the leaf tissue.

In their investigation of the toxic limits of replaceable Zn for corn and cowpeas [Vigna unguiculata] grown on three Florida soils, Gall and Barnette (14) observed the replaceable Zn became toxic at concentrations of from 0.28-2.2 milli-equivalents per 100 gm of soil [180-1400 lbs/acre] depending on soil and crop types.

Scharrer and Jung (29) reported that plant concentrations of over 0.25 mg Zn/gm dry weight had toxic effects on beans. They noticed decreased bean yields with increased concentrations of Zn and concluded that increasing concentrations of Zn may possibly exert an antagonistic effect on Fe and Cu.

Adriano et al. (1, 2) also observed the negative correlation of high application rates of Zn on P and Fe concentrations in the plant tissues.

They concluded that excessive amounts of available Zn can influence the uptake and metabolism of other elements.

Although some crops may be tolerant to high concentrations of Zn, it is possible that high Zn levels in plants fed to livestock may be toxic to the animals. Underwood (37) studied micronutrients in human and animal nutrition and observed the tolerance of swine, chickens, and cattle to Zn concentrations of 500 ppm or much higher in feeds. His data revealed that the seed produced where the various levels of Zn were applied to the soils would not be toxic to the farm animals.

MATERIALS AND METHODS

This investigation was divided into growth chamber, greenhouse, and field studies.

(a) Growth Chamber Study

The growth chamber portion of the work was conducted to investigate the effects of zinc fertilization on Calland soybeans grown on a zinc deficient soil [Muir silt loam], obtained from a site in Pottawatomie County, Kansas. Soil analysis results showed that the soil possessed the characteristics shown in table 1.

Table 1. Soil characteristics.

	Pottawatomie county site	Pawnee county site
pH	7.4	7.1
Available P	20.0 kg/ha	32.5 kg/ha
Exchangeable K	473.8 kg/ha	560.0 kg/ha
Organic matter content	1.9%	2.6%
Available Zn [DTPA extracted]	0.34 ppm	0.70 ppm

The dry soil was sieved and 800gms weighed into each of the 2 liter paper pots.

Four zinc sources were employed. Supplemental amounts of P, Mg, N and K were supplied in the forms indicated below:

$Zn-NH_3$ complex . . . . Fertilizer grade

$ZnSO_4$ . . . . Reagent grade

ZnO . . . . Reagent grade

Zn-EDTA . . . . Fertilizer grade

Phosphorus . . . . . . Supplied as *15-27-0 solid

Magnesium . . . . . . Supplied as $MgSO_4$--reagent grade

Nitrogen . . . . Supplied partly by the P carrier and $Zn-NH_3$ and the remainder as urea.

Potassium . . . . . . Supplied as KCl--reagent grade

Sulfur was not held constant.

Constant rates of P, Mg, N and K were used as follows:

P -- 40 ppm
Mg -- 50 ppm
N -- 16 ppm
K -- 100 ppm

Table 2. Zinc treatments.

ppm Zn	Zinc source
0	Control
2	$Zn-NH_3$
4	$Zn-NH_3$
8	$Zn-NH_3$
2	$ZnSO_4$
4	$ZnSO_4$
8	$ZnSO_4$
2	ZnO
4	ZnO
8	ZnO
2	Zn-EDTA
4	Zn-EDTA
8	Zn-EDTA

*15-27-0 means 15% N, 27% P and 0% K by weight.

Strict measures were taken to prevent zinc contamination in preparation of these treatments. Containers were washed with 10% (v/v) HNO_3, 0.1M EDTA and deionized, distilled water. The nutrient carriers were thoroughly mixed with the soil by gently shaking and swirling the soil in the paper pots, prior to planting. Treatments were replicated three times.

The soybean seeds were inoculated two hours prior to planting and 8 seeds were planted per pot. Immediately after planting, each pot was given 200 mls of deionized, distilled water, and pots were arranged in the growth chamber in a completely randomized fashion. The growth chamber was set to provide 25°C and 15°C day-night temperatures, respectively, with a 16 hour photoperiod for the 21 day growth period.

The seedlings were thinned to 3 per pot 2 days after emergence. Thinning was carefully done to ensure similar plant spacing in all pots.

A constant weight for the pots was maintained with deionized distilled water for the first week, after which constant amounts of deionized distilled water were supplied to the pots daily.

The plants were harvested 20 days after planting. Harvesting was done by cutting the plants 1 cm above the soil surface with stainless steel scissors. The plants were washed in deionized, distilled water and dried in an oven at 70°C for 48 hrs. The dried plants were ground through a small Wiley mill with stainless steel knives and a 2 mm stainless steel screen.

A 0.5 gm portion of the plant samples was weighed into 50 ml beakers and digested by employing a nitric acid-perchloric acid method. The ternary mixture used for digestion was prepared by mixing equal volumes (1:1:1) of 70% perchloric acid, concentrated nitric acid, and deionized distilled water. The samples were evaporated to dryness and taken up in 0.1N HCl. The solution was filtered through Whatman 42 filter paper and made to 25 ml volume in 25 ml volumetric flasks. Zinc was determined on this stock solution by atomic absorption spectrophotometry [Appendix] using a Perkin-Elmer model 303 instrument.

Phosphorus determination was done by the vanadate-molybdate yellow color procedure [Appendix]. Nitrogen was determined by the steam distillation procedure of Brenner and Keeney while potassium was determined by flame photometry.

A second crop was re-seeded shortly after harvesting the first crop to test residual effects of the treatments. Five seeds were planted per pot with roots of previous plants still in the soil. The plants were thinned to 3 per pot 2 days after germination. The same watering procedure was employed for the same period of study.

(b) Greenhouse Study

The soil used for this portion of the work was obtained from the site in Pawnee county where the field portion of the investigation was conducted. The main objectives were to evaluate the zinc carriers and application rates with a view to making a zinc fertilizer recommendation.

The soil, Carwile loamy fine sand [Typic Argiaquolls, Fine, Mixed, Thermic] was suspected to be low in zinc due to levelling for irrigation but soil analysis revealed only a border-line Zn deficiency (table 1).

The dry soil was ground and 800 gms were weighed into individual 2 liter paper pots. The paper pots were not washed since they were newly purchased from the factory.

In this study, seven zinc sources were used, including the four previously used in the growth chamber study. The zinc carriers (fertilizer grade) were $Zn-NH_3$, $ZnSO_4$, ZnO, Zn-EDTA, Zn-Frit 197, Zn-Frit 247-G and Urea-coated-ZnO.

Phosphorus, magnesium, nitrogen and potassium were supplied at the same rates used in the growth chamber study described earlier. Sulfur was not supplied.

Treatment of the soil with the nutrient combinations, watering, planting and thinning were carried out in the same manner as described for the growth chamber study. The treatments were replicated three times.

Columbus variety of soybeans was used in this study. A completely randomized design was also employed in the arrangement of the pots.

The plants were harvested 28 days after planting. Harvesting, drying of the samples, grinding, and analysis for Zn and P were carried out in the manner described earlier for the growth chamber study.

A second crop was also grown to test the residual effects of the zinc treatments.

(c) Field Study

The site selected for this study had been recently levelled for furrow irrigation. The soil characteristics for the site were reported earlier in table 1. The same zinc sources employed for the greenhouse study were also used except Frit 197 which was replaced by Sherwin-Williams (SW-1) experimental ZnO.

Phosphorus was supplied at a constant rate of 38.9 kg P/ha as 11-14-0. Nitrogen was supplied preplant at a constant rate of 168 kg/ha [supplied partly by the P carrier, sulphur carrier, Zn carriers and the remainder as urea-ammonium nitrate solution]. A constant rate of 22 kg sulphur per hectare was applied as ammonium thiosulfate. The fertilizer materials were

Table 3. Treatments used for field study of soybeans responses to zinc.

	Zn treatments (kg/ha)	Zn carriers	Form of Zn application
1.	Control	--	--
2.	2.2	$ZnSO_4$	Fluid
3.	4.5	$ZnSO_4$	Fluid
4.	9.0	$ZnSO_4$	Fluid
5.	2.2	ZnO	Fluid
6.	4.5	ZnO	Fluid
7.	9.0	ZnO	Fluid
8.	2.2	Zn-EDTA	Fluid
9.	4.5	Zn-EDTA	Fluid
10.	9.0	Zn-EDTA	Fluid
11.	2.2	$Zn-NH_3$	Fluid
12.	4.5	$Zn-NH_3$	Fluid
13.	9.0	$Zn-NH_3$	Fluid
14.	2.2	SW-1	Fluid
15.	4.5	SW-1	Fluid
16.	9.0	SW-1	Fluid
17.	2.2	Urea-ZnO	Solid
18.	4.5	Urea-ZnO	Solid
19.	9.0	Urea-ZnO	Solid
20.	2.2	Frit-247-G	Solid
21.	4.5	Frit-247-G	Solid
22.	9.0	Frit-247-G	Solid

incorporated into the soil by a roto-tilling operation. The treatments were replicated three times and a completely randomized design was employed.

Columbus soybeans, used in the greenhouse study, was planted in the field at a seeding rate of 67 kg/ha and row spacing of 76 cm. Seeding operations were carried out by the cooperator.

Treflan was applied at the rate of 1.1 kg/ha [active ingredient] for weed control.

The field was furrow irrigated to ensure adequate supply of moisture to the crop.

Plant tissue samples were taken at two stages of plant growth, early bloom and early pod stages. The youngest fully developed trifoliate leaves [12 per plot] were collected for analysis, placed in brown paper bags, were washed thoroughly in the laboratory with deionized, distilled water before drying. Drying, grinding, and analysis of the samples for P and Zn were carried out in the same manner described for the growth chamber study.

The plots were harvested mechanically (combine) at full maturity and seed samples taken for Zn and P determination.

RESULTS AND DISCUSSION

Growth Chamber Study

Soybean plant heights were measured weekly but were not significantly affected by the various zinc treatments [Table 4]. Plants in the control pots were of equal height compared to those receiving zinc.

Although the available zinc content of the soil was low (0.34 ppm DTPA extractable Zn), no distinct zinc deficiency symptoms were observed on the control pots during the short growth chamber growth period (21 days). A locally distributed, slight general chlorosis of leaves was observed among some of the treatments but was not considered to be a general zinc deficiency symptom.

Dry weights of plant tops [Table 5] were not significantly increased by zinc application. A similar lack of zinc effect on plant dry weights was recorded for the second crop which tested the residual effects of the treatments [Table 6].

Determination of plant zinc concentrations in the first crop [Fig. 1, Table 7] indicated highly significant differences between the control and the various treatments. A comparison of the three rates of zinc application indicated that the 8 ppm Zn rate produced the highest zinc concentrations. The 4 ppm rate was not significantly better in performance than 2 ppm Zn. In terms of increased zinc concentration in the plants, both Zn-EDTA and $ZnSO_4$ were found to be significantly more effective than ZnO and Zn-NH_3 complex. Zn-EDTA and $ZnSO_4$ were equally effective, Zn-NH_3 being somewhat more effective than ZnO.

Table 4. Effects of zinc treatments on plant height (cm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	15.9	16.3	14.5	15.6
$ZnSO_4$	13.8	14.9	15.0	14.5
ZnO	15.6	16.5	15.7	15.9
Zn-EDTA	15.3	15.4	15.8	15.5
Rate Means	15.2	15.8	15.3	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 15.0

Table 5. Effects of zinc treatments on plant dry weights (gm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	1.14	1.17	0.99	1.10
$ZnSO_4$	1.12	1.02	1.24	1.13
ZnO	1.19	1.13	1.20	1.17
Zn-EDTA	1.20	1.11	1.20	1.17
Rate Means	1.16	1.11	1.16	

$LSD_{.05}$ Treatments = 0.19

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 0.90

Table 6. Residual effects of zinc treatments on plant dry weights (gm). Growth Chamber Study.

Zinc carriers	Application rate (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	1.17	1.21	1.23	1.20
$ZnSO_4$	1.25	0.99	1.00	1.08
ZnO	1.20	1.24	1.27	1.24
Zn-EDTA	1.30	1.37	0.96	1.21
Rate Means	1.23	1.20	1.12	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 0.94

Table 7. Effects of zinc treatments on plant zinc concentrations (ppm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	10.0	12.1	17.7	13.3
$ZnSO_4$	11.7	12.3	17.4	13.8
ZnO	9.8	10.7	12.9	11.1
Zn-EDTA	10.6	14.4	21.9	15.6
Rate Means	10.5	12.4	17.5	

$LSD_{.05}$ Treatments = 3.5

$LSD_{.05}$ Rates = 1.8

$LSD_{.05}$ Carriers = 2.0

Control 9.2

In the second crop which tested the residual effects of zinc treatments, similar performance in plant growth (visually), to the first crop was observed. Plant zinc concentrations [Fig. 2, Table 8] showed no significant difference between the treatments and the control. The surprising, relatively high plant zinc concentrations on the control pots may have been due to two possible reasons. First, applied Zn might have increased native soil zinc uptake and utilization in the first crop and may have depleted the soil zinc level below that of the control in the second crop. Secondly, the ratio between soil P and Zn [and possibly Fe and Zn] in the second crop might have been so wide that P depressed Zn uptake further.

Calculation of plant uptake of zinc [Table 9] revealed Zn-EDTA to be significantly more effective as a zinc source at 8 ppm and equally effective with Zn-HN_3 at 4 ppm. Failure of $ZnSO_4$ to maintain its equal effectiveness with Zn-EDTA [as observed for plant zinc concentrations] is undoubtedly due to the low total dry weights of plant tops recorded for this zinc carrier [Table 9]. The 8 ppm Zn rate still produced the highest zinc uptake while the 2 and 4 ppm Zn rates remained equally effective. Overall effects of the zinc carriers indicated Zn-EDTA to be the most effective. This agrees with the results obtained for plant zinc concentrations which revealed Zn-EDTA to be the most effective at 4 and 8 ppm Zn rates. They suggest that determination of plant zinc concentrations alone may be inadequate in determining material effects. The second crop [Table 10] produced similar results.

Plants receiving no zinc were found to be significantly lower in phosphorus concentrations than those that received zinc [Table 11, Fig. 3]. No significant differences in plant phosphorus concentrations due to mean

Fig. 1 Effects of zinc treatments on plant zinc concentrations (ppm).
$LSD_{.05}$ Treatments = 3.5
Rates = 1.8
Carriers = 2.0

Fig. 2 Residual effects of zinc treatments on plant zinc concentrations (ppm).
$LSD_{.05}$ Treatments = 4.6
Rates = 1.8
Carriers = 2.1

Fig. 3 Influence of zinc treatments on plant P concentrations (ppm).
$LSD_{.05}$ Treatments = 198
Rates NS
Carriers = 118

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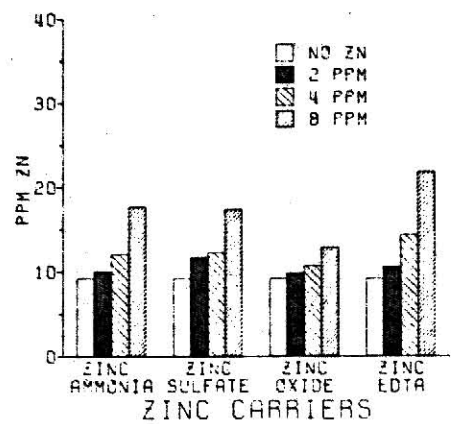
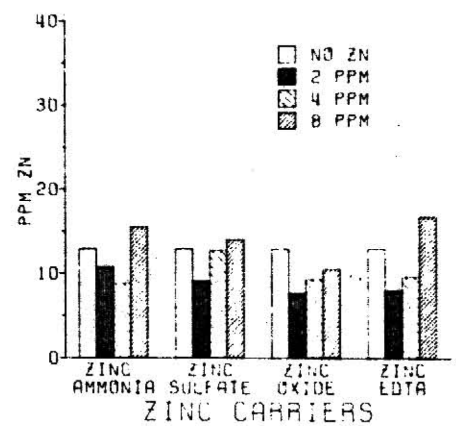


Figure 1



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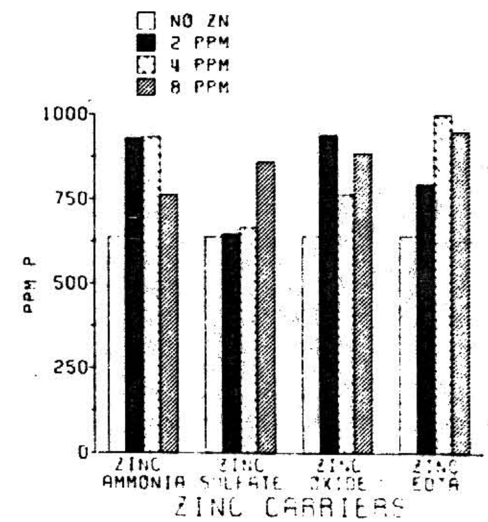

Figure 3

Table 8. Residual effects of zinc treatments on plant zinc concentrations (ppm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	10.8	8.8	15.5	11.7
$ZnSO_4$	9.1	12.7	14.0	11.9
ZnO	7.7	9.3	10.5	9.2
Zn-EDTA	8.0	9.6	16.7	11.4
Rate Means	8.9	10.1	14.2	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 1.8

$LSD_{.05}$ Carriers = 2.1

Control 12.9

Table 9. Effects of zinc treatments on zinc uptake (μg) by plant tops. Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	11.1	14.1	17.6	14.3
$ZnSO_4$	13.1	12.6	21.5	15.7
ZnO	11.6	12.1	15.4	13.0
Zn-EDTA	12.7	15.9	26.4	18.3
Rate Means	12.1	13.7	20.2	

$LSD_{.05}$ Treatments = 4.8

$LSD_{.05}$ Rates = 2.5

$LSD_{.05}$ Carriers = 2.9

Control 8.2

Table 10. Residual effects of zinc treatments on zinc uptake (μg) by plant tops. Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn) 2	4	8	Carrier Means
$Zn\text{-}NH_3$	12.5	10.6	18.9	14.0
$ZnSO_4$	11.0	12.4	13.8	12.4
ZnO	9.2	11.5	13.3	11.3
Zn-EDTA	10.4	13.0	16.1	13.2
Rate Means	10.8	11.9	15.5	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 2.2

$LSD_{.05}$ Carriers = 2.5

Control 9.6

Table 11. Influence of zinc treatments on plant P concentrations (ppm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn) 2	4	8	Carrier Means
$Zn\text{-}NH_3$	929	933	762	874
$ZnSO_4$	646	665	858	723
ZnO	937	762	884	861
Zn-EDTA	792	996	946	912
Rate Means	826	839	863	

$LSD_{.05}$ Treatments = 198

$LSD_{.05}$ Rates - NS

$LSD_{.05}$ Carriers = 118

Control 638

zinc rates were recorded; however, highest plant zinc concentrations were also recorded where P concentrations were highest. It is perhaps logical to infer that zinc enhances P uptake in soybeans although more zinc rates would have to be studied to get a better picture of the relationship between the two elements.

Plant concentrations of iron (Fe) [Table 12] showed no significant difference due to zinc rates or carriers although the values were quite low. Similar results were obtained for potassium (K) concentrations [Table 13].

Zinc treatments tended to depress plant nitrogen concentrations [Table 14]. Zn-NH_3, however, produced significantly higher N concentrations than the other three zinc carriers. This cannot be attributed to the nitrogen content of Zn-NH_3 since this was taken into consideration when a constant rate of N was supplied to all the zinc treatments. The relationship between plant N concentrations and plant zinc concentrations and zinc uptake was not well-defined from the data but appeared to be negative. Zn-EDTA for which the highest zinc concentrations and uptake were recorded, had the lowest plant nitrogen concentrations. This is not surprising because some experiments [Viet, Boawn, and Crawford, 1957] had indicated the effect of N on Zn concentrations in plants to be complicated by the effect of the carrier on soil pH and the total amount of plant growth.

Greenhouse Study

Seven zinc carriers were studied.

Plant concentrations of zinc were again found to be significantly affected by zinc treatments [Table 15, Fig. 4]. Interaction between zinc carriers and rates was significant. Except for Frit 247-G, a positive

Table 12. Effects of zinc treatments on plant Fe concentrations (ppm). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	37.6	27.3	29.7	31.6
$ZnSO_4$	34.0	32.0	33.3	33.1
ZnO	34.0	31.3	26.7	30.7
Zn-EDTA	31.3	36.8	31.7	33.3
Rate Means	34.2	31.9	30.3	

$LSD_{.05}$ Treatments NS

Control 36.0

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Table 13. Effects of zinc treatments on plant K concentrations (%). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	1.17	1.28	1.44	1.30
$ZnSO_4$	1.35	1.40	1.39	1.38
ZnO	1.31	1.24	1.31	1.29
Zn-EDTA	1.38	1.43	1.16	1.32
Rate Means	1.30	1.34	1.33	

$LSD_{.05}$ Treatments NS

Control 1.40

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Table 14. Effects of zinc treatments on plant nitrogen concentrations (%). Growth Chamber Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	2.02	1.82	1.86	1.90
$ZnSO_4$	1.70	1.66	1.74	1.70
ZnO	1.92	1.66	1.69	1.76
Zn-EDTA	1.71	1.80	1.61	1.71
Rate Means	1.84	1.74	1.73	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 0.19

Control 2.04

Table 15. Effects of zinc treatments on plant zinc concentrations (ppm). Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	26.6	27.1	38.1	30.6
$ZnSO_4$	28.2	32.7	38.6	33.1
ZnO	28.1	29.5	36.4	31.3
Zn-EDTA	49.2	56.0	68.9	58.1
Zn Frit 197	26.4	36.1	48.4	36.9
Zn Frit 247-G	26.1	24.7	27.9	26.2
Urea-ZnO	39.3	46.5	70.5	52.1
Rate Means	32.0	36.1	47.0	

$LSD_{.05}$ Treatments = 6.6

$LSD_{.05}$ Rates = 2.5

$LSD_{.05}$ Carriers = 3.9

$LSD_{.05}$ Interaction = 6.7

Control 23.5

Fig. 4 Effects of zinc treatments on plant zinc concentrations (ppm).

$LSD_{.05}$ Treatments = 6.6
Rates = 2.5
Carriers = 3.9
Interaction = 6.7

Fig. 5 Residual effects of zinc treatments on plant zinc concentrations (ppm).

$LSD_{.05}$ Treatments = 7.5
Rates = 2.9
Carriers = 4.4
Interaction = 7.6

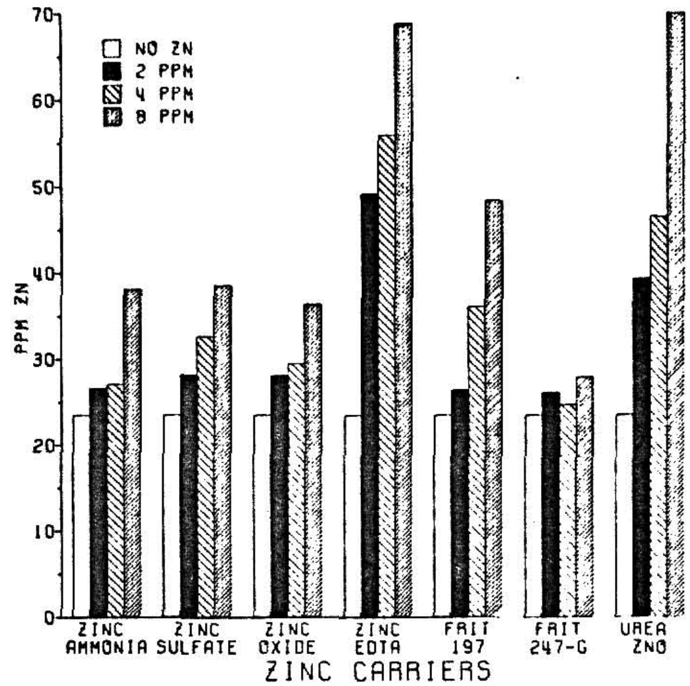

Figure 4

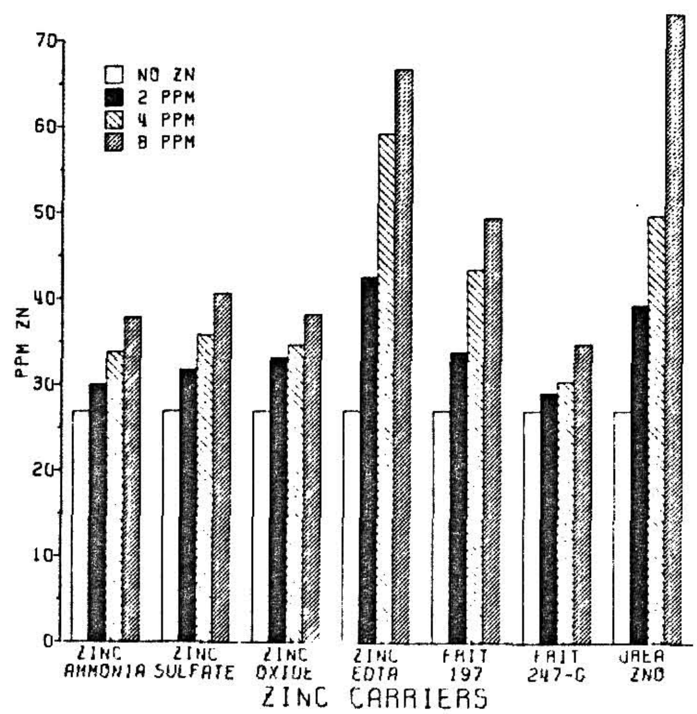

Figure 5

correlation was observed between plant zinc concentrations and rates of zinc application for the zinc carriers. Overall effects of the three rates of zinc application showed significant differences among the rates. Eight ppm produced the highest zinc concentrations, followed by 4 ppm and 2 ppm zinc application rates.

Among the zinc carriers, Zn-EDTA was found to be the most effective source of zinc at both 2 ppm and 4 ppm rates. At 8 ppm, Zn-EDTA and urea-ZnO were equal and more effective than the other zinc carriers.

Plant concentrations of zinc [Table 16, Fig. 5] resulting from a test of residual effects of the zinc treatments indicated significant differences between the treatments and the control. A trend similar to that of the first crop was noted in second crop zinc response [Fig. 5]. Residual zinc from both Zn-EDTA and urea-ZnO treatments was significantly more available to the plants than that from the other carriers. Interaction between zinc carriers and application rates was also significant. Plant concentrations of zinc from Zn-EDTA treatments were still significantly highest at 2 and 4 ppm application rates.

Plant zinc uptake [Tables 17 and 18] significantly increased with zinc treatments and both zinc application rates and carriers produced significant effects. Interaction was also significant. The 8 ppm rate still produced the highest zinc uptake, an effect similar to that reported for plant zinc concentrations. A similar trend in carrier effect to that of plant zinc concentrations was noted.

Plant heights [Table 19] were significantly increased by zinc treatments. These data contrast to results obtained in the growth chamber study. The difference in response may be attributable to the longer growth

Table 16. Residual effects of zinc treatments on plant zinc concentrations (ppm). Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	30.0	33.8	37.8	33.9
$ZnSO_4$	31.7	35.8	40.6	36.0
ZnO	33.1	34.6	38.1	35.2
Zn-EDTA	42.5	59.2	66.7	56.1
Zn Frit 197	33.7	43.3	49.3	42.1
Zn Frit 247-G	29.0	30.3	34.7	31.3
Urea-ZnO	39.2	49.6	73.1	54.0
Rate Means	34.2	40.9	48.6	

$LSD_{.05}$ Treatments = 7.5

$LSD_{.05}$ Rates = 2.9

$LSD_{.05}$ Carriers = 4.4

$LSD_{.05}$ Interaction = 7.6

Control 26.9

Table 17. Effects of zinc treatments on zinc uptake (μg) by plant tops. Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	35.3	33.3	48.8	39.1
$ZnSO_4$	33.0	41.0	47.1	40.4
ZnO	35.2	36.3	42.1	37.9
Zn-EDTA	62.3	62.6	83.4	69.4
Zn Frit 197	33.4	42.5	56.6	44.2
Zn Frit 247-G	30.0	29.4	32.6	30.7
Urea-ZnO	50.2	53.3	79.1	60.8
Rate Means	40.0	42.6	55.7	

$LSD_{.05}$ Treatments = 9.2

$LSD_{.05}$ Rates = 3.8

$LSD_{.05}$ Carriers = 5.8

$LSD_{.05}$ Interaction = 10.0

Control 27.2

Table 18. Residual effects of zinc treatments on zinc uptake (μg) by plant tops. Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	26.1	27.7	32.6	28.8
$ZnSO_4$	27.3	27.3	33.8	29.5
ZnO	29.1	30.7	32.0	30.6
Zn-EDTA	36.0	51.6	56.0	47.9
Zn Frit 197	27.1	33.2	41.5	34.0
Zn Frit 247-G	27.5	26.0	26.5	26.7
Urea-ZnO	35.3	48.3	62.7	48.7
Rate Means	29.8	35.0	40.7	

$LSD_{.05}$ Treatments = 9.4

$LSD_{.05}$ Rates = 3.6

$LSD_{.05}$ Carriers = 5.5

$LSD_{.05}$ Interaction = 9.5

Control 20.4

Table 19. Effects of zinc treatments on plant heights (cm). Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	9.6	15.4	10.1	11.7
$ZnSO_4$	9.6	10.2	9.5	9.7
ZnO	9.2	9.9	9.4	9.5
Zn-EDTA	9.6	8.8	9.7	9.4
Zn Frit 197	10.1	9.4	9.4	9.6
Zn Frit 247-G	8.8	9.0	9.2	9.0
Urea-ZnO	9.9	9.0	8.8	9.3
Rate Means	9.5	10.2	9.4	

$LSD_{.05}$ Treatments = 4.4

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 2.0

Control 4.7

period (28 days) used for the greenhouse study. Zinc carriers, but not application rates, affected plant heights, Zn-NH_3 producing the tallest plants.

Plant dry weights [Tables 20 and 21] were increased by zinc treatments but the increase was not significant statistically. Zinc carriers, but not rates, had significant effects on plant dry weights. Zn-NH_3 was the most effective material.

Plant phosphorus concentrations were not significantly increased by zinc treatments [Table 22, Fig. 6]. Zinc carriers, but not application rates, had significant effects on P concentrations. Plant P concentrations recorded for this study were generally higher than those observed in the growth chamber study. This may be due to the higher P content of the soil used for this study than that used for the growth chamber study.

The residual effects of the zinc treatments on plant P concentrations also indicated equal P concentrations of the control pots with the zinc treated pots [Table 23, Fig. 7]. Within the zinc treatments, both zinc application rates and zinc carriers affected P concentrations. Overall effects of the zinc application rates revealed the 4 ppm rate to be significantly higher in plant P concentrations than the 8 ppm Zn rate but not the 2 ppm Zn rate. These data further suggest that P uptake may not be depressed as much by Zn in soybean as has been observed in other crops such as corn.

<u>Field Study</u>

Soil characteristics used for this study are available in Table 1.

Plants in the control plots exhibited conspicuous inter-veinal chlorosis of young trifoliate leaves about 8 weeks after germination. Those plants were generally shorter than those receiving zinc treatments.

Table 20. Influence of zinc treatments on dry weights (gm) of plant tops. Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	1.32	1.23	1.28	1.28
$ZnSO_4$	1.17	1.26	1.22	1.22
ZnO	1.26	1.23	1.16	1.22
Zn-EDTA	1.26	1.12	1.21	1.20
Zn Frit 197	1.26	1.18	1.17	1.20
Zn Frit 247-G	1.14	1.20	1.16	1.17
Urea-ZnO	1.28	1.15	1.12	1.19
Rate Means	1.24	1.19	1.19	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 0.10

Control 1.16

Table 21. Residual effects of zinc treatments on dry weights (gm) of plant tops. Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn-NH_3$	0.87	0.81	0.86	0.87
$ZnSO_4$	0.88	0.77	0.84	0.83
ZnO	0.87	0.89	0.84	0.87
Zn-EDTA	0.85	0.87	0.84	0.86
Zn Frit 197	0.81	0.77	0.84	0.81
Zn Frit 247-G	0.95	0.86	0.76	0.86
Urea-ZnO	0.90	0.97	0.85	0.91
Rate Means	0.87	0.85	0.84	

$LSD_{.05}$ Treatments = 0.17

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 0.75

Table 22. Influence of zinc treatments on plant phosphorus concentrations (ppm). Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	1227	1266	1266	1253
$ZnSO_4$	1306	1424	1385	1372
ZnO	1425	949	1266	1213
Zn-EDTA	1227	1266	1424	1332
Zn Frit 197	1147	1148	1187	1160
Zn Frit 247-G	1148	1148	1345	1213
Urea-ZnO	1108	1108	1148	1121
Rate Means	1238	1187	1289	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 192

Control 1066

Table 23. Residual effects of zinc treatments on plant phosphorus concentrations (ppm). Greenhouse Study.

Zinc carriers	Application rates (ppm Zn)			Carrier Means
	2	4	8	
$Zn\text{-}NH_3$	1795	1923	1667	1795
$ZnSO_4$	1795	1753	1453	1667
ZnO	1710	1538	1881	1710
Zn-EDTA	2052	1881	1624	1852
Zn Frit 197	1496	1667	1538	1566
Zn Frit 247-G	1623	1710	1154	1496
Urea-ZnO	1538	1709	1453	1567
Rate Means	1716	1740	1538	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 196

$LSD_{.05}$ Carriers = 299

Control 1795

Fig. 6 Influence of zinc treatments on plant P concentrations (ppm).

$LSD_{.05}$ Treatments NS
Rates NS
Carriers = 192

Fig. 7 Residual effects of zinc treatments on plant P concentrations (ppm).

$LSD_{.05}$ Treatments NS
Rates = 196
Carriers = 299

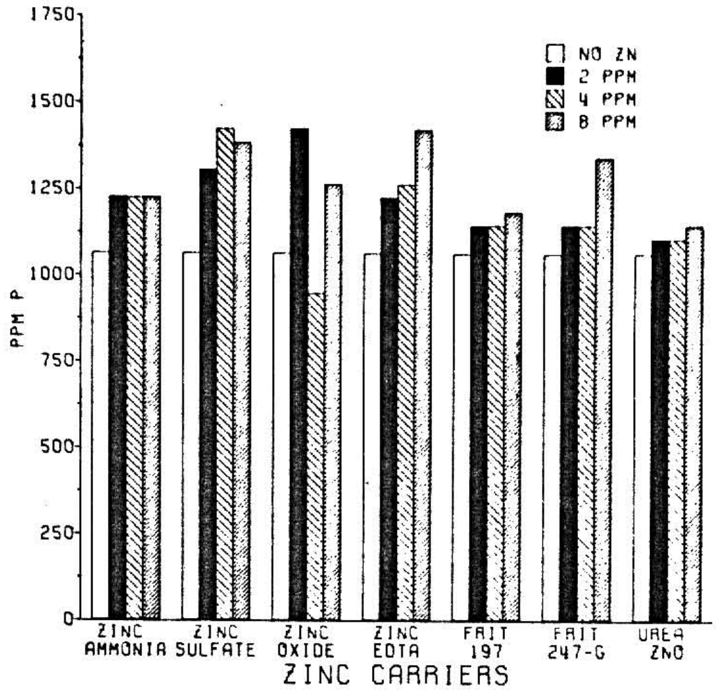

Figure 6

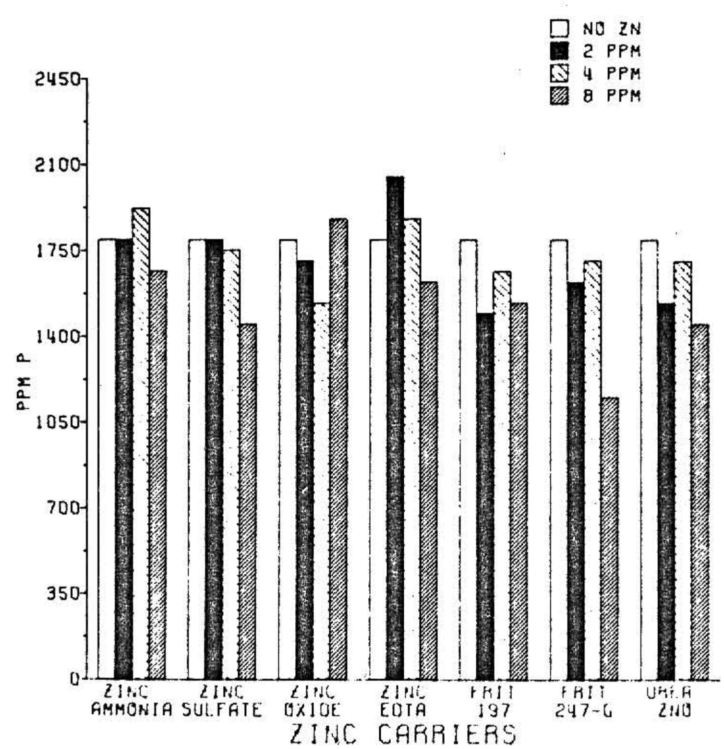

Figure 7

Zinc deficiency symptoms became more severe as maturity progressed. These characteristics are opposite to those usually observed for corn in which zinc deficiency symptoms decrease in severity as maturity progresses. Satisfactory plant growth was observed on the Zn treated plots. Visual observations (not statistically rated) indicated that Zn-EDTA, SW-1, $ZnSO_4$ and $Zn\text{-}NH_3$ materials produced generally taller plants with dark green leaves.

Plant zinc concentrations at the first sampling date increased with zinc treatments [Table 24, Fig. 8]. A general increase in plant zinc concentrations was recorded with increasing rates of zinc application. The 9.0 kg Zn/ha rate was significantly more effective than the 2.2 kg Zn/ha, but equally effective with the 4.5 kg Zn/ha rate. The latter rate did not significantly increase plant zinc concentrations above the lowest rate.

Zn-EDTA was the most efficient source at 9.0 kg Zn/ha. Urea-ZnO and $ZnSO_4$ treatments produced the lowest zinc concentrations at that sampling stage. Overall performance of the zinc carriers on plant zinc concentrations at the first sampling ranked Zn-EDTA as the most efficient zinc carrier.

As plant maturity progressed to the early pod stage, plant zinc concentrations in soybeans generally increased. This is in agreement with the observation that zinc concentration in soybean leaves increases slightly from emergence to maturity [Jones and Mederski, 1964]. This situation is opposite of that observed for corn in which zinc decreases with maturity [Gorsline et al., 1965]. Similar trends in plant zinc concentrations comparable to the first sampling [Table 25, Fig. 9] were observed. The highest rate of zinc application produced significantly higher concentrations than did the lowest rate but not significantly higher

Table 24. Effects of zinc treatments on plant zinc concentrations (ppm). 9 July 1974.

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	10.6	11.4	18.8	13.6
ZnO	21.2	22.1	19.5	20.9
Zn-EDTA	19.8	26.2	44.0	30.0
$Zn\text{-}NH_3$	17.5	17.3	22.1	19.0
SW-1	20.5	17.0	17.3	18.3
Urea-ZnO	9.8	10.8	16.2	12.3
Frit 247-G	11.7	21.8	20.7	18.1
Rate Means	15.9	18.1	22.7	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 4.7

$LSD_{.05}$ Carriers = 7.1

Control 7.8

Table 25. Effects of zinc treatments on plant zinc concentrations (ppm). 7 August 1974.

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	21.1	21.6	40.7	27.8
ZnO	28.2	26.5	29.5	28.1
Zn-EDTA	28.1	41.0	40.5	36.5
$Zn\text{-}NH_3$	32.0	35.0	31.1	32.7
SW-1	28.1	28.0	32.7	29.6
Urea-ZnO	17.0	19.3	21.6	19.3
Frit 247-G	18.6	16.0	19.8	18.2
Rate Means	24.7	26.8	30.8	

$LSD_{.05}$ Treatments = 10.0

$LSD_{.05}$ Rates = 3.9

$LSD_{.05}$ Carriers = 5.9

Control 10.8

Fig. 8 Effects of zinc treatments on plant zinc concentrations (ppm). 9 July 1974.

$LSD_{.05}$		
Treatments		NS
Rates	=	4.7
Carriers	=	7.1

Fig. 9 Effects of zinc treatments on plant zinc concentrations (ppm). 7 August 1974.

$LSD_{.05}$		
Treatments	=	10
Rates	=	3.9
Carriers	=	5.9

Fig. 10 Effects of zinc treatments on seed yield (kg/ha).

$LSD_{.05}$		
Treatments	=	782
Rates		NS
Carriers	=	466

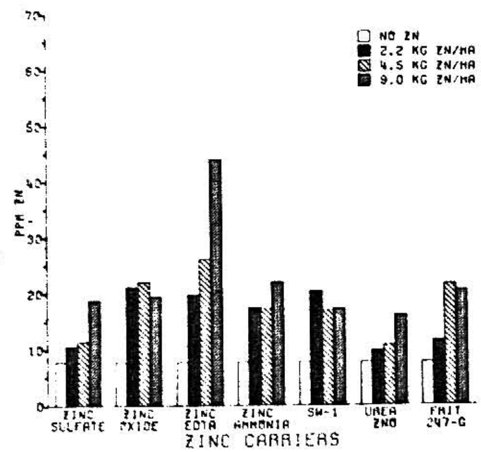

Figure 8

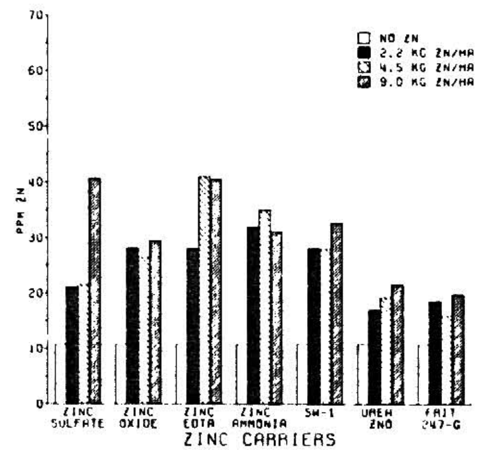

Figure 9

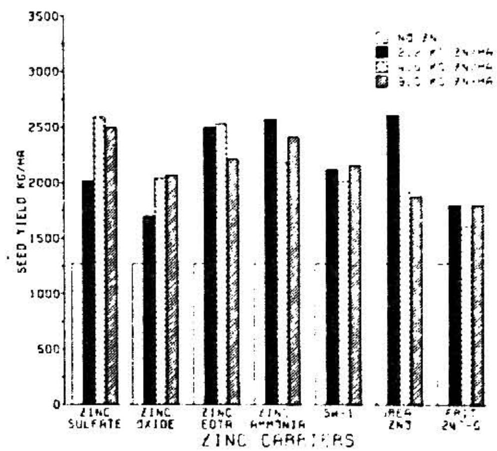

Figure 10

than the 4.5 kg Zn/ha rate. Zn-EDTA and $ZnSO_4$ produced significantly higher concentrations than the other carriers except SW-1 at 9.0 kg Zn/ha. At 4.5 kg Zn/ha, Zn-EDTA remained the most efficient zinc carrier. Comparative overall effects of the zinc carriers on plant zinc concentrations indicated Zn-EDTA and Zn-NH_3 to be the most efficient carriers. The poorest performances were recorded for urea-ZnO and Frit 247-G, both applied as granular materials.

Trends similar to those recorded for plant zinc concentrations were noted for plant zinc uptake [Tables 26 and 27]. Despite this similarity observed on the field, results of both growth chamber and greenhouse studies have suggested inadequcy of one measurement alone [plant concentration or uptake] in drawing conclusions about Zn nutrition of soybeans.

The outstanding performance of Zn-EDTA in the growth chamber, greenhouse, and field studies in increasing plant zinc concentrations may be attributable to an increase in diffusion of soil zinc by addition of EDTA. Zn-EDTA is readily soluble thus increasing the concentration gradient of diffusable zinc [Elgawhary et al., 1970]. Although a negative correlation is reported to exist between diffisuion of zinc and soil pH [Clark and Graham, 1968], the general performance of the zinc carriers on the soils used for the study [pH 7.4 for the growth chamber study and 7.1 for the field study] can be considered satisfactory in terms of plant uptake of zinc.

More zinc was absorbed by the plants from the field soil used in the greenhouse study [pH 7.1] than was the case in the growth chamber study [pH 7.4]. Considering the overall effects of zinc application rates on plant zinc concentrations and uptake in both the growth chamber and greenhouse studies, the superiority of the highest rate of zinc application in

Table 26. Effects of zinc treatments on plant zinc uptake (μg) by twelve trifoliates. 9 July 1974.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	45.6	61.9	88.3	65.3
ZnO	85.9	86.4	82.2	84.8
Zn-EDTA	105.1	96.2	199.8	133.7
$Zn\text{-}NH_3$	71.0	99.2	112.7	94.3
SW-1	94.3	79.0	81.8	85.0
Urea-ZnO	38.6	43.0	67.8	49.8
Frit 247-G	52.4	97.7	85.1	78.4
Rate Means	70.4	80.5	102.5	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 22.1

$LSD_{.05}$ Carriers = 33.8

Control 41.8

Table 27. Effects of zinc treatments on plant zinc uptake (μg) by twelve trifoliates. 7 August 1974.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	137.7	160.7	313.5	204.0
ZnO	218.4	215.1	178.3	203.9
Zn-EDTA	231.5	272.6	265.9	256.7
$Zn\text{-}NH_3$	221.2	270.1	217.4	236.2
SW-1	180.8	189.2	212.0	194.0
Urea-ZnO	123.1	123.2	138.7	128.3
Frit 247-G	117.4	105.9	125.2	116.2
Rate Means	175.7	191.0	207.3	

$LSD_{.05}$ Treatments = 88.5

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 52.1

Control 77.5

increasing plant zinc concentrations may be attributed to availability of an adequate supply to the plants over the amount lost through possible formation of precipitates [e.g. $Zn(OH)_2$ and $CaZn(OH)_4$] of low solubility [Clark and Graham, 1968].

Trifoliate dry weights in the field [Tables 28 and 29] were not significantly increased by zinc application. Within the treatments, neither zinc application rates or zinc carriers had significant effects on trifoliate dry weights.

Differences in plant P concentrations were observed at the two sampling stages. Plant P concentrations at both the early bloom and early pod stages were not significantly higher in the zinc treated plots [Fig. 11]. At the early bloom stage, both zinc carriers and zinc application rates did not produce significant differences in plant P concentrations [Table 30].

During the early pod stage plant P concentrations were significantly increased by rates of zinc application but not by zinc carriers [Fig. 12]. Overall effects of the zinc treatment rates on plant P concentrations showed 9.0 kg Zn/ha to have produced significantly lower P levels than the other two rates [Table 31]. Although 4.5 kg Zn/ha produced higher plant P concentrations than the 2.2 kg Zn/ha, the difference was not statistically significant. These results showed that plant P concentrations increased from the 2.2 kg Zn/ha rate to the 4.5 kg Zn/ha rate and declined at the 9.0 kg Zn/ha. This type of response suggests that zinc may enhance P uptake to a point beyond which any further increase in zinc application decreases P uptake. The reverse nutrient relationship may be the case when rates of P application are varied.

Zinc carriers effects were equal on plant P concentrations [Tables 30 and 31].

Table 28. Dry weights (gm) of twelve trifoliates as affected by zinc treatments. 9 July 1974.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	4.35	5.40	4.83	4.86
ZnO	4.03	4.16	4.20	4.13
Zn-EDTA	4.79	3.75	4.53	4.36
$Zn\text{-}NH_3$	3.88	5.77	5.24	4.96
SW-1	4.32	4.96	4.73	4.67
Urea-ZnO	3.97	4.12	4.28	4.12
Frit 247-G	4.69	4.52	4.65	4.62
Rate Means	4.29	4.67	4.64	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 5.48

Table 29. Dry weights (gm) of twelve trifoliates as affected by zinc treatments. 7 August 1974.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	6.60	7.40	7.66	7.22
ZnO	7.79	8.16	6.01	7.32
Zn-EDTA	8.17	6.69	6.42	7.10
$Zn\text{-}NH_3$	6.73	7.66	6.82	7.07
SW-1	6.50	6.80	6.60	6.64
Urea-ZnO	7.27	6.79	6.49	6.85
Frit 247-G	6.35	6.54	6.24	6.38
Rate Means	7.06	7.15	6.61	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Sources NS

Control 7.20

Table 30. Effects of zinc treatments on plant phosphorus concentrations (ppm). 9 July 1974.

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	2003	2104	1719	1941
ZnO	1942	1922	1739	1868
Zn-EDTA	1821	1497	1659	1659
$Zn\text{-}NH_3$	1902	1861	1861	1875
SW-1	1821	1962	1841	1875
Urea-ZnO	2063	1639	1800	1834
Frit 247-G	1507	1871	1760	1713
Rate Means	1865	1837	1769	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers NS

Control 2185

Table 31. Effects of zinc treatments on plant phosphorus concentrations (ppm). 7 August 1974.

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	2003	2130	1815	2049
ZnO	1283	2082	1825	1730
Zn-EDTA	1482	1912	1646	1680
$Zn\text{-}NH_3$	2517	2178	1573	2090
SW-1	2469	2445	1791	2235
Urea-ZnO	2420	2130	1404	1985
Frit 247-G	2178	2130	1568	1959
Rate Means	2079	2144	1660	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates = 366.0

$LSD_{.05}$ Carriers NS

Control 1985

Fig. 11 Effects of zinc treatments on plant P concentrations (ppm). 9 July 1974.

$LSD_{.05}$	Treatments	NS
	Rates	NS
	Carriers	NS

Fig. 12 Effects of zinc treatments on plant P concentrations (ppm). 7 August 1974.

$LSD_{.05}$	Treatments	NS
	Rates	= 366.0
	Carriers	NS

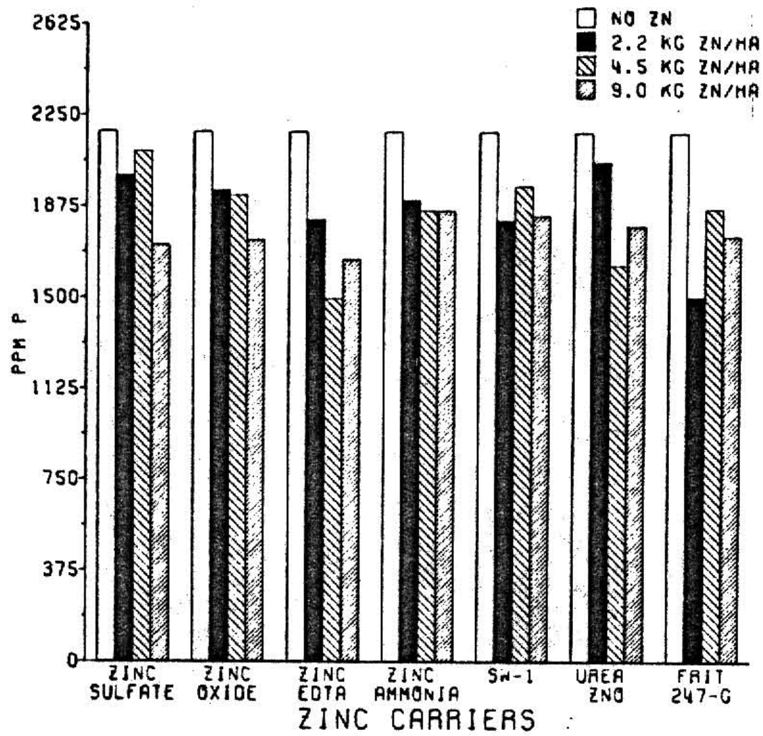

Figure 11

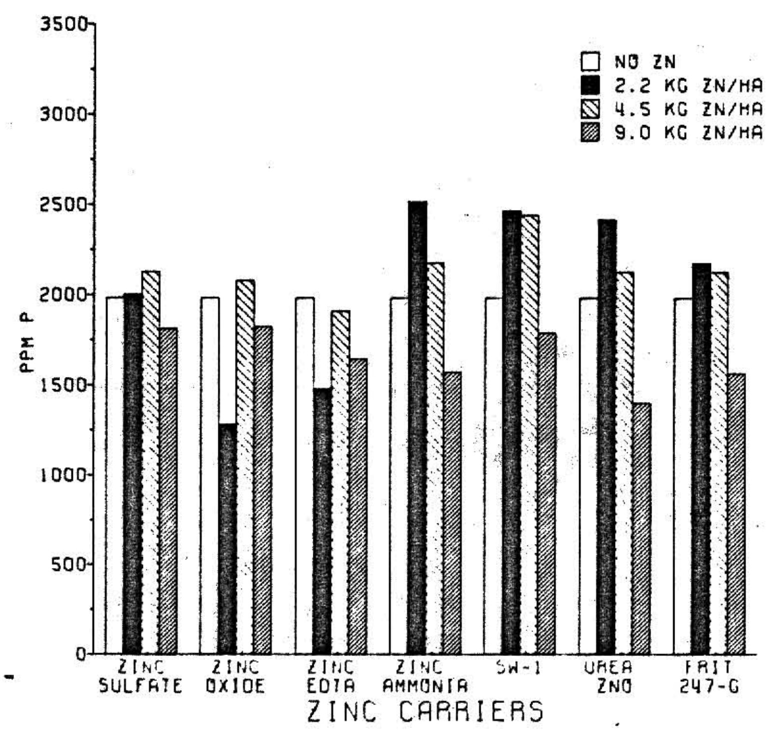

Figure 12

Soybean seed zinc concentrations [Table 32] were significantly influenced by both zinc carriers and application rates. Beans from the treated plots contained much higher zinc concentrations than those from the control plots. The 9.0 kg Zn/ha rate was more effective than the 2.2 kg Zn/ha but equal to the 4.5 kg Zn/ha rate in increasing zinc concentration. Zn-EDTA was significantly more efficient in this regard than $ZnSO_4$, urea-ZnO and Frit 247-G.

Zinc in bean seeds has been reported to be readily translocated [Bukovac and Riga, 1962] and the high concentrations or large reserves of this element in bean seeds enable emerging bean seedlings to better withstand some degree of zinc deficiency than some other crop seedlings. Therefore, in border-line zinc deficiency situations, bean seedlings may be able to perform better than some other crop seedlings, notably corn.

Phosphorus concentrations in the soybean seeds [Table 33] were not significantly affected by rates of zinc application. Soybean seeds from the control plots contained less P than those from the zinc treated plots but the difference was not statistically significant. Zinc carriers significantly affected P concentrations in soybean seeds. ZnO treatments induced significantly higher soybean seed P concentrations than those treated with SW-1, $Zn\text{-}NH_3$ and Frit 247-G at 9.0 kg Zn/ha. $ZnSO_4$ treated plots produced significantly higher soybean seed P concentrations than those treated with SW-1, Frit 247-G, $Zn\text{-}NH_3$, Zn-EDTA and ZnO at 4.5 kg Zn/ha.

A generally negative relationship was noted between soybean seed Zn and P concentrations. This was more prominent in the zinc carrier effect. Soybean seeds from Zn-EDTA treated plots contained the highest overall average Zn concentrations but these seeds contained the least overall

Table 32. Influence of zinc treatments on zinc concentrations (ppm) in soybean seed.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	34.2	33.4	42.8	36.8
ZnO	39.9	38.0	38.5	38.8
Zn-EDTA	40.5	39.0	51.4	43.6
$Zn\text{-}NH_3$	41.3	40.9	36.5	39.6
SW-1	38.6	34.9	42.2	38.5
Urea-ZnO	30.2	33.0	33.0	32.1
Frit 247-G	29.5	30.4	34.4	31.4
Rate Means	36.3	35.7	39.8	

$LSD_{.05}$ Treatments = 9.1

$LSD_{.05}$ Rates = 3.5

$LSD_{.05}$ Carriers = 5.3

Control 19.8

Table 33. Influence of zinc treatments on phosphorus concentrations (ppm) in soybean seed.

Zinc carriers	Application rates (kg Zn/ha) 2.2	4.5	9.0	Carrier Means
$ZnSO_4$	3962	4110	3704	3925
ZnO	3962	3666	4037	3888
Zn-EDTA	3407	3480	3555	3481
$Zn\text{-}NH_3$	3666	3592	3444	3567
SW-1	3444	3259	3332	3345
Urea-ZnO	3999	4073	3777	3950
Frit 247-G	3888	3592	3518	3666
Rate Means	3761	3682	3624	

$LSD_{.05}$ Treatments NS

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 484

Control 3444

Table 34. Effects of zinc treatments on seed yield (kg/ha).

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	2018	2594	2498	2370
ZnO	1700	2043	2070	1938
Zn-EDTA	2495	2529	2215	2413
$Zn-NH_3$	2565	2182	2408	2385
SW-1	2117	2012	2153	2094
Urea-ZnO	2607	1917	1873	2132
Frit 247-G	1799	1608	1797	1734
Rate Means	2186	2126	2145	

$LSD_{.05}$ Treatments = 799

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 466

Control 1272

Table 35. Comparison of the effects of 5 zinc carriers, applied as a fluid suspension, on soybean seed yield (kg/ha).

Zinc carriers	Application rates (kg Zn/ha)			Carrier Means
	2.2	4.5	9.0	
$ZnSO_4$	2018	2594	2498	2370
ZnO	1700	2043	2070	1938
Zn-EDTA	2495	2529	2215	2413
$Zn-NH_3$	2565	2182	2408	2385
SW-1	2117	2012	2153	2094
Rate Means	2179	2272	2269	

$LSD_{.05}$ Treatments = 782

$LSD_{.05}$ Rates NS

$LSD_{.05}$ Carriers = 460

Control 1272

average P concentrations. This is further evidence of the existence of a negative correlation between the two elements.

Application of zinc significantly increased seed yield [Tables 34 and 35, Fig. 10]. Although application of 2.2 kg Zn/ha produced the highest overall average seed yield, this rate was not significantly different from the other two rates.

The type of zinc carrier used also affected soybean seed yield. Zn-EDTA was significantly more efficient in this respect than ZnO and Frit 247-G. $ZnSO_4$ was significantly better than Frit 247-G. Differences in seed yield between Zn-EDTA, $ZnSO_4$, Zn-NH_3, SW-1, and urea-ZnO treatments were non-significant.

It is rather interesting to note the existence of a positive relationship between plant concentrations of zinc and seed yield. Except for urea-ZnO, seed yield was noticeably commensurate with plant zinc concentrations. The seed yield for this treatment [urea-ZnO] was much higher than expected for the plant zinc concentrations as compared with other zinc carriers. This effect may be due to the slow release of the nitrogen content of urea-ZnO.

CONCLUSIONS

The significant increases in plant concentrations of Zn, P and uptake of Zn as a result of applied Zn rates provide further evidence that soybeans will respond to zinc fertilization.

Except in the growth chamber study where Zn-EDTA showed equal performance with $ZnSO_4$, overall effects of zinc carriers on plant zinc concentrations or uptake ranked Zn-EDTA as the most efficient source of zinc at either 2 ppm or 4 ppm Zn rates. At 4.5 kg Zn/ha application rate in the field, Zn-EDTA was 1.9, 1.5 and 1.2 times more efficient than $ZnSO_4$, ZnO, and Zn-NH_3 respectively in increasing plant Zn concentrations.

Variations in zinc application rates from 2.2 to 9.0 kg Zn/ha did not significantly increase seed yield in the field although yield increases over the control were highly significant.

Differences in zinc carriers significantly affected soybean seed yield. Overall performance of the zinc carriers revealed Zn-EDTA to be significantly more efficient (1.3 times) than Frit 247-G with other carriers being generally comparable. Zn-EDTA was, on the average, 1.11 times better than the other zinc carriers [ZnO, $ZnSO_4$, $ZnNH_3$, SW-1 and urea-ZnO].

The poorest performances among the zinc carriers were recorded for Frit 247-G and urea-ZnO which were applied in granular form (others in liquid form). This suggests that particle size is important in zinc application. The fact that smaller particle size favors Zn availability was demonstrated in the acceptable performance of Frit 197 in the greenhouse.

Application of zinc should improve the nutritive value of soybean seeds as the effects of zinc rate on seed concentrations of zinc and P were significant at the 5% probability level. However, the net value of this effect can only be real if other nutritive components such as proteins, amino acids, Ca and Fe are evaluated simultaneously. The high Zn concentrations observed in soybean seeds may enable emerging seedlings to better withstand some degree of zinc deficiency than some other crop seedlings [corn, grain sorghum].

Plant zinc concentrations increased with advancing plant maturity. This illustrates the influence of the time of sampling on relative plant zinc concentrations and suggests that the greatest treatment effects may be determined with late season sampling.

The non-significant effect of zinc treatments on plant P, Fe and K concentrations emphasizes the need for care in making generalizations about nutrient interactions in plants. Other studies have shown strong P-Zn relationships in corn but such a relationship does not seem to be so strong in soybeans. Zinc application generally did not depress P concentrations.

On the basis of the overall performance of the zinc carriers and application rates in increasing plant zinc concentrations, zinc uptake, and seed yield, it is evident that an application of 2.2-4.5 kg Zn/ha as several different carriers will promote the production of a good crop of soybeans. Zn-EDTA was usually the more efficient source of Zn. However, the relatively higher cost of chelates and the non-comparable performance of the inorganics should be a factor in considering a source of zinc for use on a large scale.

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APPENDIX

Zinc determination in plant material by Atomic Absorption Spectrophotometer.

The sensitivity of the determination is about 0.04 ppm per 1% absorption. The sensitivity for zinc can be increased about two times by using a low-temperature flame.

Reagents:

Nitric acid

Zinc of high purity

Double distilled water

Standard solutions:

Stock zinc solution: Dissolve 0.50 grams of high purity zinc in 100 ml. nitric acid (1 - 1). Cool and dilute to one liter. This provides a stock zinc solution containing 500 mg Zn/ml.

Zinc standards: Prepare four 25-ml. standard solutions containing 1.0, 2.0, 3.0, and 5.0 ppm of zinc by diluting the stock solution as required.

Operating condition:

Wavelength 215 mμ

Range UV

Slit 5 (3mm, 20A)

Source 10 ma, hollow cathode

Burner Perkin-Elmer premix

Air-pressure 20-30 psi; flow 2-6 on flow meter

Auxiliary Air: Increase air flow to 9.0 on flow meter by setting the air needle valve

Fuel Acetylene pressure 8 psi; flow 5.0 on flow meter

Flame Clear and non-luminescent

Sample uptake rate 2-5 ml./minute

Procedure:

Follow routine procedure using SCALE control at setting that includes analytical absorption range.

Plot absorption vs. concentration for working curve.

Determine the sample concentration.

Note:

Allow the lamp to warm up for twenty minutes at a current of 10 ma, then optimize the lamp current by adjusting the SOURCE.

Control to obtain a noise level of one to two divisions on the NULL meter.

Blank solution is required for setting zero percent absorption.

It is necessary to determine the working curve with at least three standards. The working curve must be prepared for every group of samples.

Data calculated by converting percent absorption to absorbance and reading sample values from the working curve drown with standard values. Parts per million were calculated based on dry weight of the samples.

Determination of Phosphorus in plant materials by the Vanadomolybdophosphoric yellow color method in Nitric Acid System.

The determination of phosphorus is based on the vanadomolybdophosphoric yellow color method in nitric acid system [M. L. Jackson, p. 151, Method V]. The only modification being that 200 ml of the vanadomolybdate reagent was premixed with 600-ml deionized distilled water giving a 2/6 ratio. This is used to make 2 ml sample to volume in a 10-ml volumetric flask.

The color thus formed is a measure of the amount of phosphomolybdic acid formed and hence of the concentration of phosphate ion originally present in the samples.

Reagents:

1. Add 600 ml deionized distilled water to 200 ml of a HNO_3 - Vanadate - molybdate solution (see Jackson) = 2/6 vanadate solution.

Glasswares needed:

1. 10-ml volumetric flasks
2. 2-ml volumetric pipets
3. Polyethylene wash bottle for 2/6 vanadate solution.

Standard curve preparation:

1. Measured amounts (1, 2, 4, 6 and 8 ml from a 20 ppm phosphorus stock solution to give a series of 2, 4, 8, 12 and 16 ppm phosphorus) are pipetted into 10-ml volumetric flasks. Two blanks are likewise prepared (2 ml from perchloric ashing blank) and used to zero the Beckman D B spectrophotometer (Crop Physio. Lab.).
2. Add 2-ml of HNO_3-Vanadate-molybdate stock solution and make up to volume with deionized distilled water.

3. Cover with parafilm and shake solution. Full color development takes 10 minutes. Color is stable for 24 hours.

Sample analysis:

1. Pipette out 2 ml from the undiluted sample stock solution into 10-ml volumetric flasks.
2. Make up to volume with 2/6 vanadate solution (use fine tipped wash bottle to deliver solution).
3. Cover with parafilm and shake to mix sample and vanadate solution.
4. Absorbance values are measured at 470 mμ.

EVALUATION OF SEVEN MATERIALS AS SOURCES OF ZINC
FOR SOYBEANS [*Glycine max* (L)]

by

ENOCH ABIODUN SALAKO

B.Sc.(Hon.), Ahmadu Bello University, Zaria, Nigeria, 1971

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agronomy

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1975

Seven zinc sources for soybeans were studied in growth chamber, greenhouse, and field investigations.

Application of zinc significantly increased soybean plant zinc concentrations and uptake under all types of culture conditions.

Zinc treatments had little effect on soybean plant dry weights and heights under controlled conditions.

Overall effects of zinc carriers on plant zinc concentrations or uptake ranked Zn-EDTA as the most efficient source of zinc at either 2 ppm or 4 ppm zinc rates under controlled conditions. At a 4.5 kg Zn/ha application rate in the field, Zn-EDTA was 1.9, 1.5 and 1.2 times more efficient than $ZnSO_4$, ZnO, and Zn-NH_3 respectively.

Soybean plant zinc concentrations in the field samples increased with advancing plant maturity. This illustrates the influence of the time of sampling on relative plant zinc concentrations and suggests that the greatest treatment effects may be determined with late season sampling (early pod set).

Soybean plant nitrogen concentrations were not significantly affected by rates of zinc application but varied between zinc carriers.

Plant P concentrations were not significantly affected by zinc treatments under controlled conditions, but were significantly increased by zinc carriers in the field.

Variations in zinc application rates from 2.2 to 9.0 kg Zn/ha did not significantly increase seed yield in the field although yield increases over the control were highly significant. Differences in zinc carriers significantly affected soybean seed yield. Overall effects of the zinc carriers showed that Zn-EDTA was significantly more efficient [1.3 X], in increasing soybean seed yield compared to Frit 247-G but was only 1.11 [average] times better than the other zinc carriers [ZnO, $ZnSO_4$, Zn-NH_3, urea-ZnO and SW-1].

Results of these investigations indicate that soybeans will respond to zinc fertilization. Zn-EDTA was the most efficient source of zinc but the higher efficiency of Zn-EDTA in these studies was not sufficient to offset the higher cost of the chelate compared to the various inorganic sources. The optimum rate of application of Zn for soybeans apparently falls between 2.2-4.5 kg Zn/ha.