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Title: THE INFLUENCE OF DIMETHYL SULFOXIDE (DMSO) ON GROWTH AND THE UPTAKE OF NUTRITIVE ELEMENTS IN PHASEOLUS VULGARIS L. AND SOLANUM TUBEROSUM L.

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Dimethyl sulfoxide (DMSO), a highly polar solvent synthesized from lignin, has been shown to have significant effects in altering the permeability of human skin. Other investigators have shown this compound to aid in the uptake of various materials when they are applied together to the foliage of higher plants, as well as to increase sprouting of the tubers of Solanum tuberosum when used as a pre-plant immersion treatment.

This study, constituting both greenhouse and field investigations, was aimed at evaluating the effects of DMSO as a soil additive, foliar spray, and pre-plant tuber treatment on growth and the uptake of nutritive elements in the bush bean (Phaseolus vulgaris L.) and the white potato (Solanum tuberosum L.).

The toxicity of DMSO was initially evaluated in both soil and nutrient solution as the growth media. Levels of DMSO in excess of 0.1% were distinctly toxic to both Phaseolus vulgaris and Solanum tuberosum when incorporated with the growth medium. Toxicity patterns resembled that of salt injury in that marginal leaf burning at the higher DMSO concentrations was evident.

As an additive to soils, DMSO at low concentrations (0.01%) was shown to enhance early plant emergence. Increasing the DMSO concentration significantly influenced the uptake of Mn and P by Phaseolus vulgaris and also lowered soil pH. A highly significant negative correlation existed between soil pH and Mn level of the plants. Radioisotope studies with ^{65}Zn and ^{54}Mn supported the hypothesis that the above enhanced uptake of Mn was a soil-mediated effect.

Field studies with Solanum tuberosum showed that foliar sprays of Zn or Zn + Mn in combination with DMSO have beneficial effects on tuber weight at harvest. Ca levels in terminal leaflets were significantly increased following DMSO application. Increasing soil P or P-K levels produced distinct effects on the contents of Ca, P, K, Mg and Zn in the plants. Zn levels were significantly depressed by soil P levels in Phaseolus vulgaris and a significant yield increase followed foliar application of Zn and DMSO to this crop. Such benefits may reflect a correction of a Zn: P imbalance in the plant tissue.

DMSO used as a pre-plant tuber treatment significantly increased

stem number, tuber number, and final tuber yield of Solanum tuberosum. Distinct and practically important changes induced by DMSO treatments, such as translocation of immobile elements (Ca) and influences on auxin level in plants, appear evident.

The Influence of Dimethyl Sulfoxide (DMSO) on Growth and the Uptake of Nutritive Elements in *Phaseolus vulgaris* L. and *Solanum tuberosum* L.

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INTRODUCTION

In recent years, widespread interest has been shown in the biological significance of dimethyl sulfoxide (DMSO) as it relates to many varied applications, particularly in medical science (Herschler and Jacob, 1965). While beneficial medicinal effects of DMSO have and are still being actively investigated, its potential for agricultural use has likewise been demonstrated by numerous workers. Among the more important properties of DMSO in this regard are its ability to readily penetrate biological membranes, to increase the uptake of essential plant nutrients, and to influence the growth habit of crops. Recently, a symposium devoted to the biological actions of DMSO was held (Leake, 1967).

Factors which can alter nutritional level or growth habit of plants are of great potential value in the production of heavily fertilized, high value agronomic and horticultural crops. Of particular interest is the possible correction of nutritional deficiency or imbalance which hinders normal growth. Improved effectiveness of foliar sprays would contribute significantly to both the areas of plant nutrition and plant pathology. Likewise, a change in plant development such as a

stimulation of sprouting, which reportedly occurs with white and sweet potatoes following immersion in DMSO, would provide potential for greater crop yields.

The literature is extensive with regard to trace or micronutrients and their importance to plants. Fortunately, several excellent reviews on this subject (Nicholas, 1961; Schutte, 1964; Comar and Bronner, 1960; Stiles, 1961) are available. The discussion which follows is therefore devoted to an appraisal of research findings relevant to this dissertation.

This study attempts to evaluate certain alterations in growth and changes in elemental composition, particularly zinc (Zn) and manganese (Mn), induced by dimethyl sulfoxide used as a foliar spray. Phosphorus (P) is of concern insofar as it is intimately associated with the physiology of Zn in crops, especially in the white potato. The uses of DMSO as a pre-plant immersion treatment for potato tubers and as a soil amendment are also evaluated. White potato (Solanum tuberosum L.) and bush bean (Phaseolus vulgaris L.) are used as indicator crops.

Dimethyl Sulfoxide (General Background)

Dimethyl sulfoxide ($CH_3-\overset{\overset{O}{\|}}{S}-CH_3$) was first synthesized in Germany in 1867 (Saytzeff, 1867). Commercially, DMSO is now manufactured by using methyl groups available from kraft lignin and is

principally used as a solvent in the production of synthetic fibers (Hearon, 1957). It is a colorless, mobile, highly polar and high boiling liquid that is miscible with water and most common organic solvents such as alcohols, ketones, chlorinated solvents and aromatics (Parker, 1965). Due to its unique properties, some reactions have been observed to be 10^3 to 10^9 times faster in DMSO than in conventional solvents. The sulfoxide linkage in DMSO is effective in complexing many inorganic chemical species. This complexing occurs principally through the oxygen atom (Kharasch and Thyagarajan, 1966). In this regard, if the decrease in the strength of the S=O bond is taken as a measure of the increase in the oxygen-metal bond strength, the following order of binding strength for divalent ions is found: $Zn < Hg < Ni < Mn < Co < Fe < Pb < Cu$ (Selbin, Bull and Holmes, 1961).

Although first synthesized over 100 years ago, interest in DMSO in the last decade has focused on its unique solvent and membrane transport properties (Jacob, Bischel, and Herschler, 1964). While the mechanism still remains unclear, the fact that DMSO has distinct membrane-influencing properties is well substantiated. This property, along with its ability to complex transition metals such as iron, zinc, and manganese, has stimulated great interest in DMSO research in the agricultural sciences.

Penetrant and Transport Properties of DMSO

The effects of DMSO as a carrier of agricultural toxicants first received attention by Norris and Freed (1963) . Subsequent studies showing it to enhance the phytotoxicity of numerous herbicides were conducted by Hart and Hurtt (1967). Garren (1967) has reported on the rapid uptake and distribution of labelled DMSO when applied to leaves and stems of fruit trees. Further, he noted its enhancing effect on phosphorus-32 transport. In this regard, Leonard (1967) has reported that DMSO improves the ability of iron to enter leaves of citrus trees while Malo (1965) has noted that the compound may be helpful in alleviating iron chlorosis in avocados. In the former study with orange and grapefruit trees, DMSO showed a marked ability to carry iron into iron-chlorotic leaves. This was shown by visible greening and a higher chlorophyll level in the leaves when dipped in various iron solutions containing DMSO compared to controls without DMSO. Anderson and Storey (1966) have shown improved zinc nutrition of pecans following DMSO-Zn treatment. Recently, Schmid (1968) has observed that Zn uptake by barley roots, unlike sodium and rubidium uptake, is stimulated by DMSO in concentrations between 1% and 10% by volume. He concludes that DMSO does not particularly change the permeability of the membrane but acts as a poisoning agent. This is based on the observation that Zn and Mn uptake by plant cells

is not impaired by poisoning agents (Schmid, 1968). In this study, Schmid also observed a depression (69%) in respiration of roots when present in a 25% DMSO solution.

From the standpoint of plant pathology, Keil (1966) obtained enhanced control of bacterial spot when DMSO was used in combination with the antibiotic oxytetracycline. He proposed that DMSO increased the penetration and translocation of the active antibiotic. The improved wetting influence and/or the systemic action of fungicides brought about by DMSO thereby improving their effectiveness has been suggested by Bean (1965).

Although being actively investigated, the manner in which DMSO enhances permeability is not fully understood. DMSO appears to be extremely effective in altering the configuration of protein molecules, a change which is reversible after the removal of the DMSO (Rammler and Zaffaroni, 1967). Franz and van Bruggen (1967) have proposed two mechanisms by which DMSO may improve passage through a diffusion barrier. The first relates to hypertonicity which would provide for a nonselective increase in the permeability of the barrier. Since DMSO shows some degree of selectivity, its movement through the membrane in some way influences the movements of other ions and molecules. Consequently, the second mechanism relates to the interaction between the movement of DMSO and the ionic species across the membrane (Franz and van Bruggen, 1967).

DMSO Effects on Plant Growth and Development

Schiuchetti (1967) has noted that growth and alkaloid content of the drug producing plant Datura are enhanced not only by growth regulators applied to DMSO but also by DMSO alone. Other work showed that relatively high DMSO concentrations (5%) completely inhibited tube initiation, stopped tube growth, and suppressed the high respiration associated with pollen tube growth of the lily (Dickinson and Cochran, 1968). The effect of DMSO on respiration appeared indirect such as through an interference with the hydrolysis of ATP to ADP, because uncoupling concentrations of 2, 4-dinitrophenol abolished the inhibition of respiration. Levels of 3% and 4% DMSO have been shown to inhibit nucleic acid synthesis which likewise drastically alters a living system (Hellman, Farrelly, and Martin, 1967).

The effect of DMSO on germination and early growth of seeds has also been investigated. Work by Mussell, Morre, and Green (1967) showed no effect upon germination of ten crop species whose seeds were soaked in DMSO concentrations up to and including 19.5%. Concentrations of 39% and 78% delayed germination and in some cases actually reduced the amount of germination. Other work, however, has shown that the growth of orchid seedlings was significantly accelerated at concentrations of 0.0001% and 0.001% DMSO when used as a preplant seed immersion treatment (Tabler, 1966).

The effect of DMSO on the sprouting of both white and sweet potatoes has recently received attention. Davidson (1967) showed, using cut potato seed pieces treated with 2, 4, 8, 16, and 32% DMSO solutions, that immersion in 4% DMSO for three minutes prior to planting significantly increased the number of stems per plot. In related work, Whatley, Thompson, and Mayes (1968), using three varieties of sweet potatoes, showed accelerated growth of and increased number of sprouts of all three varieties. Evidence from the above two studies indicate that DMSO may break the proximal end dominance of potato tubers or roots. The practical significance of such a finding is evident due to the potential for increased crop yields.

Nutrient Considerations and Related Interactions

Zinc

Among the micronutrients needed for plant growth, Zn is one of the most extensively investigated at the present time. Its importance in plant nutrition, however, has been studied since 1869 (Raulin, 1869). The first paper to show the indispensable role of Zn for higher plants was by Maze (1914). A similar report followed by Sommer and Lipman (1926).

Since Zn is involved in tryptophan synthesis (Nason, 1950), an increased Zn availability and uptake may produce an elevated level of

indole acetic acid, the primary auxin and growth stimulant in plants (Skoog, 1940; Tsui, 1948). In this respect, the role of auxin as the prime inhibitor in apical dominance was earlier shown by Thimann and Skoog (1933).

The stimulation of RNA and protein synthesis by Zn and thus its relation to nitrogen metabolism, has also been shown (Wegener and Romano, 1963). According to Price and Quigley (1966), rates of protein formation may be a "linear function of the Zn content". Lastly, Zn is an essential constituent of a number of other enzyme systems in plants, such as carbonic anhydrase (Wood and Sibly, 1952).

Zinc is considered to be of intermediate mobility in plants (Bukovac and Wittwer, 1957), to be transported predominately as an inorganic cation in the stem exudate (Tiffin, 1967), and to be absorbed by plants by a passive process since respiratory uncoupling agents such as DNP do not depress its uptake (Broda, 1962). The greatest amount of Zn in plant cells is found in the cytoplasmic fraction, not in chloroplasts (Johnson and Schrenk, 1963).

The availability of Zn in soils is commonly very low. When applied to soils, Brown, Krantz and Martin (1962) have shown that Zn is quickly immobilized and not readily available to plants. Soil acidity is important in regulating Zn availability and Wear (1956) has shown that increasing soil pH produces a marked reduction in Zn uptake by plants. Foliar sprays of Zn have proved successful in some cases for

correction of a Zn deficiency (Klostermen and Clagett, 1956). In other cases however, definite Zn deficiencies were not corrected by such a method (Singleton, et al., 1950). Widespread usage of Zn-containing fungicides such as Zineb may inadvertently be meeting the nutritional needs of many crops for this element. For example, foliar sprays of Zineb in citrus have been shown to markedly increase leaf content of Zn (Smith, 1966).

The interaction of Zn, particularly with P in plants is especially noteworthy. The induction of visible Zn deficiency as a result of high levels of soil P has been reported by numerous workers (Burleson, Dacus, and Gerard, 1961; Boawn and Leggett, 1964; Martin, McLean, and Quick, 1965; Burleson and Page, 1967).

Recent studies attempt to relate this antagonism (P-induced Zn deficiency) to a physiological imbalance between P and Zn. Boawn and Brown (1968) showed that P fertilization of both Phaseolus vulgaris and Solanum tuberosum induced visible symptoms of a Zn deficiency as shown through leaf chlorosis and malformation. Of particular interest is the fact that these symptoms were induced without changing either the Zn concentration (ppm) or total Zn accumulation (mg/plant) in the plants. For example, the Zn content of both crops was not changed as the P level was increased from 2.2 to 8.8 ppm in the growth medium. The P level in the plant tissue, however, increased markedly with an increase in solution culture P. As a result, a

pronounced increase in the P/Zn concentration ratio occurred which was associated with the onset of growth malformations.

The specific site of the Zn: P antagonism is still being studied. The effect of P on Zn appears to originate in the roots and alters the translocation of Zn to the upper plant parts (Paulsen and Rotimi, 1968). This observation was made since high P levels affected root content of Zn to a lesser degree than leaf content. If P had induced visible symptoms of Zn deficiency by inhibiting absorption of Zn, root content of Zn likely would have been depressed more than leaf content. Further evidence that the Zn: P interaction problem is not in the soil external to the plant is that high P additions to sand cultures increased the amount of water extractable Zn in the growth medium (Pauli, Ellis, and Moser, 1968). If indeed the P and Zn react together within roots in a manner that reduces the translocation of Zn, corrective foliar applications of Zn would appear as a reasonable measure on crops where the problem exists, such as potatoes.

Important relationships also exist whereby Zn may influence P metabolism. Such a relationship is presented in a review by Paribok and Alekseeva-Popova (1965). A Zn deficiency leads to disturbances in P metabolism, in that exceptionally high accumulations of inorganic P reportedly occur in tissues under conditions of Zn deficiency against a background of a reduced content of organic forms of P. Thus, there is evidence of an inhibition of the esterification of P in the

absence of Zn. Work by Kravitz and Guarino (1958) indicates that the amount of inorganic P in proportion to the amount of organically bound P may have an influence on the Embden-Meyerhof cycle. Since inorganic P inhibits glucose-6-phosphate dehydrogenase (Theorell, 1935), the enzyme that catalyzes the first reaction of the hexose monophosphate shunt pathway, Zn is certainly indirectly related to carbohydrate metabolism.

Manganese

Manganese deficiency is a serious plant nutritional problem in the United States and has been reported from 25 states in one or more crops (Berger, 1962). Levels of soil Mn range from a trace to several thousand pounds per acre, the availability of which is highly correlated with low soil pH (Tisdale and Nelson, 1966).

Higher plants do show however, a marked variation in sensitivity and need for Mn. Maize, for example, first shows toxicity at relatively high concentrations (62.5 ppm), while decreased growth is seen in other crops in the presence of only one ppm of Mn. Surprisingly, dwarf bean plants show normal growth at levels of 536 ppm of Mn (Stiles, 1961).

The essentiality of Mn for plants was first shown by McHargue (1922). In recent years, Mn has been shown to be required in photosynthesis (Kessler, 1955) as evidenced by its participation in the

Hill reaction and its concentration in the chloroplast (Possingham and Spencer, 1962). In addition, Mn has been shown to be responsible for the basic oxidation step of indole acetic acid (IAA) with the production of carbon dioxide (Waygood, Oaks and MacLachlan, 1956).

Like Zn, a Mn: P interaction is also apparent in plant nutrition. In this respect, P has been shown to increase the availability of soil Mn (Mederski and Hoff, 1958). Research with Phaseolus vulgaris has also shown an inhibition of Zn absorption at high Mn levels (Hawf and Schmid, 1967). The distribution of labelled Zn was not altered however, in that the percentage of ^{65}Zn in the root and shoot remained constant at each Mn level.

Correction of Mn deficiency can be effected either by foliar or soil applications of the element. Soil applications of Mn are, however, not entirely successful due to rapid conversion of the applied Mn to forms unavailable to plants (Sherman and Harmer, 1942).

Objectives of the Study

The objectives of this study were to evaluate the effectiveness of dimethyl sulfoxide in altering the growth and elemental composition of the white potato (Solanum tuberosum) and the bush bean (Phaseolus vulgaris).

Among the aspects covered were studies of the toxicity of DMSO on the two crop species, growth and developmental changes produced

by various DMSO treatments, penetrant carrier properties of DMSO for ^{65}Zn and ^{54}Mn and several stable elements, and the modifying influence of DMSO when applied singly and in conjunction with foliar sprays of Zn and Mn on the transport of selected elements within the plant. In addition, the effect of DMSO as a pre-plant immersion treatment on final tuber number and weight of Solanum tuberosum following harvest was evaluated.

Incorporated into the experimental design of the field studies were two soil P levels, over which were superimposed foliar applications of Zn and Mn. This was done in order to observe the possible beneficial effects of the respective foliar treatments on the Zn: P interaction in both Phaseolus vulgaris and Solanum tuberosum.

The ultimate purpose, however, was to ascertain the usefulness of DMSO in promoting beneficial changes in chemical composition and growth of both crop species.

MATERIALS AND METHODS

Greenhouse Studies

DMSO Phytotoxicity (Study I)

During the summer of 1967, preliminary studies were undertaken to evaluate the effects on germination and growth of Phaseolus vulgaris L. (var. Tendercrop) when DMSO is incorporated with the growth medium. The substratum used was a 1:1 mixture (w/w) of Chehalis silty loam soil and washed sand. Prior to use, the mixture was passed through a 1 mm sieve. The chemical characteristics of this growth medium are given in Table 1. Data regarding the mechanical analysis of the Chehalis soil are presented in Table 3. These mechanical analyses were performed by the Pipette method (Kilmer and Alexander, 1949), while chemical analyses were conducted as outlined by Alban and Kellog (1959).

Table 1. Chemical characteristics of the growth medium used in Study I.

Phosphorus	31.4 ppm
Zinc	6.0 ppm
Potassium	0.76 meq/100 g
Magnesium	9.40 meq/100 g
Cation exchange capacity	15.06 meq/100 g
Total nitrogen	0.09 %
Organic matter	1.86 %
pH	6.40

A randomized block design consisting of five replications and five treatments (0%, 0.01%, 0.1%, 0.5%, and 1.0% soil-incorporated DMSO based on dry soil weight) was used. A finely ground 8-24-8 fertilizer was added at a rate equivalent to 2000 pounds per acre and mixed thoroughly with the 2000 grams of soil used per crock in this study. This soil was then placed in glazed clay crocks which were fitted with rubber stoppers to prevent nutrient losses by leaching. Moisture was subsequently maintained at 70% of field capacity on a weight basis. Supplemental light was provided daily by means of a bank of cool-white and Gro-Lux fluorescent lamps to simulate a 14 hour day giving approximately 1000 foot-candles light intensity at the top of the plants. Temperature was maintained at 26°C during the day and 21°C at night.

Ten seeds of Phaseolus vulgaris were planted in each crock on August 1, 1967. Observation and notation was made of percent emergence following which plants were thinned to five per crock and heights periodically measured.

Following harvest of the plants by cutting at the soil level on October 3, 1967, samples were dried at 70°C for 24 hours and dry weights recorded.

Preliminary Observations of the Effects of DMSO on Nutrient Uptake (Study II)

Study II served as a preliminary greenhouse investigation to

evaluate the effects of DMSO when applied at a relatively high level on the uptake of ^{65}Zn and five stable elements (N, P, K, Mn, Zn) by Phaseolus vulgaris following soil incorporation.

In the experiment eight 2-gallon glazed crocks filled with 9000 grams of a soil-sand mixture were used (the chemical characteristics of which were presented in Table 1). Duplicate samples and treatments consisting of a control and ^{65}Zn application with and without soil-incorporated DMSO were used.

Twenty microcuries (μCi) of ^{65}Zn in the chloride form (specific activity: 4.24 mCi ^{65}Zn/mg total Zn) were then added to a volume of DMSO (81.7 ml) which represented 1% DMSO based on soil weight. This combination was then thoroughly mixed with the soil.

To optimize N, P, and K levels, a finely ground 8-16-8 fertilizer was applied to all soils at a rate equivalent to 2000 pounds per acre. Soil moisture, light, and temperature were maintained as in Study I.

Five seeds of Phaseolus vulgaris were planted in each crock on July 14, 1967. At weekly intervals one plant per pot was removed by cutting at the soil level, cotyledons removed, stems washed in distilled water, and the ^{65}Zn activity counted in an Armac large volume liquid scintillation counter (Model 446) coupled to a Packard Tri-Carb scintillation spectrometer (Model 3002). This counting assembly, shown in Figure 1, yielded a counting efficiency of 10%

Figure 1. View of counting assembly used in measuring ^{65}Zn activity in plant samples of Study II.

for ^{65}Zn with a 5% gain and 300-700 window setting.

After being counted in plastic vials, the tissues were dried at 70°C for 24 hours and dry weights recorded. Composited samples (replications I + II) were analyzed for total N, P, K, Mn, and Zn. Total N was determined by Kjeldahl analysis, P by the molybdenum blue method of Fiske and Subbarow (1925) and K, Zn, and Mn by atomic absorption spectrometry.

Effect of DMSO on Nutrient Uptake from Soil by Phaseolus vulgaris (Study III)

To substantiate and further the findings of the above two experiments, Study III was undertaken during the fall of 1967 to evaluate growth and elemental composition of Phaseolus vulgaris as influenced by soil-incorporated DMSO.

Based on the DMSO phytotoxicity information found in Studies I and II, a randomized block design with seven replications and five DMSO concentrations (0%, 0.001%, 0.01%, 0.05%, and 0.1% DMSO based on dry soil weight) was set up under similar conditions as described earlier. Since DMSO proved severely toxic to plant growth when incorporated with soil in excess of 0.1% of the dry soil weight, this concentration of DMSO represented the upper limit used in Study III. Glazed porcelain crocks containing 1400 grams of dry soil-sand mixture (described in Table 1) were used. The sources and rates of nutrient applications are shown in Table 2.

Table 2. Nutrient additions, respective sources, and equivalent rates of application used in Study III.

Nutrient	Equivalent rate of application	Source
Nitrogen (N)	100 pounds N/acre	NH_4NO_3
Phosphorus (P)	200 pounds P_2O_5/acre	KH_2PO_4
Potassium (K)	100 pounds K_2O/acre	K_2SO_4
Magnesium (Mg)	50 pounds MgO/acre	MgO
Calcium (Ca)	1000 pounds $CaCO_3$/acre	$CaCO_3$

On November 13, 1967, three seeds of Phaseolus vulgaris were planted in each crock. Following germination, plants were reduced to one per crock. Light and soil moisture were provided as in Study I. A general view of Study III is shown in Figure 2.

Soil pH determinations were made at harvest by use of a Zeromatic pH meter. These pH values were verified by use of colorimetric indicators (Bromcresol Green, pH 3.8-5.4; Chlorphenol Red, pH 5.2-6.8; Bromthymol Blue, pH 6.0-7.6) on similar soil samples.

At harvest on January 29, 1968, plants were cut at soil level, washed with distilled water, dried at 70°C for 24 hours, weighed, ground, and the foliage and fruit (pods) analyzed separately for Zn, P, and Mn. The methods of analysis were as described under Study II.

Figure 2. View of experimental conditions used in Study III.

Effect of DMSO on the Uptake of ^{65}Zn and ^{54}Mn from Hydroponic Solution (Study IV)

In an attempt to evaluate the influence of DMSO on ^{65}Zn and ^{54}Mn uptake in Solanum tuberosum L. (var. Kennebec), Study IV was undertaken employing nutrient solution cultures. The choice of crop was governed by recent work of Schmid (1968) and the current importance of these elements in potato nutrition.

The experimental design for each study (^{65}Zn and ^{54}Mn applications) consisted of seven replications and five treatments: control, isotope only, isotope + 0.1% DMSO, isotope + 0.01% DMSO, isotope + 0.001% DMSO. The percentage of DMSO was based on the volume of the solution culture (1 liter).

Uniformly sized, whole tubers of Solanum tuberosum were sprouted in vermiculite. Three week old sprouts were removed from the parent tuber and transferred to a complete nutrient solution which consisted of a modified Hoagland's No. 2 solution (Hoagland, 1938) with iron (1 ppm) being supplied as ferric citrate at weekly intervals. One microcurie of ^{65}Zn or ^{54}Mn, both in the chloride form, (Specific activities: ^{65}Zn - 4.3 mCi/mg, ^{54}Mn - carrier free) was combined with the DMSO and brought to a standard volume (2 ml) with distilled water prior to addition to the respective crocks. Preparation of crocks and acrylic holders (described below) consisted of washing with detergent solution, rinsing with 6N HCl and

finally rinsing thoroughly with distilled water.

Plants were grown for three weeks in removable black polyethylene cups which were supported on black acrylic resin squares. These squares (5" x 5") in turn, covered the one liter glazed crock containing the nutrient solutions. Air was continuously and slowly bubbled into the solution. A polyvinylidene chloride resin mesh[1] was attached to the bottom of the cups. Hewitt (1966) has described this means of supporting plants for nutrient solution cultures. To hold the plants erect, Dacron fiber was packed around the potato stems. Other environmental conditions were as discussed for Study I. The experimental arrangement is shown in Figure 3.

Periodically, samples (5 ml) of nutrient solution were removed from the crocks, placed in plastic counting tubes and assayed for ^{65}Zn activity using a 3" x 3" NaI well crystal detector coupled to a two-channel Packard Tri-Carb scintillation spectrometer (Model 3002). In the case of ^{65}Zn, counting to a 1% relative standard deviation was done using a 20% gain and a window setting of 470-600. These conditions yielded a counting efficiency of 11%. For ^{54}Mn, the counting conditions involved the same statistical accuracy as with ^{65}Zn. A 40% gain and a window setting of 740-980 were used, which gave a counting efficiency of 20%.

[1] The mesh is sold under the commercial name "Saran" by National Filter Media Corp., Salt Lake City, Utah.

(a)

(b)

Figure 3. Photographs showing experimental conditions used in Study IV. (a) Overall experimental arrangement. (b) Individual growth container.

After three weeks of growth in the nutrient solutions, the terminal growing tips of the plant shoots were removed, dried at 70°C for 24 hours, weighed, and the isotope activity determined as discussed above. The foliar portions of the plants were also harvested, prepared as above, and dry weights determined.

Effect of DMSO on Tuber Reproduction in Solanum tuberosum (Study V)

During the summer of 1968, a greenhouse study was undertaken to evaluate the effects of immersing whole tubers of Solanum tuberosum (var. Kennebec) in various DMSO solutions prior to planting on the number and weight of tubers produced at harvest.

The experimental design consisted of a randomized block with five replications and eight treatments (control, 0.001%, 0.01%, 0.1%, 0.5%, 1%, and 10% DMSO solutions). Glazed porcelain crocks were filled with 8000 grams of dry soil-sand mixture with the chemical characteristics described in Table 1, which served as the growth medium. Greenhouse conditions and moisture levels were maintained as discussed for Study I.

Whole, uniform Kennebec potato tubers weighing approximately 60 grams each were soaked in the respective DMSO solutions (w/v) for 30 minutes prior to planting (June 11, 1968). A water soak for 30 minutes served as the control. Shoots were thinned to one shoot per crock which was periodically measured during the course of the

study. At harvest (August 28, 1968) the number and weight of tubers were recorded.

Field Studies

Effect of DMSO on Foliar Spray Applications to Solanum tuberosum (Study VI)

Study VI was conducted during the summer of 1968 to evaluate the effectiveness of DMSO applied in conjunction with foliar sprays of Zn and Mn to Solanum tuberosum (var. Norgold Russett). The site of the study was the Horticultural Vegetable Research Farm, Corvallis, Oregon. The soil type was a Chehalis silty loam soil, the physical properties of which are given in Table 3.

The experimental design was a randomized block of six replications and eight treatments conducted at two soil P levels. Individual treatments consisted of 14 foot rows with a three foot distance allowed between each treatment within rows and four feet allowed between rows. The high P plots were prepared by application of a 0-20-0 fertilizer at a rate of 1000 pounds P_2O_5/acre and incorporated with the soil prior to planting. At planting, one band of 10-20-20 fertilizer was applied at a rate of 1500 pounds/acre beneath the seed pieces. The field design along with the ingredients of each treatment is shown in Figure 4.

Treatment Number		Zn	Mn	Replication I	II	III	IV	V	VI
1	- DMSO	0	0						
2		0	+						
3		+	0						
4		+	+						
5	+ DMSO	0	0						
6		0	+						
7		+	0						
8		+	+						
					High		P	Plot	
1	- DMSO	0	0						
2		0	+						
3		+	0						
4		+	+						
5	+ DMSO	0	0						
6		0	+						
7		+	0						
8		+	+						
					Low		P	Plot	

Figure 4. Experimental design used in Study VI showing the field layout. Broken lines represent rows of plants depicting individual treatments (14 feet; 12 parent tubers). The presence or absence of the trace elements (Zn and Mn) in the foliar spray is shown as + or -, respectively.

On May 11, 1968, twelve cut tubers of uniform size which had been allowed to suberize for 24 hours were planted, equally spaced along each 14 foot row which represented an individual treatment. Soil moisture was maintained by use of sprinkler irrigation with weekly application of approximately one and one-half inches of water being made. Applications of water continued throughout the summer unless unwarranted by rainfall and were terminated two weeks prior to harvest.

Soil samples from within and between plant rows from both the high and low P plots were taken for chemical analysis on June 18, 1968. Three representative samples each were taken from the within-row and between-row locations at the two soil P levels. These 12 soil samples were then subjected to soil chemical analysis by methods described by Alban and Kellogg (1959). The results of these chemical tests are shown in Table 3 as averages of the three samples from each location.

Table 3. Chemical and mechanical analyses of the Chehalis silty loam soil samples taken for Study VI. Values represent averages of three samples from each location.

		Chemical Analysis					
Sample Number	Location	pH	P (ppm)	Zn (ppm)	K (meq/ 100 g)	Ca (meq/ 100 g)	Mg (meq/ 100 g)
1	In-Row (High P)	5.0	186,5	12.1	3.45	11.3	6.1
2	Between-Row (High P)	5.4	107.7	8.7	2.02	12.8	6.8
3	In-Row (Low P)	4.9	88.6	10.4	3.27	12.1	5.8
4	Between-Row (Low P)	5.3	54.1	6.4	1.17	12.6	6.5

Mechanical Analysis		
Constituent		Percent of Total
Sand	(2 - 0.05 mm)	8.96
Silt	(0.05 - 0.002 mm)	65.06
Clay	(< 0.002 mm)	25.98

DMSO was applied at a rate of 100 ppm based on greenhouse findings (Mack, 1968), while Zn and Mn were each applied to the plant foliage at a rate of 10 ppm. Three spray applications were made

at a rate of 130 gallons per acre on June 14, 1968, July 3, 1968, and July 29, 1968. A general view of Study VI is given in Figure 5.

On August 6, 1968, samples of terminal foliage (leaflets) were removed from plants at random throughout each treatment, washed in 10^{-3}M EDTA solution, rinsed in distilled water, and then dried at 70^{o}C. Chemical analyses for Ca, Mg, Zn, P, and Mn were then conducted on these samples of potato foliage according to the methods discussed in Study III.

On August 29 and 30, 1968, three representative plants from each treatment were harvested and total tuber weight determined.

Effect of DMSO on Foliar Spray Applications to Phaseolus vulgaris (Study VII)

The experiment was conducted during the summer of 1968 using Phaseolus vulgaris (var. Tendercrop) as the indicator crop. Soil type and experimental conditions were similar to those used in Study VI. The experimental design consisted of a randomized block with six replications, eight treatments, and two soil fertility (P-K) levels. The field design and treatment information are presented in Figure 6.

Treatments consisted of 25 foot rows of plants spaced three feet apart. The differential soil P-K levels were established in 1966 by application of both P and K at rates of either 100 or 1000 pounds per acre of each element as shown in Table 4. In 1968, a uniform nitrogen application was made to all plots at a rate equivalent to 100

Figure 5. View of Study VI showing experimental field conditions and potato growth on July 3, 1968.

pounds per acre. Soil moisture was maintained by sprinkler irrigation as in Study VI.

Treatment Number		Zn	: Mn	Replication I	II	III	IV	V	VI
1	- DMSO	0	0						
2		0	+						
3		+	0						
4		+	+		High	P-K	Plots		
5	+ DMSO	0	0						
6		0	+						
7		+	0						
8		+	+						
1	- DMSO	0	0						
2		0	+						
3		+	0						
4		+	+		Low	P-K	Plots		
5	+ DMSO	0	0						
6		0	+						
7		+	0						
8		+	+						

Figure 6. Experimental design used in Study VII showing the field layout. Broken lines represent rows of plants depicting individual treatments (25 feet; 125 plants). The presence or absence of the trace elements (Zn and Mn) in the foliar spray is shown as + or - respectively.

Soil samples from both the high and low P-K plots were taken for chemical analysis on June 18, 1968. Three representative samples were taken from between the rows from each of the two soil fertility plots. These six soil samples were then dried and subjected to chemical analysis by methods described by Alban and Kellogg (1959).

The results of these tests are presented in Table 4.

Table 4. Chemical analyses of the Chehalis silty loam soil samples taken for Study VII. Values represent averages of three samples from each of the two soil P-K plots.

Number	Treatment	pH	P (ppm)	Zn (ppm)	K (meq/ 100 g	Ca (meq/ 100 g	Mg (meq/ 100 g
1	100 lbs. P - 100 lbs. K plots	5.8	58.7	5.5	0.83	14.3	6.9
2	1000 lbs. P - 1000 lbs. K plots	5.9	129.3	5.4	2.08	14.3	6.6

On June 13, 1968, the beans were planted. They were thinned to 125 plants per treatment in the third week of growth. DMSO was applied at a rate of 100 ppm, while Zn and Mn were applied to the foliage at a rate of 10 ppm. Sprays were applied at a rate of 130 gallons per acre on July 8, 1968 (three leaf stage), and on July 30, 1968 (first pods).

On August 6, 1968, samples of terminal leaves were removed from plants at random in each treatment, washed with 10^{-3} M EDTA solution, rinsed with distilled water, and dried at 70°C. Figure 7 shows the experimental design and plant growth at the time of sampling.

Beans grown on the low fertility plots were harvested on August 8, 1968, while those grown at the higher fertility level were harvested on August 12, 1968. Following harvest, pod weights as

Figure 7. View of Study VII showing experimental field conditions and plant growth on August 6, 1968.

well as size distribution of pods were obtained on composite samples of all six replications from each treatment.

Effect of DMSO on Tuber Reproduction in Solanum tuberosum (Study VIII)

This study, similar to Study V in terms of experimental design, was conducted in the field during the summer of 1968 using Solanum tuberosum (var. Kennebec). Soil type and experimental conditions were similar to those used in Study VI. The experimental design consisted of a randomized block of six replications and two soil P levels. The lower soil P level represents the soil conditions used in Study V. The field design and the treatments used are given in Figure 8.

Individual treatments consisted of 14 foot rows with a three foot spacing allowed between treatments. A four foot spacing between rows was employed. The high soil P plot was prepared by application of 0-20-20 fertilizer at a rate of 1000 pounds P_2O_5 per acre and incorporation into the soil by roto-tilling to a depth of six inches prior to planting. In addition, a 10-20-20 fertilizer was uniformly applied to all treatments at a rate of 1500 pounds per acre and likewise incorporated by roto-tilling to a six inch depth.

On June 12, 1968, small, whole tubers of Solanum tuberosum were soaked in the respective DMSO solutions for 30 minutes, after which 12 tubers were planted with equal spacing in each 14 foot row.

Treatment		Replication					
Number	Percent DMSO	I	II	III	IV	V	VI
1	0.0						
2	.001						
3	.01						
4	.1						
5	.5		High	P	Plots		
6	1.0						
7	5.0						
8	10.0						
1	0.0						
2	.001						
3	.01						
4	.1						
5	.5		Low	P	Plots		
6	1.0						
7	5.0						
8	10.0						

Figure 8. Experimental design used in Study VIII showing the field layout. Broken lines represent rows of plants depicting individual treatments (14 feet; 12 parent tubers). Pre-plant DMSO tuber immersion treatments are shown in the left part of the figure.

On June 18, 1968, soil samples were taken from between the plant rows from both the high and low P plots and subjected to chemical analysis by methods previously described (Alban and Kellogg, 1959). Three representative samples were taken from each of the two soil P plots. The results of the analyses performed on these six soil samples are presented in Table 5.

Table 5. Chemical analyses of the Chehalis silty loam soil samples taken for Study VIII. Values represent averages of three samples from each soil P plot.

Sample Number	Location	pH	P (ppm)	Zn (ppm)	K (meq/ 100 g)	Ca (meq/ 100 g)	Mg (meq/ 100 g)
1	High P plot	5.2	136.8	7.8	1.35	12.0	7.0
2	Low P plot	5.3	64.6	7.5	1.27	13.1	6.7

On September 16, 1968, all plants were sprayed with Dinitro defoliant and all tubers were harvested on September 24, 1968. These tubers were then weighed, their numbers recorded, and their size distribution determined.

RESULTS

Greenhouse Studies

DMSO Phytotoxicity (Study I)

The influence of five levels of soil-incorporated DMSO on percentage emergence of Phaseolus vulgaris is summarized in Table 6 from data found in the Appendix (Table 8). While enhanced emergence is noted at both the 0.01% and 0.1% level of DMSO, higher levels tended to decrease percent emergence.

Table 6. Percentage emergence of Phaseolus vulgaris five days following planting as influenced by five levels of soil-incorporated DMSO. Values represent means of five replications ± one standard deviation based on ten plants per treatment.

	Treatment (% DMSO)			
Control	0.01	0.1	0.5	1.0
84.0 ± 5.5	94.0 ± 5.5	92.0 ± 4.5	84.0 ± 5.5	82.0 ± 4.5

The results of five levels of soil incorporated DMSO on height of Phaseolus vulgaris is shown in Figure 9. The 0.01% level of DMSO markedly increased height of the plants over the controls up to ten days after planting. Subsequently, however, the control plants showed greatest height over all other treatments.

Soil-incorporated levels of DMSO based on 0.5% and 1.0% of the soil weight resulted in reduced vigor and visible deterioration of the

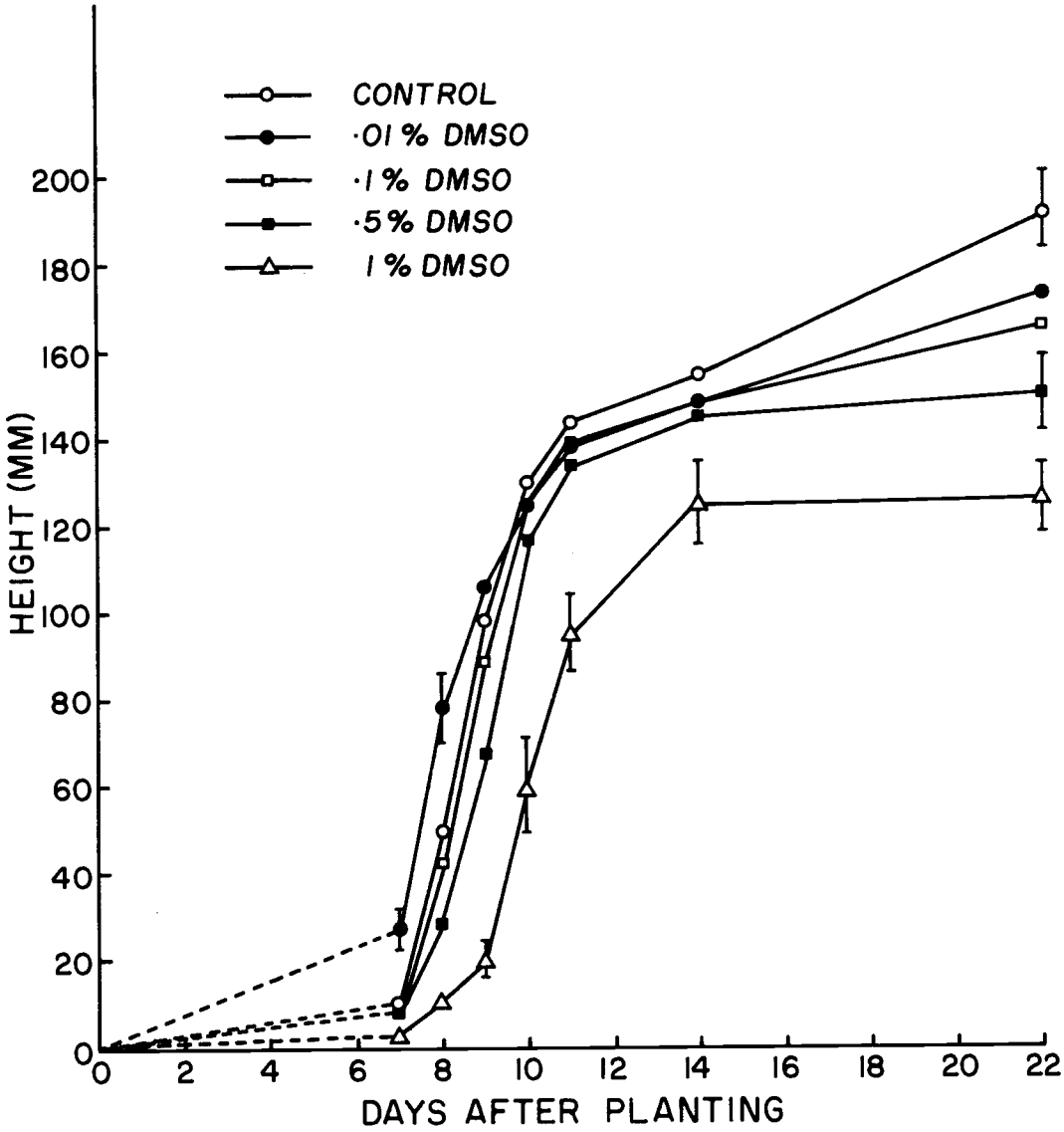

Figure 9. Height with time after planting of Phaseolus vulgaris under five different treatments of soil-applied DMSO (Study I). Each point represents the mean of five replications with standard deviations noted at selected points.

plants by the second week following planting. The final height of the plants was directly correlated with level of DMSO and control plants attained the greatest height at harvest.

The dry weight of the plants at harvest, represented by the total of five plants from each treatment is summarized in Table 7 from data shown in the Appendix (Table 9). While DMSO tended to promote increased plant height during the early growth period, no beneficial effects were seen on the final dry weight of the plants.

Table 7. Dry weight of Phaseolus vulgaris foliage at harvest (Study I). Values represent total dry weight (g) of plant foliage of five plants as a mean of five replications ± one standard deviation.

Treatment (% DMSO)				
Control	0.01	0.1	0.5	1.0
11.42 ± 1.06	10.88 ± 0.98	9.07 ± 0.97	4.69 ± 1.17	1.64 ± 0.37

A serious toxicity which showed up as a curling and burning of leaf margins with subsequent dessication and defoliation commenced two weeks after planting. These effects are shown in Figure 10.

DMSO Preliminary Nutrition Study (Study II)

The uptake of ^{65}Zn with time following soil-incorporation in combination with 1% DMSO (based on dry soil weight) is graphically depicted in Figure 11.

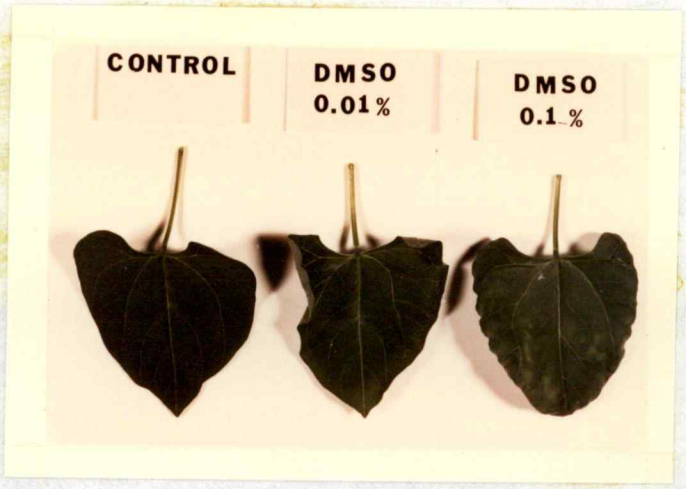

Figure 10. Photographs showing toxicity symptoms apparent on Phaseolus vulgaris following growth in soil treated with various levels of DMSO (Study I).

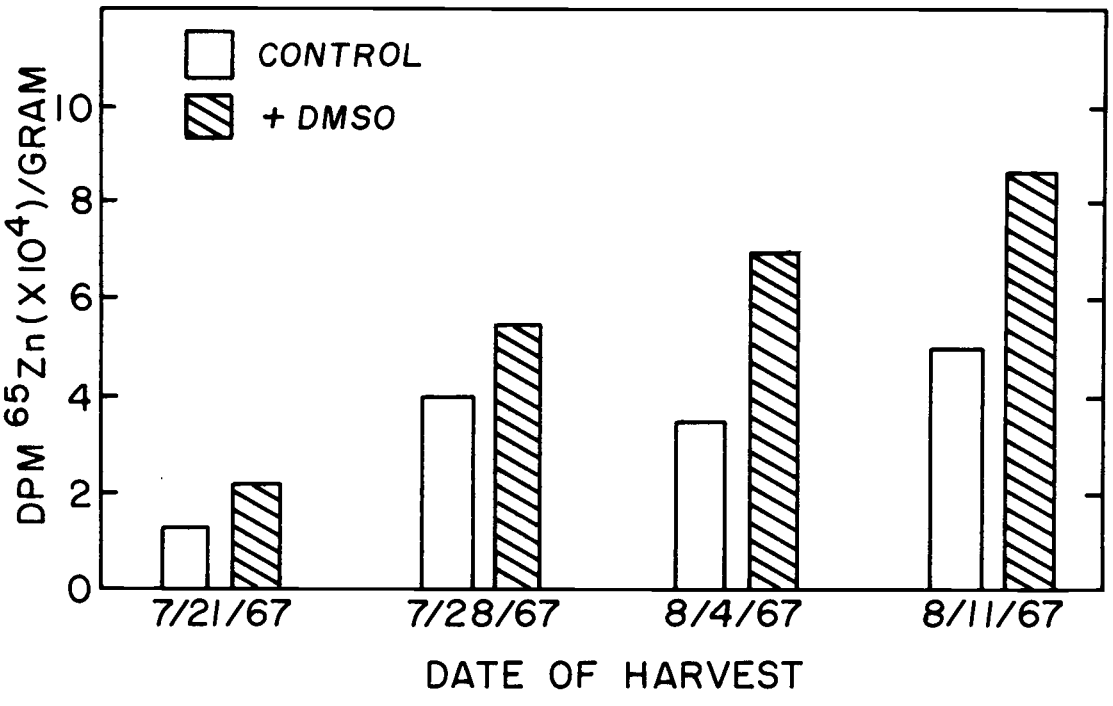

Figure 11. The influence of DMSO on ^{65}Zn uptake at four harvest dates (Study II). Data represent an average of duplicate plant samples.

The presence of DMSO consistently resulted in greater levels of ^{65}Zn in the plant foliage, although a deterioration of plants at this level was evident.

The deleterious effect of soil-incorporated DMSO applied at a level of 1.0% (based on dry soil weight) on dry weight of the plants is shown in Figure 12.

Following harvest, analyses for total N, P, K, Mn, and Zn were performed on the composite control samples (without ^{65}Zn) which were harvested on August 11, 1967. The results of these analyses are presented in Table 8.

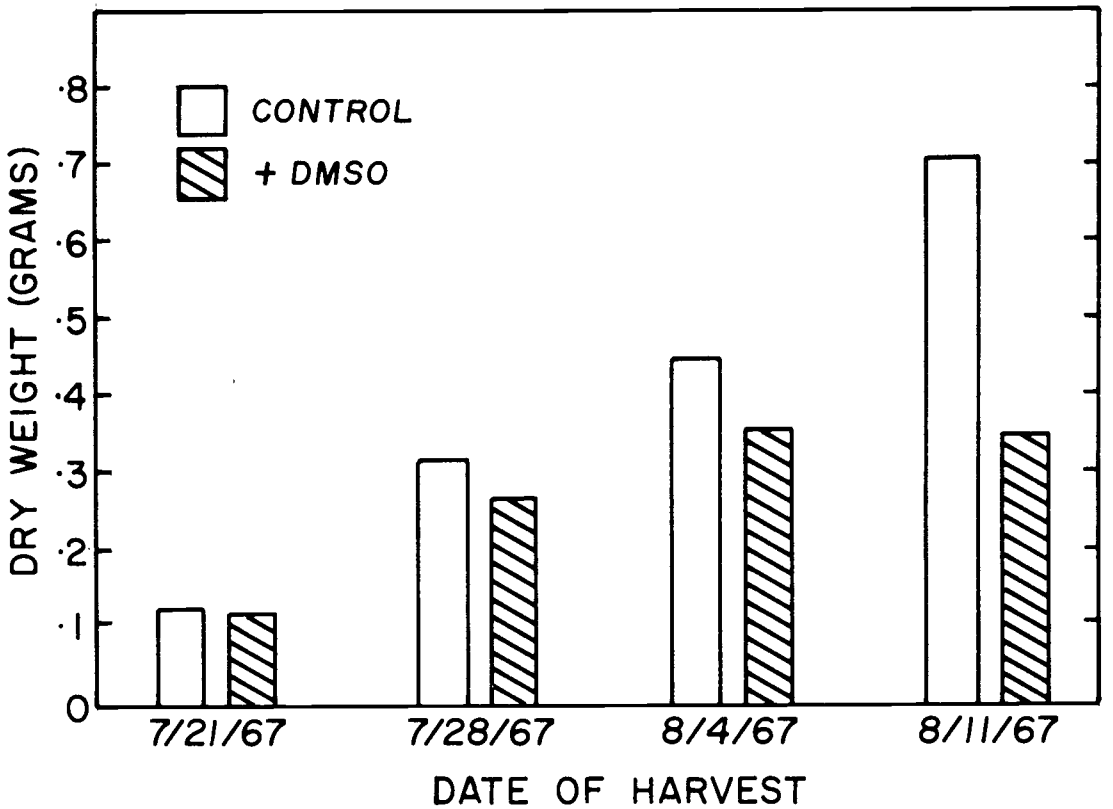

Figure 12. Dry weight of foliage of Phaseolus vulgaris at four harvest dates (Study II). Values represent weight (g) of one plant as an average of two replications for each treatment.

Table 8. Total N, P, K, Mn, and Zn content of plant tissue of Phaseolus vulgaris at harvest (Study II).

	Element				
Treatment	N(%)	P(%)	K(%)	Mn(ppm)	Zn(ppm)
- DMSO	4.55	0.313	3.65	116	135
+ DMSO	5.64	0.517	4.06	409	152

With regard to the above cursory study, a profound enhancement of Mn uptake by plants subjected to DMSO was noted. In addition, levels of P and to a lesser degree those of Zn, K, and N, were

higher in plants grown in soil treated with DMSO.

The mechanism by which these changes were induced appears to involve soil mediated changes, root cell membrane changes, or the solvent action of DMSO on specific nutritive elements. In an attempt to further elucidate these findings, Study III was undertaken with principal emphasis on plant chemical composition as affected by soil-incorporated DMSO.

Effect of DMSO on Nutrient Uptake from Soil in Phaseolus vulgaris (Study III)

The results of soil-incorporated DMSO concentrations up to 0.1% (based on dry soil weight) on the dry weight of the foliage of Phaseolus vulgaris showed no statistically significant effects (Table 1, Appendix). With regard to elemental composition, however, the Mn content of the plant foliage was significantly increased (Table 1, Appendix) as shown in Table 9.

Table 9. Mn content of foliage of Phaseolus vulgaris (Study III). Values are Mn (ppm) on a dry weight basis.

	Replication							
Treatment	I	II	III	IV	V	VI	VII	Mean
Control	81	76	73	77	70	59	72	72.6
.001% DMSO	75	78	66	73	68	57	85	71.7
.01 % DMSO	81	129	208	119	73	77	84	110.1
.05 % DMSO	309	133	144	155	184	307	561	256.1
.1 % DMSO	342	602	862	578	390	369	425	509.7

Least significant difference at the 5% level($LSD_{.05}$) = 126.1
Least significant difference at the 1% level($LSD_{.01}$) = 170.9

Since a well established relationship exists between Mn uptake and soil pH (Tisdale and Nelson, 1966), the pH change of the soil used in Study III following DMSO incorporation was measured. These pH changes are presented in Table 10.

Table 10. Soil pH at harvest following soil-incorporation of various concentrations of DMSO (Study III).

Treatment	Replication							Mean
	I	II	III	IV	V	VI	VII	
Control	5.69	5.37	5.72	5.57	5.37	5.43	5.55	5.53
.001% DMSO	5.38	5.46	5.48	5.48	5.70	5.62	5.42	5.51
.01% DMSO	5.56	5.40	5.24	5.49	5.48	5.40	5.51	5.44
.05% DMSO	5.02	5.08	5.12	5.14	5.15	5.04	4.97	5.07
.1% DMSO	4.91	5.03	5.05	4.89	4.98	4.96	4.98	4.97
	$LSD_{.05} = 0.12$			$LSD_{.01} = 0.17$				

As noted in Table 10, DMSO additions to the soil caused a marked reduction in pH. In an attempt to elucidate the relationship between soil pH and nutrient content of the plant tissue, correlation coefficients were calculated. In this regard, a significant negative correlation coefficient ($r = -0.768$) was noted between soil pH and Mn content of foliage.

While the manner in which DMSO causes this alteration in pH is not clear, its effect on soil pH is apparently of great importance in rendering Mn available to the plants.

In the chemical analysis of the fruit (pods) of the plants, Zn levels tended to be higher in plants grown in soil receiving relatively

high DMSO levels, although no statistically significant enhancement was noted. Mn and P contents of the fruit were significantly affected by DMSO treatments as noted from mean values in Table 11 derived from data in Tables 11 and 12 in the Appendix.

Table 11. Mn and P levels in pods of Phaseolus vulgaris as affected by soil incorporated DMSO (Study III). Values represent an average of seven replications.

Treatment	Mn(ppm)	P(%)
Control	21	0.230
.001% DMSO	21	0.237
.01 % DMSO	26	0.216
.05 % DMSO	49	0.203
.1 % DMSO	108	0.185
	$LSD_{.05}$ = 21 $LSD_{.01}$ = 28	$LSD_{.05}$ = 0.035 $LSD_{.01}$ = 0.048

As was determined in the above case with plant foliage, correlation coefficients were computed between Mn and P contents of plant pods and soil pH. In this regard, a highly significant negative correlation coefficient (r = -0.643) was obtained between Mn level in the pods and soil pH. Likewise, the P level in the plant pods was significantly, but positively correlated to soil reaction (r = +0.590). The limited availability of phosphorus in acid soils (Tisdale and Nelson, 1966) is undoubtedly a major reason for lower P levels in plants grown at the higher concentration of soil-incorporated DMSO.

To further determine whether the above enhancement of Zn and

Mn uptake was soil-mediated, a nutrient culture technique was utilized (Study IV) employing ^{65}Zn and ^{54}Mn. A time course study of radiotracer uptake from the nutrient medium was performed with pH measurements made following harvest of the crop. In this study, the potato (Solanum tuberosum) was used as an indicator plant since Schmid (1968) earlier had shown no enhancement of ^{65}Zn uptake by Hordeum vulgare. In addition, an important Zn: P interaction characteristic of Solanum tuberosum is currently of great interest to plant and soil scientists.

DMSO, ^{65}Zn and ^{54}Mn Hydroponics Study (Study IV)

The effect of various concentrations of DMSO applied in combination with ^{65}Zn on dry weight and ^{65}Zn activity in the plant tissue is shown in Table 12.

Table 12. Influence of DMSO on (a) Dry weight of potato foliage at harvest, and (b) ^{65}Zn level in potato apical tissue (Study IV). Each value represents the mean of seven replications $\pm$ one standard deviation.

Treatment	(a) Dry Weight(g)	(b) ^{65}Zn Activity(dpm/g x 10^3)
^{65}Zn (Control)	4.07 $\pm$ 0.67	302 $\pm$ 35
^{65}Zn + 0.001% DMSO	3.80 $\pm$ 0.52	314 $\pm$ 29
^{65}Zn + 0.01% DMSO	2.99 $\pm$ 0.46	293 $\pm$ 51
^{65}Zn + 0.1% DMSO	0.54 $\pm$ 0.26	327 $\pm$ 38

As noted in Table 12, DMSO at concentrations of 0.1% down to 0.001% yielded plants which were of less weight than the controls. The marked reduction in weight of plants at the 0.1% DMSO level resulted in eventual death. No specific growth or developmental habits were noticeably changed such as stem elongation, increased branching, or stimulation of root growth.

With regard to ^{65}Zn uptake into the apical foliage, DMSO - ^{65}Zn treatments showed no marked increase over plants subjected to ^{65}Zn in the absence of DMSO. These results concur with findings of Study III in that foliage levels of Zn from DMSO treated soil were not significantly greater than controls.

During the course of this experiment (three weeks), the nutrient solution was sampled seven times to follow the uptake pattern of the ^{65}Zn by the plant roots. The results of this sampling for three treatments is given in Figure 13, plotted from data found in Table 17 of the Appendix.

With reference to Figure 13, addition of DMSO to nutrient cultures at concentrations of either 0.1% or 0.01% (v/v) did not markedly enhance the removal of ^{65}Zn from the solution compared to controls. When applied at levels of 0.1%, DMSO resulted in eventual death of the plants thereby decreasing their ability to remove the isotope from the medium.

Plants exposed to 0.1% DMSO in nutrient culture showed visible

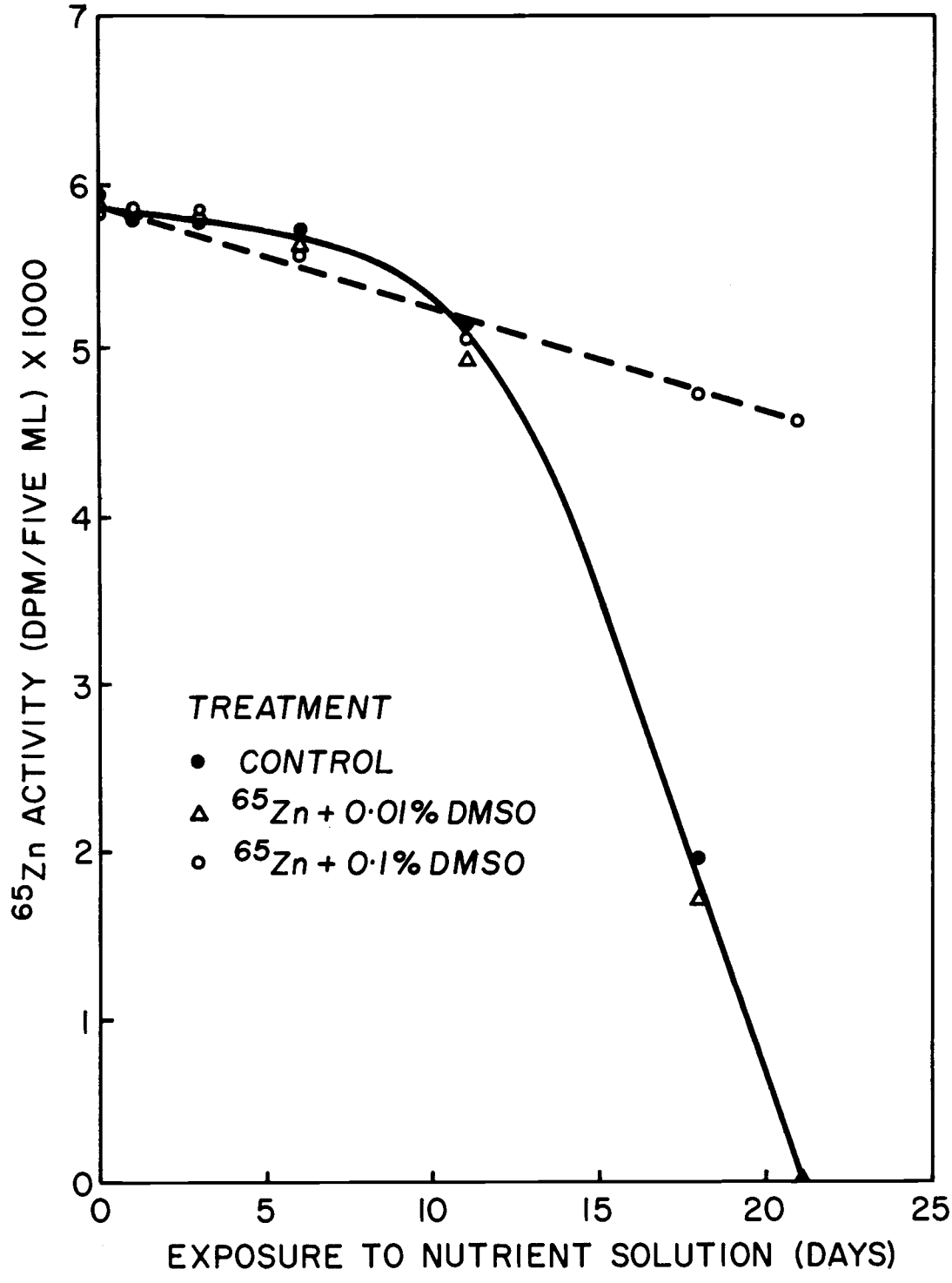

Figure 13. Effect of three concentrations of DMSO in nutrient culture on the uptake of ^{65}Zn by roots of Solanum tuberosum (Study IV). Each point represents an average of seven replications.

toxicity symptoms within three days after initial exposure. Reduced growth of the plants was evident down to 0.001% DMSO although these differences were not pronounced at this concentration (Table 12). Figure 14 shows apparent phytotoxicity symptoms evident on Solanum tuberosum following exposure to DMSO.

The toxic effects of DMSO appear first on lower leaf margins and tips, showing symptoms typical of salt injury. Prolonged exposure to the 0.1% concentrations of DMSO resulted in total dessication of the tissue by the end of the 21-day experimental period.

The results of various concentrations of DMSO on dry weight and ^{54}Mn activity in terminal foliage of Solanum tuberosum are shown in Tables 15 and 16 of the Appendix. Dry weight changes were similar to those found in the first investigation involving ^{65}Zn with the exception of the 0.001% DMSO treatment, where no weight reduction was obtained (Table 15, Appendix). Manganese-54 levels in the plant foliage were not markedly altered by DMSO treatment. As in the first investigation, the ^{54}Mn level of the nutrient culture at various sampling intervals was measured (Table 18, Appendix). The results are presented in Figure 15.

The results of this periodic sampling showed the presence of DMSO to have little influence on ^{54}Mn uptake by the root system of the plant. The fact that uptake essentially ceased where a toxic level of DMSO was present (0.1%), as is also seen in Figure 13 with ^{65}Zn,

Figure 14. Apparent toxicity symptoms on Solanum tuberosum following exposure to 0.1% DMSO (v/v) in nutrient culture (Study IV).

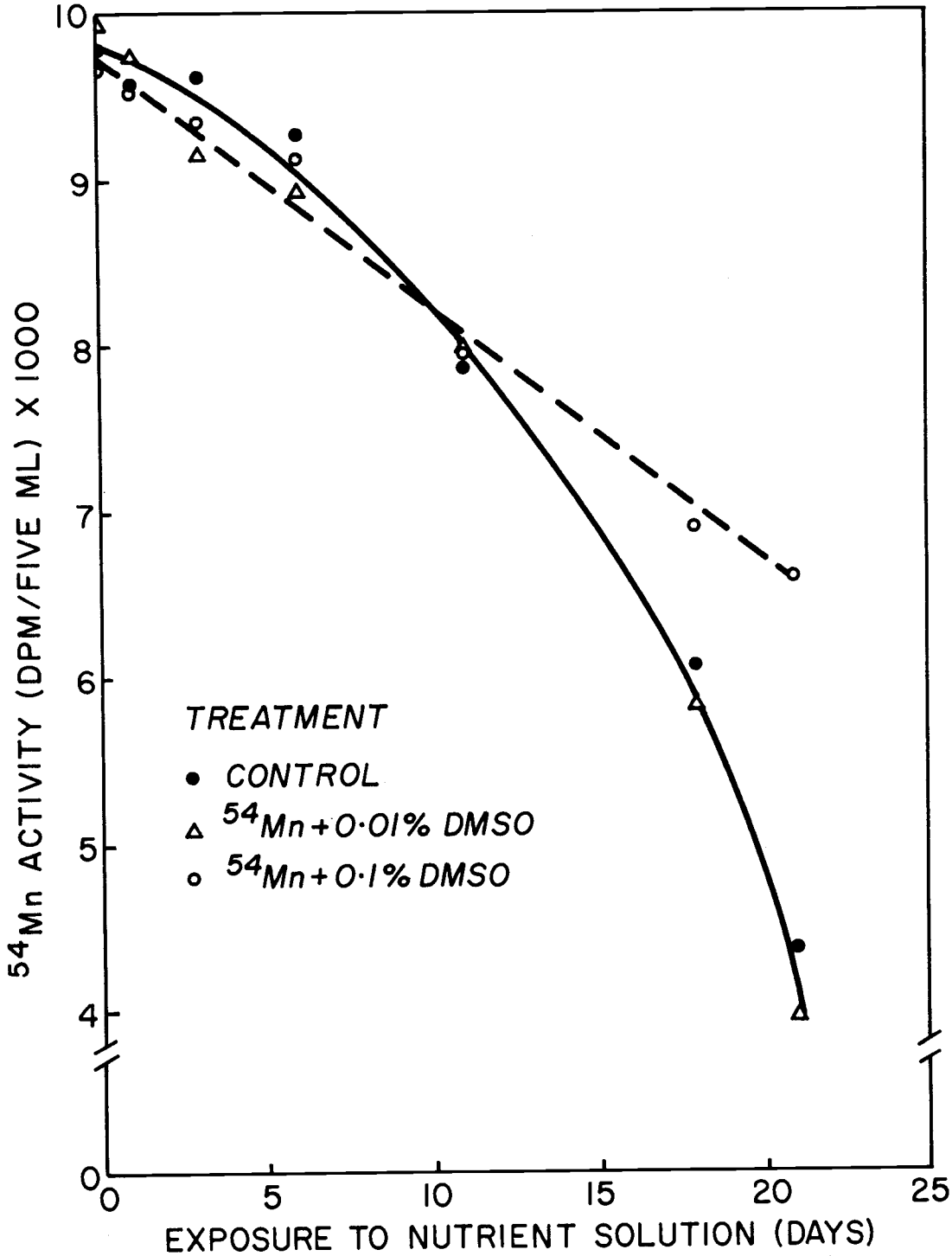

Figure 15. Effect of three concentrations of DMSO in nutrient culture on the uptake of ^{54}Mn by roots of Solanum tuberosum (Study IV). Each point represents an average of seven replications.

would seem to indicate that actual uptake by the root system is involved rather than removal by adsorption to container walls or by precipitation. Net removal of ^{54}Mn was slower than ^{65}Zn (Figure 13) in that the solution was essentially devoid of ^{65}Zn within three weeks after initial exposure of the plants to the isotope. Conversely, only slightly more than half of the ^{54}Mn was removed in this same period by the plant.

With regard to pH change in the nutrient media, a factor which was considered earlier (Table 10), no statistically significant alteration of solution pH was noted following addition of DMSO (Table 19, Appendix). In the first investigation involving ^{65}Zn, the solution pH varied from 4.8 to 5.6, irrespective of treatment. Such minute quantities of the isotope solutions were involved that pH determinations were not made during the second investigation (^{54}Mn), since the isotope additions were not likely to cause pH differences between treatments.

Effect of DMSO on Tuber Reproduction in Solanum tuberosum (Study V)

This investigation was concerned with greenhouse studies conducted in the summer of 1968. The effects of seed potato immersion in various DMSO concentrations prior to planting on number and weight of tubers at harvest are shown in Tables 20 and 21, respectively, in the Appendix. No statistically significant treatment

effects were shown on either number or weight of tubers following harvest (Table 4, Appendix). Distinct trends exist in both cases, however, in that higher concentrations of DMSO, especially the 10% (v/v) DMSO immersion treatment, resulted in slightly higher tuber numbers and weights.

The somewhat higher soil temperatures which are an inevitable result of a greenhouse study of this type with container-grown plants, may be noteworthy especially from the standpoint of tuberization, since lowered temperatures can promote potato-tuber formation (Werner, 1935). While soil temperatures were not evaluated in this study, such a variable might be expected to produce results unlike a more natural environment.

Field Studies

Effect of DMSO on Foliar Spray Applications to Solanum tuberosum (Study VI)

Tuber Weight. The influence of eight foliar spray treatments on tuber yield of Solanum tuberosum at harvest are given in Table 13, summarized from data shown in Table 22 of the Appendix.

Table 13. Influence of foliar spray treatments on tuber yield of Solanum tuberosum at harvest (Study VI). Values represent the total weight (lbs) of tubers from three plants as a mean of six replications.

	Treatment									
	1	2	3	4	5	6	7	8		
Soil P	-DMSO				+DMSO				LSD	
Level	Control	+Mn	+Zn	Mn+Zn	Control	+Mn	+Zn	Mn+Zn	5%	1%
High	26.0	21.9	24.9	22.9	25.7	24.5	26.4	24.1		
Low	24.2	22.4	24.8	25.8	23.1	23.4	27.0	29.9	3.8	5.1
Mean	25.1	22.2	24.8	24.3	24.4	23.9	26.7	27.0	2.9	3.9

As noted above and from analysis of variance data (Table 5, Appendix), the treatments exhibited no statistically significant influence on tuber yield at the high soil P level although significant effects were obtained at the low P level. In the latter case, foliar sprays of Zn (treatment 7) or Zn + Mn (treatment 8) in combination with DMSO produced the highest yields. Specifically, a highly significant yield increase (23.6%) compared with the control resulted from treatment 8. When the means of both soil P levels are considered in Table 13 above, foliar applications of Mn with or without DMSO as an adjuvant (treatments 2 and 6 respectively) tended to produce the lowest crop yields. When Zn sprays were applied in the absence of DMSO (treatment 3), no enhanced tuber yield resulted when compared to control plants. In combination with DMSO however, such sprays tended to produce a slightly higher crop yield although statistically, no differences from the control values were significant.

Plant Nutrient Levels. Terminal foliage samples from each of the 96 field plots of Solanum tuberosum (Study VI) were subjected to chemical analyses for Zn, Mn, P, Ca, Mg and K.

Among the nutrients which were notably altered by the respective treatments and particularly by DMSO applications was Ca, results of which are shown in Table 14.

Table 14. Ca level in terminal foliage of Solanum tuberosum grown under high soil P conditions as influenced by three DMSO foliar sprays (100 ppm) (Study VI). Values represent Ca (%) on a dry weight basis.

Treatment	Replication						Mean	Treatment LSD 5%
	I	II	III	IV	V	VI		
1 (Control)	0.66	0.74	0.73	0.51	0.60	0.90	0.69	0.21
5 (DMSO)	0.80	1.39	1.34	0.69	0.83	1.06	1.02	

These results show that spray applications of DMSO significantly ($P = 0.05$) increased the Ca level of the terminal foliage of the plants. This effect was not obtained when sprays were applied in the absence of DMSO nor to such a degree when Zn or Mn were added to the sprays (Table 23, Appendix).

The Mn content of the plant tissue was likewise significantly altered by foliar sprays of this element as noted in Table 15.

Table 15. Mn level in terminal foliage of Solanum tuberosum grown under two soil P conditions (Study VI). Values represent Mn (ppm) on a dry weight basis as a mean of six replications.

	Treatment								
	1	2	3	4	5	6	7	8	
Soil P	-DMSO				+DMSO				LSD
Level	Control	+Mn	+Zn	Mn + Zn	Control	+Mn	+Zn	Mn + Zn	5%
High	102	131	133	127	152	136	113	114	27
Low	131	123	114	124	109	131	114	121	

The results in Table 15 above, summarized from data in the Appendix (Table 24), show that under high soil P levels, DMSO applied singly (treatment 5) or in combination with Mn (treatment 6) significantly ($P = .05$) increased the Mn level of the plant tissue when compared with the control (treatment 1). Significant treatment effects on the elevation of Mn in the tissue were also seen, however, in the absence of DMSO (treatments 2 and 3). Surprisingly, plants receiving Zn or Mn + Zn applied in combination with DMSO (treatments 7 and 8, respectively) did not show an increased Mn level in the terminal leaflets of plants grown at the high soil P level.

Under low soil P conditions, Mn levels were markedly lower in plants treated with DMSO alone (treatment 5) when compared to the same treatment under high soil P conditions. In addition, Mn levels in control plants (treatment 1) were distinctly altered by the soil P conditions. Hence, as shown statistically (Table 5, Appendix), a highly significant treatment x P level interaction is apparent, implying

that phosphorus fertilization significantly alters Mn uptake and/or distribution in Solanum tuberosum.

The P content of terminal leaflets of the plants grown under high soil P conditions was significantly ($P = .05$) reduced by DMSO applied singly as a foliar spray (treatment 5) compared to the control (treatment 1). No statistically significant differences were apparent in treatments other than the above. These results which are summarized from Table 25 of the Appendix are presented below.

Table 16. P level in terminal foliage of Solanum tuberosum grown under high soil P conditions (Study VI). Values represent P (%) on a dry weight basis as an average of six replications.

Treatment								
1	2	3	4	5	6	7	8	
-DMSO				+DMSO				LSD
Control	+Mn	+Zn	Mn + Zn	Control	+Mn	+Zn	Mn + Zn	5%
0.500	0.484	0.476	0.489	0.424	0.481	0.483	0.481	0.041

With regard to Mg, K, and Zn levels in terminal foliage of the plants, no statistically significant treatment effects were noted (Tables 26-28, Appendix). Changes in these elements as well as those presented earlier (Mn, Ca, P) were apparent however, as influenced by soil P level. Table 17, a summary of data found in the Appendix, illustrates these soil P induced effects.

With respect to the results in Table 17, the Ca and P levels in the foliage were significantly higher at the higher soil P level. This

Table 17. Nutrient levels of terminal foliage of Solanum tuberosum grown under two soil P conditions (Study VI). Values represent an average of eight treatments and six replications (48 tissue samples).

Soil P Level	Element					
	Mn (ppm)	Ca** (%)	P** (%)	Mg** (%)	K (%)	Zn** (ppm)
High	126	0.86	0.477	0.459	2.85	36.1
Low	121	0.69	0.386	0.410	2.89	31.9

**Significant differences between soil P levels at the 1% level.

effect is most likely a result of the contribution of both these elements from the superphosphate used to establish the differential levels of soil P prior to planting the crop.

Magnesium was significantly increased as was Zn by the higher soil P levels which may reflect an increased root growth and greater zone of nutrient absorption.

The effect of foliar sprays of DMSO applied singly (treatment 5) on the nutrient composition of terminal tissue of the plants is presented in Table 18.

Table 18. Nutrient levels of terminal foliage of Solanum tuberosum as influenced by three foliar sprays of DMSO (100 ppm) (Study VI). Values represent an average of six replications and two soil P levels (12 tissue samples).

Treatment	Element					
	Mn (ppm)	Ca (%)	P (%)	Mg (%)	K (%)	Zn (ppm)
Control	116	0.79	0.45	0.44	2.90	38.6
DMSO	125	0.84	0.43	0.45	2.84	31.2

As noted in Table 18, DMSO sprays applied without an adjuvant such as Zn or Mn did not significantly alter the measured chemical constituents of the plant foliage when averages of both soil P levels are considered. Of consequence in this regard is the highly significant soil P level interaction which occurred with several of the nutrients (Table 5, Appendix). It may be noteworthy to point out for the benefit of future research, however, that Ca and Mn levels tended to be higher in terminal foliage of DMSO-treated plants.

Effect of DMSO on Foliar Spray Applications to Phaseolus vulgaris (Study VII)

Crop Yield. The influence of eight foliar sprays on yield of pods of Phaseolus vulgaris grown at the two soil P-K levels is given in Table 19 (based on data in Table 29, Appendix).

Table 19. Influence of foliar spray treatments on pod weight of Phaseolus vulgaris grown at two soil P-K levels (Study VII). Values represent the total pod weight (lbs) from 125 plants as a mean of six replications.

	Treatment								
	1	2	3	4	5	6	7	8	
Soil P-K	- DMSO				+DMSO				LSD
Level	Control	+Mn	+Zn	Mn + Zn	Control	+Mn	+Zn	Mn + Zn	5%
High	25.4	24.0	22.6	22.8	23.3	23.6	22.9	23.2	1.6
Low	18.7	18.9	19.4	18.7	19.3	19.7	20.9	19.6	1.3

A highly significant effect due to soil P-K level is seen in Table 6 of the Appendix. At the lower soil P-K level significant yield

benefits were shown with plants treated with Zn in combination with DMSO (treatment 7). Of interest at this point is the observation that tuber yield of Solanum tuberosum (Table 13) was also enhanced by Zn and Mn sprays in combination with DMSO at the lower soil P level.

Plant Nutrient Levels. Foliage samples of Phaseolus vulgaris were analyzed from each of the 96 plots for the identical elements as with Solanum tuberosum, specifically Zn, Mn, P, Ca, Mg, and K.

Results of foliar spray treatments on Ca content of the tissue of Phaseolus vulgaris are presented in Table 20 (based on data in Table 30 of the Appendix).

Table 20. Ca level in terminal foliage of Phaseolus vulgaris grown under two soil P-K conditions (Study VII). Values represent Ca (%) on a dry weight basis as a mean of six replications.

	Treatment								
Soil	1	2	3	4	5	6	7	8	
Fertility	-DMSO				+DMSO				LSD
Level	Control	+Mn	+Zn	Mn + Zn	Control	+Mn	+Zn	Mn + Zn	5%
High P-K	1.58	1.58	1.54	1.59	1.57	1.52	1.52	1.51	
Low P-K	1.60	1.57	1.79	1.73	1.72	1.77	1.69	1.75	0.13

In addition to significant ($P = 0.05$) treatment effects on Ca content of plant tissue at the low soil P-K level, a statistically significant difference was shown in Ca content of the plant tissue as affected by soil P-K level (Table 6, Appendix). This difference

becomes readily apparent in viewing Table 20. In all cases, Ca content was higher in plants grown at the low soil P-K level although differences were slight in some cases. This influence which may appear surprising, is an apparent reflection of the antagonistic effect of high soil K levels on Ca uptake by plants. At this point it is timely to recall the results of soil test data (Table 4, Materials and Methods) showing the level of K in the high and low soil P-K plots to be 2.08 and 0.83 meq/100 g respectively.

No statistically significant differences in the other plant nutrients were observed as influenced by the various treatments. Pronounced and significant differences were evident however, in various plant nutrients as influenced by soil P-K level, data for which are shown in Table 21 (based on data in Tables 30-35 of the Appendix).

Table 21. Nutrient levels of terminal foliage of Phaseolus vulgaris grown under two soil P-K conditions (Study VII). Values represent an average of eight treatments and six replications (48 tissue samples).

Soil Fertility Level	Element					
	Mn (ppm)	Ca** (%)	P** (%)	Mg** (%)	K** (%)	Zn** (ppm)
High P-K	31	1.55	0.337	0.427	1.85	17.7
Low P-K	32	1.70	0.276	0.460	1.50	21.4

**Significant differences between soil P-K levels at the 1% level.

Levels of Ca and Mg were significantly lower under the higher soil P-K level. These changes are undoubtedly due to the

comparatively high soil K levels which may be antagonistic to the uptake of Ca and Mg by the plant.

Phosphorus and potassium levels of the plant foliage showed the expected higher values under the higher soil P-K conditions. Conversely, Zn levels were significantly lower under higher soil P-K conditions. Unlike the results of Study VI where higher Zn levels were noted at the higher soil P levels, results with this study showed lower Zn levels in the plant following P fertilization. An important point in this regard is the observation of soil test data (Table 3, Materials and Methods) which shows soil levels of Zn to be higher in the higher soil P plots of Study VI. Hence, this supply of Zn has likely provided for the direct relationship which is apparent with Solanum tuberosum in Study VI. In the present situation, however, soil levels of Zn were similar in both the high and low P-K soil plots (Table 4, Materials and Methods). The inverse relationship which is apparent was, therefore, seemingly induced by the differential in soil P-K levels.

Effect of DMSO on Tuber Reproduction in Solanum tuberosum (Study VIII)

At harvest, the effect of tuber immersion in DMSO solutions prior to planting was evaluated by counting the total number of stems emerging from the row of each treatment (14 feet; 12 tubers). The results of this aspect of Study VIII are presented in Table 22 (based on data in Table 36, Appendix).

Table 22. Total number of stems per plot of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Values represent the total number of stems per plot (14 feet; 12 parent tubers) as a mean of six replications.

Soil P	Treatment (% DMSO)									LSD	
Level	Control	.001	.01	.1	.5	1	5	10	Mean	5%	1%
High	53	50	51	53	47	54	58	58	53		
Low	58	58	56	57	53	59	62	64	58		
Mean	55	54	53	55	50	56	60	61		5	7

As noted above, no statistically significant treatment effects were observed between the separate soil P levels. However, statistically significant differences ($P = .05$) were found between the two highest treatments (5 and 10% DMSO) and the control when combined soil fertility levels were considered. In addition, a definite reduction in stem production was observed at the intermediate treatments, particularly the 0.5% DMSO treatment.

The soil P level also showed a significant effect (Table 7, Appendix) in that a greater number of stems was evidenced at the lower soil P level. Of relevance is the fact that the P level of the high and low soil P plots were 136.8 and 64.6 ppm respectively.

The effect of pre-plant immersion of the parent tuber in DMSO on eventual stem production in Solanum tuberosum is shown visually in Figure 16.

The effect of immersion of parent tubers in eight concentrations

(a)

(b)

Figure 16. Effect of DMSO on stem production of Solanum tuberosum. (a) Control (b) Treated parent tubers (10% DMSO pre-plant immersion) (Study VIII).

of DMSO prior to planting on final tuber number at harvest is summarized in Table 23 (based on data in Table 37, Appendix).

Table 23. Total number of tubers per plot of Solanum tuberosum at harvest (Study VIII). Values represent total tuber number per plot (14 feet; 12 parent tubers) as a mean of six replications.

Soil P Level	Treatment (% DMSO)								LSD	
	Control	.001	.01	.1	.5	1	5	10	5%	1%
High	154	157	151	156	155	162	170	160		
Low	160	158	157	149	153	162	175	174	5	6
Mean	157	158	154	153	153	162	173	167	9	12

Total number of tubers per plot was significantly increased by treatments compared to controls. In this regard, the 5% level of DMSO appeared optimal in that some reduction in yield was noted at the 10% DMSO level.

It should be noted at this point that prior to initiation of this study, cursory studies showed that a 30-minute tuber immersion in DMSO concentrations of 50% and 100% proved damaging to sprouting, with a resultant poor stand of plants being obtained. Consequently, the concentrations noted in Figure 8 of the Materials and Methods section (0, 0.001, 0.01, 0.1, 0.5, 1.0, 5.0, and 10% DMSO) were employed and no adverse effects were noted on percent stand.

The results of pre-plant immersion treatments on total tuber weight at harvest are presented in Table 24 (based on data in Table

38, Appendix).

Table 24. Total weight of tubers of Solanum tuberosum as influenced by eight DMSO pre-plant immersion treatments and two soil P levels (Study VIII). Values represent tuber weight (lbs) per plot as a mean of six replications.

Soil P Level	Treatment (% DMSO)								LSD	
	Control	.001	.01	.1	.5	1	5	10	5%	1%
High	53.7	53.3	56.0	54.6	51.5	61.3	66.6	59.0	8.6	
Low	57.6	54.3	57.5	51.5	56.5	57.9	64.1	67.6		
Mean	55.6	53.8	56.7	53.1	54.0	59.6	65.3	63.3	7.1	9.4

From the standpoint of fertility level influence on total tuber weight, treatments exhibited a significant effect only at the high soil P level. When overall averages were computed, however, significant differences were evident in that pre-plant tuber immersion in a 5% DMSO solution increased yields to the greatest extent compared to the control. Reference to Table 7 of the Appendix shows a highly significant treatment x soil P interaction, which indicates that P is important in altering treatment response. The fact that P is significantly related to tuber yield has been reported elsewhere (Estes, 1959).

As was evident with stem number (Table 22), intermediate levels of DMSO (0.01-0.5% DMSO) tend to produce lower final yields than either the control or the 5% or 10% DMSO treatments.

While it is of basic interest that the number of both stems and tubers is increased following immersion of parent tubers in DMSO

solutions, any practical value will only result from an increase in marketable (U. S. No. 1) size tubers. Hence, an evaluation was made of size distribution of the total tuber yield in an attempt to determine if treatments significantly influenced the number and yield of marketable tubers. The results of treatment effect on the number of U. S. No. 1 tubers is presented in Table 25.

Table 25. Number of U. S. No. 1 tubers of Solanum tuberosum as influenced by eight DMSO pre-plant immersion treatments and two soil P levels (Study VIII). Values represent total number of tubers per plot as a mean of six replications.

Soil P	Treatment (% DMSO)								LSD	
Level	Control	.001	.01	.1	.5	1	5	10	5%	1%
High	73	72	76	71	72	83	91	75	10	14
Low	77	79	86	85	88	95	99	83	12	
Mean	75	75	81	78	80	89	95	79	8	10

As noted in Table 25, the number of marketable tubers was significantly increased by the higher DMSO concentrations, with maximum benefits being obtained with 5% DMSO. The higher soil P level yielded fewer tubers compared with the lower soil P levels, an effect which was statistically significant (Table 7, Appendix).

The results of treatments on tuber yield are shown in Figure 17 (based on data in Table 40, Appendix). These results show that both total weight and weight of this category of tuber is increased compared with control plants following pre-plant treatments of 1%,

5%, and 10% DMSO.

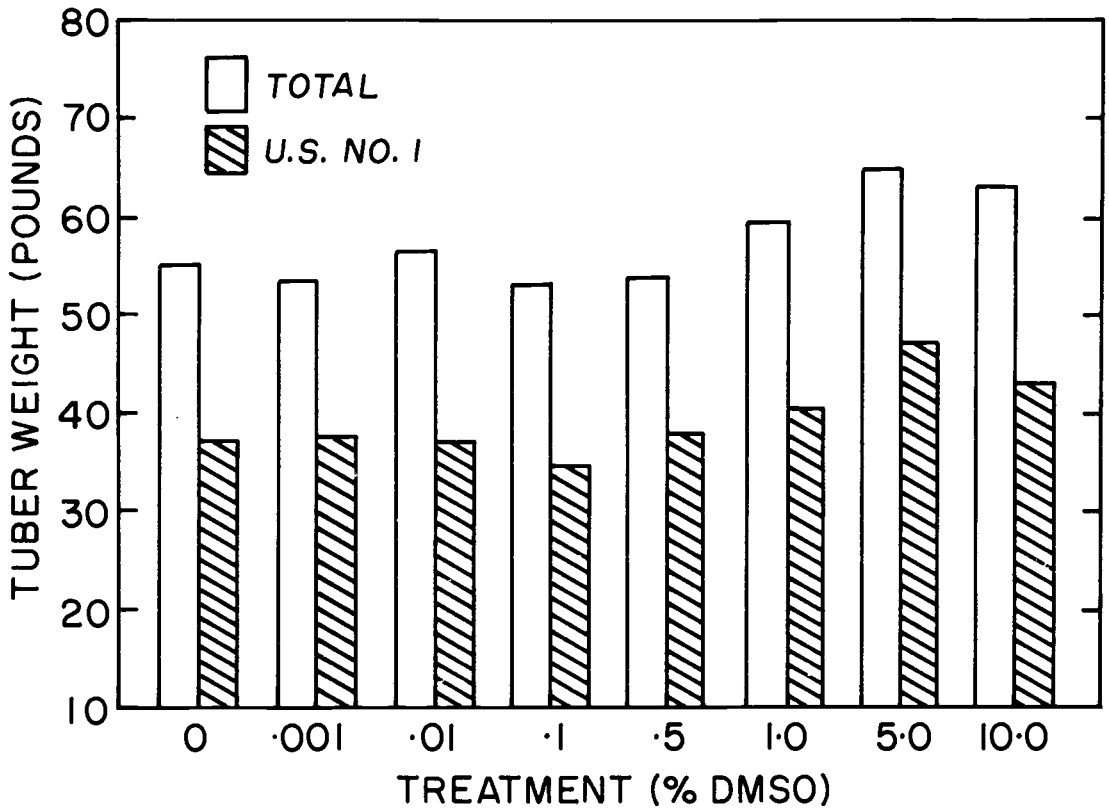

Figure 17. Effect of pre-plant tuber treatment on final tuber weight at harvest (Study VIII). Data represents averages of two soil P levels and six replications.

Statistical analyses show that yield (lbs) of marketable tubers is not significantly increased if the combined values of both soil P levels are evaluated (Table 7, Appendix). If yields of tubers of this size category from the high soil P plots are observed, however, as presented in Table 26 below, a significant treatment effect is noted. In this respect, significant ($P = .01$) beneficial treatment treatment effects are observed in the case of the 5% DMSO level compared with

the control.

Table 26. Yield of marketable tubers (U. S. No. 1) of Solanum tuberosum as influenced by eight DMSO pre-plant immersion treatments and two soil P levels (Study VIII). Values represent tuber weight (lbs) per plot as a mean of six replications.

Soil P Level	Treatment (% DMSO)								LSD	
	Control	.001	.01	.1	.5	1	5	10	5%	1%
High	36.0	37.2	34.3	33.7	37.0	40.7	47.5	40.0	7.0	9.4
Low	39.0	38.2	39.8	35.8	39.7	40.8	47.0	46.7		
Mean	37.5	37.7	37.0	34.7	38.3	40.7	47.2	43.3		

Thus, while total number of U. S. No. 1 tubers produced appears to be adversely affected at the rather high P level (Table 25) the final weight of total tubers (Table 24) as well as those of the marketable size category are not so affected.

The number of marketable size tubers was significantly influenced by treatments at both soil P levels (Table 7, Appendix). In addition, soil P levels exerted a significantly different effect on tuber number of this size category.

DISCUSSION

Nutritional and Physiological Aspects

Toxicity Studies

The initial studies performed on this problem were concerned with the toxicity of DMSO following incorporation into the growth medium. Results of Study I showed that both emergence and early growth of Phaseolus vulgaris were enhanced by 0.01% DMSO incorporated on the basis of soil weight. Increasing the concentration of DMSO in the soil medium, however, produced serious toxicity shown by reduced emergence and dessication of the plant tissue (Table 6; Figure 10). Other work dealing with seed germination of Phaseolus vulgaris indicated that no germination occurred in 10% or higher concentrations of DMSO in water solutions (Erdman, 1967). Further, reduced germination (84%) was noted at 1% DMSO levels compared to controls which exhibited 100% germination.

The severity of the toxic symptoms was directly correlated with the DMSO concentration in the growth medium. In soil, severe symptoms occur at a 1% DMSO concentration (Figure 9), but no visible, adverse effects are seen at the 0.001% DMSO concentration. Although no statistically different treatment effects were observed at the 0.01% DMSO level, slight weight reductions were noted commencing

with the 0.01% DMSO concentration (Table 10, Appendix). In hydroponic solutions, Solanum tuberosum was totally dessicated at harvest at the 0.1% DMSO level while no significant weight reductions or visible toxicity symptoms were apparent at the 0.001% level.

The mechanism by which DMSO produces its toxic effects remains uncertain. DMSO is extremely hygroscopic and miscible with water, with a probability that a 2:1 association complex is formed between water and DMSO (Cowie and Toporowski, 1961). Thus, the possibility exists that plasmolysis of the tissue may occur. An extreme and continued plasmolysis, which visibly appears much like the effects following heavy applications of salt or soluble fertilizers to plants, occurred at the higher DMSO concentrations (Figure 14). In work closely allied with the above, Erdman (1967) observed that bean seedlings grown in standard nutrient solution wilted one half hour following addition to the solution of DMSO at concentrations of 2% or more. After three days, wilting was evident at DMSO concentrations as low as one percent. While evidence does not exist to absolutely correlate marginal burning of the plant foliage with accumulation of DMSO or its degradative products, regions of accumulation of ^{35}S in foliage of Solanum tuberosum (Estes, 1959), as well as in Phaseolus vulgaris (Biddulph et al., 1958), correspond closely with regions of toxicity observed following exposure of these crop species to DMSO.

Sulfur is a constituent of DMSO and both materials likely follow

the transpirational stream upward into the plant. The localization of ^{35}S in a particular region following administration of DMSO-^{35}S indicates a similar site for the DMSO molecule assuming no significant degradation of DMSO occurs within the first few hours following absorption. Of relevance in this regard is the finding that sulfate-sulfur, while freely mobile, was quickly captured in metabolic processes which immobilized it (Biddulph et al., 1958). This metabolic capture of tracer sulfur, which generally occurred within 24 hours following root exposure, took place largely in the apical portion of the plant.

As expected, a significant reduction in plant dry weight at harvest was noted when levels of DMSO equaled or exceeded 0.1% when applied to soil with Phaseolus vulgaris as the test crop (Table 7). Likewise, when added to nutrient solution at levels greater than 0.01%, DMSO exerted toxic effects on Solanum tuberosum (Table 13, Appendix). Consequently, the phytotoxicity of DMSO becomes exceedingly important when considering agricultural applications of DMSO which would involve the incorporation of this chemical with the growth medium. In certain uses such as an adjuvant to herbicides, its value has been documented (Hart and Hurtt, 1967; Keil, 1967, Bean, 1965). However, the selective character of certain soil-active herbicides could be altered, if applied in combination with DMSO, due to the phytotoxicity of the latter when added to soils.

Nutrient Uptake from Soil and Water Culture as Influenced by DMSO

Preliminary work relating to the influence of DMSO on nutrient uptake by Phaseolus vulgaris (Study II) showed that the uptake of Mn particularly, and to a lesser degree P, was increased in plant foliage following soil incorporation of DMSO (Table 8). Subsequent studies (Study III) showed that Mn content was markedly increased in foliage (Table 9) and to a lesser degree in pods (Table 11) by increasing soil-incorporated DMSO levels up to one percent.

Regarding the uptake of related elements, Erdman (1967) observed that the uptake of Ca, Mg, K, and P by seedlings of Phaseolus vulgaris appeared to have been stimulated by DMSO at levels of 1-2% of the nutrient medium when measured in terms of wet weight. However, when evaluated on the basis of dry weight no significant changes occurred except for K, which showed a slight increase after 48- and 96-hour exposures. He concluded that this difference between wet and dry weight analyses is a reflection of the DMSO-induced wilting and suggested that the plant either lost capacity to absorb water or to retain water, or both. Hence, Erdman's work implies that DMSO may not exert a direct enhancing effect on nutrient uptake by root systems of plants thereby agreeing with the findings of this study.

Since the availability of Mn to plants is known to be largely regulated by soil pH (Tisdale and Nelson, 1966) and this soil

characteristic is significantly reduced following incorporation of DMSO (Table 10), the influence of DMSO on Mn availability and uptake by plants appears to be a soil-mediated change. Manganese is released from soil by lowering pH and a significant negative correlation ($r = -0.768$) is seen between soil pH and Mn content of foliage of Phaseolus vulgaris (Tables 9 and 10). Likewise, a good correlation exists between the amount of Mn^{++} extractable by ammonium acetate and the pH of soils (Tisdale and Nelson, 1966). In this regard, it was noted that the conversion of Mn^{++} (available form) to Mn^{++++} (unavailable form) is a linear function of pH between values of 3.2 and 8.0. It is noteworthy, however, that a reduction of Mn^{++++} to more soluble, available forms may be brought about by means such as soil sterilization or addition of certain reducing compounds and thus a pH change may not of itself be the only method of increasing Mn solubility.

In support of the above work, Beauchamp and Crete (1968) have shown a dependence on temperature for the decrease in pH due to DMSO as evidenced through a statistically significant DMSO x temperature interaction. Consequently, microbial decomposition of DMSO may play a role in the above discussed pH change. At higher temperatures, however, much greater amounts of sulfate are extracted from soils than can be accounted for by the sulfur added from DMSO. As in most biological reactions, an increase in temperature

increases the rate at which soil-sulfur (of which a large amount is in organic form) is oxidized (Li, 1964). Such a change likely contributes to the higher level of extractable sulfate observed by Beauchamp and Crete (1968).

The P change which was observed in pods of Phaseolus vulgaris may likewise be linked to changes in soil pH, since the concentration of the major phosphate ions ($H_2PO_4^-$ and $HPO_4^=$) in the soil solution is largely dependent on soil pH conditions. Under acid conditions, the insoluble phosphates of iron and calcium will be precipitated, thereby lowering their potential availability to plants (Tisdale and Nelson, 1966), as occurred in this study.

Related work with soil-incorporated DMSO (0 - 0.06%) produced decreased N uptake and increased S and Mn contents of shoots in Phaseolus vulgaris (Beauchamp and Crete, 1968). Contrary to the findings of this study, these workers found no effect on the P content of the plants following soil treatment with DMSO. The N reduction was believed due to reduced nodulation on the roots of the legume, a likely effect of pH reduction.

Hydroponic studies were undertaken to further substantiate the above work relating to pH changes induced by DMSO additions to soil and to determine if DMSO exerted a distinct effect on the uptake of Zn and Mn by the roots of Solanum tuberosum. The results of this work showed that DMSO did not materially alter the pH of the nutrient

medium nor influence the uptake of these two nutritive elements (Figures 13 and 15). Such an effect supports the hypothesis that DMSO induces changes in the uptake of such elements as Mn, Zn, and P by higher plants due to changes in their availability, rather than through enhancement of their penetration through the plant membrane.

Corroborating evidence for the findings of Study IV, which dealt with ^{65}Zn and ^{54}Mn uptake by Solanum tuberosum, is seen in recent work by Schmid (1968). Working with excised roots of Hordeum vulgare, he showed that ^{65}Zn absorption did not increase until concentrations in excess of 1.0% DMSO in the nutrient medium were employed. The greatest increases in ^{65}Zn were obtained at the highest DMSO concentration (10%). Opposite effects were seen with Na and Rb uptake, which were dramatically decreased at these DMSO levels. While this work is of fundamental importance, profound toxicity occurs at such high levels of DMSO in the growth medium.

Since Zn and Mn appear to be passively absorbed by plants and are thereby independent of a metabolic energy requirement, poisoning agents such as dinitrophenol (DNP) should elicit no impairment of their uptake (Schmid, 1968). With Rb and Na, however, which are actively absorbed, any inhibitor of metabolism would drastically reduce their uptake. Consequently, since DMSO retards respiration (Franz and Van Bruggen, 1967; Schmid, 1968), altered uptake of some cations by plant roots in the presence of DMSO may not be due to a particular change in

cell permeability, but to a change in respiratory pattern within the plant. In the case of the uptake of anions, such as phosphate, by plants, enhancement has been seen upon addition of DMSO to the growth medium (Garren 1967). In this work, which involved one-year old strawberry plants (Fragaria ananassa), addition of a concentration level of 0.055% DMSO in No. 2 Hoagland solution significantly increased the uptake of ^{32}P by the plants. This is noteworthy since it may imply that the influence of DMSO on anion uptake is different from its effect on cation uptake by plants. Such an effect is readily conceivable in light of the different plant uptake mechanisms for anions as compared to cations which have been proposed by Lundegardh (1950).

Nutrient Changes in Plant Tissue Following DMSO Foliar Treatments

Following three applications of DMSO foliar spray (100 ppm), the Ca level in terminal foliage of Solanum tuberosum grown under high soil P conditions was significantly higher than in comparable tissues from control plants (Study VI).

In respect to Phaseolus vulgaris (Study VII), Ca levels in the terminal foliage were consistently greater under the low soil P-K treatments. This effect is an apparent reflection of the antagonistic interaction between Ca and K in uptake and translocation (Resnik, 1963). Levels of Ca and Mg were significantly greater under the low

soil P-K conditions compared to plants grown under high soil P-K levels. Treatments in which DMSO was included at the low P-K level yielded terminal foliage which was higher in Ca content than control plants.

Such findings as the above may indicate that the mobility of Ca in the tissue is being altered. This is of interest particularly since a very high degree of immobility is displayed by this element in plant tissue (Biddulph et al., 1958). Using ^{45}Ca administered to root systems of Phaseolus vulgaris, it was observed that the isotope ascended the stem of the plant and was delivered to the growing tissue. With continued growth it remained in the lower, more mature plant parts. Since plant growth occurs from the apical region, Ca deficiency therefore may occur in this region due to this characteristic of immobility. Hence, the results shown in the current study (Study VII), which indicate greater quantities of Ca in the terminal foliage following DMSO treatment, would imply that Ca is partially mobilized following spray applications of DMSO.

The Mn content in terminal foliage of Solanum tuberosum was also significantly increased following DMSO applications to the foliage (Table 15). However, this effect occurred only at the higher soil P levels. Since the availability of soil Mn has been shown to increase with increasing soil P (Mederski and Hoff, 1958), this effect may simply be due to enhanced root growth and expansion. Another

explanation for the influence of soil P level may be a lowered soil pH which often accompanies soil P additions although such a change was not measurable (Table 3). It is also conceivable that DMSO further reduced soil pH in the vicinity of the plant roots. This effect seems unlikely, however, due to the small quantity of DMSO employed. Thus, as in the case of Ca, a direct effect of DMSO on Mn translocation following foliar application seems apparent although further confirming work is warranted.

The uptake of Zn by Phaseolus vulgaris was significantly reduced at the higher soil P-K treatment (Table 21). These results are in accord with other work dealing with a phosphate-induced Zn deficiency, for which a pertinent literature coverage is provided by Boawn and Brown (1968).

With Solanum tuberosum, which was planted in close proximity to a band of 10-20-20 fertilizer, Zn concentrations were not reduced by the differential soil P levels. These results, in contrast to those obtained with Phaseolus vulgaris discussed above, may have occurred due to the greater root expansion by the potato plants, thus providing more root exposure for Zn absorption. While the solubility of Zn decreases in high concentrations of the phosphate ion (Tisdale and Nelson, 1966), impurities in the fertilizer may also be of some consequence. Evidence of this appears in the results of the soil tests (Table 3) where the in-row samples showed 28% and 39% more

extractable Zn present than the between-row samples at the high and low soil P levels, respectively.

The methods and rates of fertilization of these two crops undoubtedly is linked to the response to Zn and P in the soil. With Phaseolus vulgaris, differential fertility levels were established two years prior to planting, lower fertilizer applications were used, and broadcasting was the mode of incorporation. Under these conditions no soil Zn differences were noted although soil P levels were markedly different between the low and high P plots (58.7 and 129.3 ppm respectively). In the case of Solanum tuberosum, differential P levels were established only weeks prior to planting, relatively high fertilizer rates were used, and band application was employed. Soil Zn as well as P was higher under the higher soil P conditions in this study (Table 3).

Since commercial fertilizers are frequently supplemented with trace elements, the above results are not surprising, but aid in explaining the higher Zn levels in the tissues of Solanum tuberosum contrasted to Phaseolus vulgaris. In the latter case, soil Zn levels were not different between the low and high fertility plots due to thorough incorporation of the fertilizer with the soil plus the length of time which elapsed between establishment of the high and low soil P-K plots and the planting of the test crop. As presented earlier, soil applied Zn is quickly immobilized (Brown et al., 1962). Suppression

of Zn uptake and/or transport by the plants following heavy soil P applications therefore appears linked to the time between Zn application to the soil and the planting of the crop.

The antagonism between Zn and P in certain plants is well substantiated and certainly is of consequence under many conditions. This study however, may illustrate that this imbalance is not necessarily a consequence of high P usage in all cases. For example, the Zn level of phosphate rock from commercial rock quarries of the Western U. S. ranges from 210 to 1046 ppm (Clark and Hill, 1958). While much of this Zn is certainly unavailable, its presence is nevertheless of importance in the Zn nutrition of plants.

The significant changes which occurred in the nutrient composition of both Solanum tuberosum and Phaseolus vulgaris as a result of the differential soil P or P-K levels are noteworthy, particularly the aspect of Zn: P ratios. The results of Studies VI and VII from control plants grown at the high and low soil P or P-K levels provide the data on Zn: P ratios listed in Table 27.

Table 27. Influence of soil P levels on Zn: P ratio in plant tissue (control treatments) of Phaseolus vulgaris and Solanum tuberosum (Studies VI and VII).

Crop Species	Soil Fertility Status	Yield (lbs)	Zn: P (ppm/%)
Phaseolus v.	High P-K	25.5	17.6/0.327 = 53.8
Phaseolus v.	Low P-K	18.7	20.4/0.294 = 69.5
Solanum t.	High P	26.0	41.5/0.500 = 83.0
Solanum t.	Low P	24.2	35.8/0.393 = 91.1

As observed in Table 27, the Zn: P ratio is greater in both crops at the lower soil P levels. Whether the addition of Zn by foliar sprays tended to correct the possible high P levels in the tissue of Phaseolus vulgaris giving rise to a Zn: P imbalance, is presumptive at this time. As reflected in higher bean yields (Table 19), however, significant benefits occurred at the lower soil P-K level following foliar sprays of Zn in combination with DMSO. Of relevance in this regard is the fact that enhanced effectiveness of various herbicides has been shown when applied in combination with DMSO (Morre, Eisenger, and Mussell, 1967; Mussell, et al., 1967).

The possibility exists that under the higher soil P-K conditions, the plant system contains P at levels which cannot be benefited from Zn addition from the standpoint of correcting the low Zn: P ratio in the tissue.

In the case of Solanum tuberosum where no yield benefits were shown by Zn additions to foliage, although significant changes in Zn were caused by the different soil P levels (Table 5, Appendix), work by Boawn and Brown (1968) appears relevant. In their research, using solution culture and a constant Zn level (1 ppm), the Zn: P ratio (ppm/%) in plant tops increased from 52 to 123 as the P level was decreased from 8. 8 ppm to 0 ppm in the solution culture in which the potatoes were growing. Such findings are of interest particularly since Wilson (1967) obtained significant yield increases following Zn

application to foliage of Solanum tuberosum, which commercially is fertilized heavily with phosphorus. Such positive yield effects may have been due, however, to overcoming a Zn deficit in the nutrition of the plant, and to implicate a correction of a Zn: P imbalance may be conjectural.

Growth and Developmental Aspects

Crop Yields as Influenced by Foliar Sprays

As discussed above, beneficial effects on crop yield of Phaseolus vulgaris grown under conditions of low soil P were noted following foliar Zn applications. While such benefits might be ascribed to improvement of the Zn: P imbalance, confirming evidence is not yet available.

In the case of Solanum tuberosum, statistically significant benefits were observed at the low soil P level when foliar sprays of Zn or Zn + Mn in combination with DMSO were applied (Table 13). Reductions in tuber yield were also encountered, particularly when Mn was applied, with or without DMSO as an adjuvant. This latter observation is noteworthy since Sherman (1957) has stated that Solanum tuberosum can be regarded as an especially sensitive plant to Mn excess. In this regard, the depressing effect of Mn sprays on crop yield was greatest at the high soil P levels with a significant treatment x soil P interaction being obtained (Table 5, Appendix). While

no significant effect of soil P was obtained on the Mn content of either crop species, investigations by Mederski and Hoff (1958), working with soybeans, have shown an increased availability of soil Mn at the higher soil P levels. The potential for toxicity from Mn-containing fungicides such as Maneb under certain crop and soil conditions is inferred from the above results.

Tuberization and Crop Yield as Influenced by Pre-Plant DMSO Tuber Immersion Treatment

Significant benefits were derived from pre-plant DMSO treatment of tubers as seen in both increased tuber numbers and weight. These benefits may be a reflection of the positive effect of DMSO on stem number. In this respect, results show optimal effects on stem number at the 5% and 10% DMSO concentrations, on tuber number at the 5% DMSO concentration, on total tuber weight at the 5% and 10% DMSO concentrations, and on yield of marketable tubers at the 5% DMSO concentration.

Results relating to enhancement of stem production are in general agreement with work by Davidson (1967) who showed enhanced sprouting of tubers of Solanum tuberosum following DMSO treatment. Additional work with sweet potatoes (Whatley et al., 1968) has shown an accelerated growth of sprouts following DMSO immersion treatments ranging from 5 - 15 minutes in a 12% solution.

In Study VIII, which was conducted entirely in the field, no

visual benefits on general vigor or accelerated growth were noted, although the treatment effects on stem number were visibly distinct. In contrast to the work with sweet potatoes, where it was concluded that DMSO levels in excess of 12% may be used for treating sweet potato roots, the current study shows that pre-plant tuber treatments (30 minutes) in excess of 10% DMSO will most likely produce adverse effects on sprouting and subsequent growth of Solanum tuberosum. Work in this area by Davidson (1967) also shows detrimental effects of DMSO on tubers when used at concentrations of 16 or 32%.

The mechanism by which DMSO exerts its beneficial effects on sprouting and subsequent crop yield may be an altering of the auxin concentration and/or distribution in the tuber. Thimann and Skoog (1933) suggest that auxin exerts a direct retarding effect on the development of lateral (adventitious) buds. According to this theory, when the auxin concentration in the tissue adjacent to a bud exceeds a given threshold, growth of the lateral bud is inhibited. Consequently, if DMSO produces such an effect as increased sprouting, the effect may seemingly be exerted through an auxin interaction such as transport or degradation within the tuber of Solanum tuberosum. Of relevance at this point is the observation that treatment of potato tubers with gibberellic acid increases sprout growth (Timm et al., 1962). In addition, Mussell et al. (1967) have shown the effectiveness of the synthetic, hormonelike compound, 2,4-dichlorophenoxyacetic

acid, in promoting abscission of leaves from Phaseolus vulgaris, to be increased fourfold by application in DMSO when compared with application in water at identical rates.

In view of the above mentioned effects of DMSO on stem and subsequent tuber production, as well as altered nutritive element balance in Solanum tuberosum and Phaseolus vulgaris, further work appears warranted to evaluate the mode of action of DMSO on the above plant characteristics and processes.

SUMMARY

DMSO, a highly polar solvent first synthesized in Germany in 1867 is presently being actively investigated for prospective use in both medicine and agriculture. Agricultural studies generally relate to its usefulness as a penetrant carrier such as in foliar sprays or as an agent which may influence growth and development of plants.

Preliminary studies dealing with DMSO showed that severe phytotoxicity occurred when soil levels in excess of 0.1% DMSO (wt/wt) were employed. Definite toxicity also occurred in hydroponic studies at this concentration with a distinct weight reduction of Solanum tuberosum being noted at the 0.01% DMSO (v/v) level. Visible symptoms of phytotoxicity such as marginal burning appeared similar to salt injury.

Soil treated with DMSO showed a reduced pH and, when used as a growth medium, provided for a dramatically increased Mn and moderately decreased P uptake by Phaseolus vulgaris. A highly significant negative correlation existed between soil pH and Mn content of the plant foliage. Nutrient solutions to which DMSO was added showed no improved uptake of ^{65}Zn or ^{54}Mn compared to controls. The influence of soil-incorporated DMSO on nutrient uptake appears to be due largely to pH alteration rather than increased root permeability.

Foliar application of DMSO singly and in combination with Zn and Mn in several cases showed significant effects on crop yield and nutrient levels in terminal plant foliage. Soil P level was a highly significant factor governing nutrient levels of Ca, P, Mg, and Zn in tissues of both Phaseolus vulgaris and Solanum tuberosum. Distinct yield benefits from DMSO + Zn applications to foliage of Phaseolus vulgaris were noted, a response strongly governed by soil P level. Adverse effects of applied foliar Mn were evident as reflected in reduced yields of both crop species and may be noteworthy in light of continued use of Mn-containing fungicides for disease control, particularly on Solanum tuberosum. DMSO exerted no statistically significant effect on plant nutrient levels when combined soil P data were evaluated.

Distinct yield benefits at harvest were found when DMSO was used as a pre-plant immersion treatment for tubers of Solanum tuberosum. When used at concentrations of 5 or 10% (v/v), DMSO enhanced stem production, tuber number, and tuber weight. Alteration of the auxin gradient within the tuber by DMSO treatment which would govern the production of lateral buds appears a possible mechanism of action.

The benefits observed following DMSO tuber treatment of Solanum tuberosum as well as benefiting nutrient transport and auxin levels in both crop species appear worthy of additional study.

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Appendix Table 1. Summary table of the analysis of variance for: (a) total dry weight of foliage of Phaseolus vulgaris (Study III); (b) Mn content of foliage of Phaseolus vulgaris at harvest (Study III); (c) soil pH at harvest (Study III).

Source of Variation	DF	Variance (a)	(b)	(c)
Total	34			
Treatment	6	0.701	244584**	0.4775**
Replication	4	0.162	8317	0.00276
Error	24	0.298	13047	0.0125

**Statistical significance at the 1% level.

Appendix Table 2. Summary table of the analysis of variance for: (a) Mn content of pods of Phaseolus vulgaris at harvest (Study III); (b) P content of pods of Phaseolus vulgaris at harvest (Study III).

Source of Variation	DF	Variance (a)	(b)
Total	34		
Treatment	6	9596**	0.00302*
Replication	4	160	0.00049
Error	24	349	0.00103

*Statistical significance at the 5% level.

**Statistical significance at the 1% level.

Appendix Table 3. Summary table of the analysis of variance for pH of nutrient solutions following harvest of Solanum tuberosum (Study IV).

Source of Variation	DF	Variance
Total	34	
Treatment	6	0.023
Replication	4	0.033
Error	24	0.030

Appendix Table 4. Summary table of the analysis of variance for: (a) total tuber number of Solanum tuberosum at harvest as influenced by pre-plant DMSO immersion treatment of parent tubers (Study V); (b) total tuber weight of Solanum tuberosum at harvest as influenced by pre-plant DMSO immersion treatment of parent tubers (Study V).

		Variance	
Source of Variation	DF	(a)	(b)
Total	39		
Treatment	7	2.57	14.84
Replication	4	1.25	9.60
Error	28	3.17	44.78

Appendix Table 5. Summary table of the analysis of variance for: (a) total tuber weight (Study VI); (b) Ca content of terminal foliage of Solanum tuberosum (Study VI); (c) Mn content of terminal foliage of Solanum tuberosum (Study VI); (d) P content of terminal foliage of Solanum tuberosum (Study VI); (e) Mg content of terminal foliage of Solanum tuberosum (Study VI); (f) K content of terminal foliage of Solanum tuberosum (Study VI); (g) Zn content of terminal foliage of Solanum tuberosum (Study VI).

			Variance						
Soil Fertility Level	Source of Variation	DF	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Low P	Total	47							
	Treatment	7	35.9**	0.05	396	0.0013	0.0085	0.026	20.2
	Replication	5	9.1	0.03	67	0.0069*	0.0030	0.062	28.9
	Error	35	10.6	0.03	579	0.0027	0.0054	0.015	47.3
High P	Total	47							
	Treatment	7	14.5	0.07*	1539*	0.0031*	0.0087	0.030	90.9
	Replication	5	7.4	0.04	120	0.0048**	0.0034	0.080	66.9
	Error	35	15.3	0.03	539	0.0012	0.0068	0.040	59.3
Combined Analysis	High vs Low P	1	6.2	0.67**	672	0.1187**	0.0578**	0.040	411.3**
	Treatment	7	28.8*	0.03	615	0.0003	0.0060	0.011	73.7
	Treatment x P Level Interaction	7	51.4**	0.22**	2031**	0.0214**	0.0257**	0.060*	169.8**
	Error	70	12.9	0.03	559	0.0020	0.0061	0.027	53.3

*Significant at 5% level.

**Significant at 1% level.

Appendix Table 6. Summary table of the analysis of variance for: (a) fresh pod weight of Phaseolus vulgaris (Study VII); (b) Ca content of terminal foliage of Phaseolus vulgaris (Study VII); (c) Mn content of terminal foliage of Phaseolus vulgaris (Study VII); (d) P content of Phaseolus vulgaris (Study VII); (e) Mg content of terminal foliage of Phaseolus vulgaris (Study VII); (f) K content of terminal foliage of Phaseolus vulgaris (Study VII); (g) Zn content of terminal foliage of Phaseolus vulgaris (Study VII).

Soil Fertility Level	Source of Variation	DF	Variance (a)	(b)	(c)	(d)	(e)	(f)	(g)
Low P-K	Total	47							
	Treatment	7	3.09*	0.0333*	13.0	0.0004	0.00035	0.03	6.36
	Replication	5	19.40**	0.0732**	94.4*	0.0050	0.00398	0.18**	78.60**
	Error	35	1.20	0.0135	27.3	0.0023	0.00076	0.03	9.26
High P-K	Total	47							
	Treatment	7	4.94*	0.0053	22.9	0.0004	0.00042	0.045	3.02
	Replication	5	8.57**	0.0416*	163.0**	0.0060**	0.00140**	0.069	59.60**
	Error	35	1.93	0.0148	15.1	0.0004	0.00057	0.051	3.46
Combined Analysis	High vs Low P	1	401.4**	0.570**	16.0	0.0898**	0.02590**	2.970**	342.80**
	Treatment	7	2.3	0.012	23.0	0.00021	0.00011	0.033	5.68
	Treatment x P Level Interaction	7	65.4**	0.120**	38.3	0.00359*	0.00445**	0.500**	58.40**
	Error	70	1.6	0.014	21.2	0.00135	0.00067	0.042	6.36

*Significant at 5% level.

**Significant at 1% level.

Appendix Table 7. Summary table of the analysis of variance for: (a) total number of stems of Solanum tuberosum per plot (Study VIII); (b) total number of tubers of Solanum tuberosum per plot (Study VIII); (c) total tuber weight of Solanum tuberosum per plot (Study VIII); (d) number of marketable size tubers (U.S. No. 1) of Solanum tuberosum per plot (Study VIII); (e) weight of marketable size tubers (U.S. No. 1) of Solanum tuberosum per plot (Study VIII).

Soil Fertility Level	Source of Variation	DF	Variance (a)	(b)	(c)	(d)	(e)
Low P	Total	47					
	Treatment	7	76.9	491.0	159.7	330.0*	94.7
	Replication	5	56.0	45.9	65.4	61.0	30.9
	Error	35	38.5	150.6	98.4	111.42	217.7
High P	Total	47					
	Treatment	7	67.0	208.1	150.9*	271.1**	118.5**
	Replication	5	64.2	23.6	49.7	42.0	42.7
	Error	35	40.7	114.8	53.9	74.9	35.8
Combined Analysis	High vs Low P	1	661.0**	213.0	45.2	2291.0**	157.8
	Treatment	7	166.3**	582.1**	255.7**	558.7**	194.0
	Treatment x P Level Interaction	7	266.6**	729.6**	317.1**	928.9**	235.7
	Error	70	39.6	132.7	76.1	93.1	126.8

*Statistical significance at the 5% level.

**Statistical significance at the 1% level.

Appendix Table 8. Percentage emergence of Phaseolus vulgaris five days following planting as influenced by DMSO soil treatment (Study I). Each value represents percent emergence based on ten plants.

	Replication					
Treatment	I	II	III	IV	V	Mean
Control	80	90	80	80	90	84
0.01% DMSO	100	90	90	90	100	94
0.1% DMSO	100	90	90	90	90	92
0.5% DMSO	90	80	90	80	80	84
1.0% DMSO	80	80	80	80	90	82

Appendix Table 9. Dry weight of total foliage of Phaseolus vulgaris at harvest (Study I). Each value represents the weight (g) of oven dried (70°C) tissue of five plants.

	Replication					
Treatment	I	II	III	IV	V	Mean
Control	10.972	12.587	11.412	9.912	12.218	11.420
0.01% DMSO	11.141	10.712	12.202	10.891	9.471	10.883
0.1% DMSO	8.216	9.706	9.004	8,116	10.299	9.068
0.5% DMSO	4.622	5.700	4.104	5.918	3.091	4.687
1.0% DMSO	1.901	2.066	1.314	1.706	1.200	1.637

Appendix Table 10. Dry weight of total foliage of Phaseolus vulgaris at harvest (Study II). Each value represents the weight (g) of oven dried (70°C) tissue of one plant.

	Replication							
Treatment	I	II	III	IV	V	VI	VII	Mean
Control	4.607	2.887	4.910	3.741	3.646	4.420	4.678	4.127
0.001% DMSO	3.969	3.480	3.845	3.682	5.124	4.606	3.778	4.076
0.01% DMSO	3.909	3.982	4.074	3.429	3.715	3.332	3.568	3.716
0.05% DMSO	3.634	3.673	2.670	5.500	3.884	3.343	3.795	3.786
0.1% DMSO	3.179	3.542	2.588	3.600	3.810	3.354	2.914	3.341

Appendix Table 11. Mn content of pods of Phaseolus vulgaris at harvest (Study III). Values represent Mn (ppm) on a dry weight basis.

Treatment	Replication I	II	III	IV	V	VI	VII	Mean
Control	20	17	33	23	20	16	17	21
0.001% DMSO	20	26	19	20	20	21	20	21
0.01% DMSO	20	26	32	26	39	18	20	26
0.05% DMSO	44	34	31	31	35	68	102	49
0.1% DMSO	102	108	156	131	77	87	93	108

Appendix Table 12. P content of pods of Phaseolus vulgaris at harvest (Study III). Values represent P (%) on a dry weight basis.

Treatment	Replication I	II	III	IV	V	VI	VII	Mean
Control	0.237	0.224	0.275	0.200	0.200	0.224	0.250	0.230
0.001% DMSO	0.288	0.224	0.211	0.200	0.262	0.250	0.224	0.237
0.01% DMSO	0.237	0.200	0.188	0.188	0.262	0.211	0.224	0.216
0.05% DMSO	0.147	0.188	0.200	0.211	0.237	0.200	0.237	0.203
0.1% DMSO	0.118	0.211	0.200	0.200	0.178	0.224	0.167	0.185

Appendix Table 13. Dry weight of total foliage of Solanum tuberosum at harvest following growth in nutrient culture at various DMSO concentrations in combination with ^{65}Zn. (Study IV). Each value represents the weight (g) of oven dried (70°C) tissue of one plant.

Treatment	Replication I	II	III	IV	V	VI	VII	Mean
^{65}Zn	4.13	3.89	2.91	4.78	3.77	4.09	4.93	4.07
^{65}Zn + 0.001% DMSO	3.20	4.21	3.87	3.37	4.04	3.33	4.58	3.80
^{65}Zn + 0.01% DMSO	2.90	3.17	2.98	2.42	3.28	2.48	3.75	2.99
^{65}Zn + 0.1% DMSO	0.40	0.64	0.52	0.47	0.91	0.77	1.03	0.54

Appendix Table 14. ^{65}Zn activity (dpm/g) of oven dried (70°C) apical tissue of Solanum tuberosum following growth in nutrient culture at various DMSO concentrations (Study IV). Values represent dpm x 10^2/g based on oven dried tissue weight.

	Replication							
Treatment	I	II	III	IV	V	VI	VII	Mean ±S. D.
^{65}Zn	3530	2945	2700	2891	3409	2582	3109	3024±351
^{65}Zn + 0.001% DMSO	2918	2691	3109	3473	3282	3009	3473	3136±290
^{65}Zn + 0.01% DMSO	3191	3536	2700	2945	3373	2773	2009	2933±510
^{65}Zn + 0.1% DMSO	3491	3382	3527	2745	2709	3609	3454	3274±379

Appendix Table 15. Dry weight of total foliage of Solanum tuberosum at harvest following growth in nutrient culture at various DMSO concentrations in combination with ^{54}Mn (Study IV). Each value represents the weight (g) of oven dried (70°C) tissue of one plant.

	Replication							
Treatment	I	II	III	IV	V	VI	VII	Mean
^{54}Mn	4.07	3.82	3.44	4.84	4.26	6.16	3.65	4.32
^{54}Mn + 0.001% DMSO	4.02	4.81	3.77	4.65	5.16	3.91	4.63	4.42
^{54}Mn + 0.01% DMSO	3.10	2.62	2.33	2.69	2.00	3.08	2.16	2.57
^{54}Mn + 0.1% DMSO	0.62	0.91	0.48	1.06	0.55	0.66	0.47	0.68

Appendix Table 16. ^{54}Mn activity (dpm/g) of oven dried (70°C) apical tissue of Solanum tuberosum following growth in nutrient culture at various DMSO concentrations (Study IV). Values represent dpm x 10^2/g based on oven dried tissue weight.

	Replication							
Treatment	I	II	III	IV	V	VI	VII	Mean±S. D.
^{54}Mn	3600	3874	4132	4379	4216	3379	3758	3906±357
^{54}Mn + 0.001% DMSO	4326	3516	3916	3568	4132	2747	3679	3700±514
^{54}Mn + 0.01% DMSO	3747	4284	4089	3384	3589	4195	4305	3941±367
^{54}Mn + 0.1% DMSO	3942	3300	4226	4205	2853	4126	4321	3856±557

Appendix Table 17. ^{65}Zn activity (dpm/ml) of the nutrient solution at various sampling intervals during the 21-day exposure period of Solanum tuberosum to the respective treatments (Study IV). Values represent dpm x 10/ml.

Day of Sampling	Treatment	Replication I	II	III	IV	V	VI	VII	Mean±S.D.
0	^{65}Zn	616	604	605	584	572	599	578	594±16
	^{65}Zn + 0.001% DMSO	611	582	553	605	597	601	631	597±24
	^{65}ZN + 0.01% DMSO	609	585	615	572	565	566	583	585±20
	^{65}Zn + 0.1% DMSO	584	574	561	553	624	594	589	583±23
1	^{65}Zn	624	589	596	565	551	565	563	579±25
	^{65}Zn + 0.001% DMSO	595	589	570	604	591	562	554	581±19
	^{65}Zn + 0.01% DMSO	592	603	579	554	617	589	572	587±21
	^{65}Zn + 0.1% DMSO	598	592	582	571	554	595	576	581±16
3	^{65}Zn	589	602	563	567	573	584	543	574±19
	^{65}Zn + 0.001% DMSO	586	587	599	554	568	579	571	578±15
	^{65}Zn + 0.01% DMSO	598	617	575	561	573	596	588	587±19
	^{65}Zn + 0.1% DMSO	576	601	555	586	592	605	556	582±20
6	^{65}Zn	601	569	592	572	550	566	543	570±21
	^{65}Zn + 0.001% DMSO	551	607	568	553	561	561	589	570±21
	^{65}Zn + 0.01% DMSO	587	583	544	533	559	584	560	564±21
	^{65}Zn + 0.1% DMSO	557	557	582	543	533	578	558	558±17
12	^{65}Zn	464	491	569	506	511	521	546	515±35
	^{65}Zn + 0.001% DMSO	471	515	434	493	500	563	531	501±42
	^{65}Zn + 0.01% DMSO	565	489	478	459	491	509	474	495±35
	^{65}Zn + 0.1% DMSO	474	477	553	492	511	546	490	506±32
18	^{65}Zn	195	169	313	120	228	208	132	195±65
	^{65}Zn + 0.001% DMSO	105	178	170	129	150	111	207	150±37
	^{65}Zn + 0.01% DMSO	165	214	144	148	112	163	250	171±46
	^{65}Zn + 0.1% DMSO	472	469	534	462	448	401	511	471±43
21	^{65}Zn	0	0	0	0	0	0	0	0
	^{65}Zn + 0.001% DMSO	0	0	0	0	0	0	0	0
	^{65}Zn + 0.01% DMSO	0	0	0	0	0	0	0	0
	^{65}Zn + 0.1% DMSO	473	475	515	418	429	423	467	456±35

Appendix Table 18. ^{54}Mn activity (dpm/ml) of the nutrient solution at various sampling intervals during the 21-day exposure period of Solanum tuberosum to the respective treatments (Study IV). Values represent dpm x 10/ml.

Day of Sampling	Treatment	Replication I	II	III	IV	V	VI	VII	Mean ± S.D.
0	^{54}Mn	967	978	1019	986	943	974	995	980±24
	^{54}Mn + 0.001% DMSO	983	924	1031	921	1011	1051	1000	989±50
	^{54}Mn + 0.01% DMSO	947	890	1045	1050	1125	897	1037	999±88
	^{54}Mn + 0.1% DMSO	932	951	1034	976	1007	927	958	969±39
1	^{54}Mn	992	923	996	939	958	933	974	959±29
	^{54}Mn + 0.001% DMSO	1053	953	958	868	953	971	948	957±53
	^{54}Mn + 0.01% DMSO	945	900	975	1046	1053	942	960	974±56
	^{54}Mn + 0.1% DMSO	918	945	981	991	966	927	941	953±27
3	^{54}Mn	988	966	1004	946	930	924	987	964±31
	^{54}Mn + 0.001% DMSO	903	896	886	814	956	910	849	888±45
	^{54}Mn + 0.01% DMSO	865	892	914	1025	917	870	928	916±54
	^{54}Mn + 0.1% DMSO	934	934	970	982	920	867	933	934±37
6	^{54}Mn	967	874	954	903	901	936	951	928±36
	^{54}Mn + 0.001% DMSO	856	882	838	762	900	869	751	837±58
	^{54}Mn + 0.01% DMSO	873	790	889	1045	819	897	918	890±82
	^{54}Mn + 0.1% DMSO	903	915	965	944	889	852	928	914±37
12	^{54}Mn	801	777	825	740	806	802	748	786±32
	^{54}Mn + 0.001% DMSO	738	725	738	824	723	648	728	732±51
	^{54}Mn + 0.01% DMSO	771	752	841	934	701	799	787	798±74
	^{54}Mn + 0.1% DMSO	785	805	832	805	743	781	793	792±27
18	^{54}Mn	588	505	688	553	640	637	625	605±61
	^{54}Mn + 0.001% DMSO	519	613	539	648	553	577	589	577±44
	^{54}Mn + 0.01% DMSO	541	475	678	529	590	632	632	582±71
	^{54}Mn + 0.1% DMSO	628	664	745	638	753	690	721	691±50
21	^{54}Mn	421	371	531	420	483	427	424	440±52
	^{54}Mn + 0.001% DMSO	346	396	508	427	528	414	458	440±64
	^{54}Mn + 0.01% DMSO	292	422	433	375	463	373	435	399±57
	^{54}Mn + 0.1% DMSO	641	642	751	657	696	689	558	662±60

Appendix Table 19. pH level of nutrient solutions containing various combinations of DMSO and ^{65}Zn following harvest of the foliage of Solanum tuberosum (Study IV).

Treatment	Replication I	II	III	IV	V	VI	VII	Mean
Control	4.9	5.1	5.2	5.0	5.3	5.3	5.0	5.1
^{65}Zn	5.2	4.9	5.2	4.9	4.8	5.0	5.2	5.0
^{65}Zn + 0.001% DMSO	5.1	5.1	5.6	5.1	4.9	5.2	4.9	5.1
^{65}Zn + 0.01% DMSO	5.3	4.9	5.2	5.0	5.1	5.1	5.4	5.1
^{65}Zn + 0.1% DMSO	5.1	5.0	5.0	5.2	5.1	5.0	4.8	5.0

Appendix Table 20. Total tuber number at harvest following pre-plant immersion of parent tubers in various concentrations of DMSO (Study V).

Treatment	Replication I	II	III	IV	V	Mean
Control	4	6	2	4	2	3.6
0.001% DMSO	2	2	5	6	4	3.8
0.01% DMSO	5	3	3	2	3	3.2
0.1% DMSO	4	4	7	3	3	4.2
0.5% DMSO	7	3	4	2	4	4.0
1.0% DMSO	2	5	3	3	3	3.2
5.0% DMSO	2	3	6	8	5	4.8
10.0% DMSO	3	4	7	5	7	5.2

Appendix Table 21. Total tuber weight at harvest following pre-plant immersion of parent tuber in various concentrations of DMSO (Study V). Values represent fresh weight (g) of tubers from one plant.

Treatment	Replication I	II	III	IV	V	Mean
Control	5.80	26.90	15.25	18.25	7.82	14.80
0.001% DMSO	25.60	7.54	8.95	10.98	12.11	13.03
0.01% DMSO	11.90	19.10	12.08	6.02	8.10	11.44
0.1% DMSO	13.80	14.10	15.41	19.40	6.60	13.86
0.5% DMSO	17.61	14.80	7.05	12.30	5.60	11.47
1.0% DMSO	10.40	5.50	16.40	10.64	20.60	12.71
5.0% DMSO	11.10	16.70	3.50	15.57	26.92	14.75
10.0% DMSO	12.62	12.87	18.22	23.00	15.10	16.36

Appendix Table 22. Total tuber weight at harvest of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent the total fresh weight (lbs) of tubers from three plants.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	24.3	23.3	26.0	25.0	29.9	27.7	26.0
		0	+	26.8	19.5	16.7	17.6	26.5	24.3	21.9
		+	0	26.3	29.7	19.3	31.9	18.9	23.3	24.9
		+	+	24.1	19.8	22.3	28.9	20.8	21.5	22.9
	+DMSO	0	0	25.7	23.0	26.7	29.0	28.4	21.2	25.7
		0	+	24.8	20.7	27.0	28.3	22.9	23.1	24.5
		+	0	20.3	22.4	28.2	24.1	32.9	30.6	26.4
		+	+	27.3	27.0	24.2	20.1	23.5	22.8	24.1
Low	-DMSO	0	0	22.9	24.6	26.0	23.7	26.3	21.8	24.2
		0	+	21.5	23.6	24.3	21.0	17.7	26.3	22.4
		+	0	25.7	24.3	24.1	30.3	21.5	22.5	24.8
		+	+	31.9	21.8	22.6	27.6	23.5	27.2	25.8
	+DMSO	0	0	30.8	19.1	20.6	24.6	18.2	25.5	23.1
		0	+	20.4	22.1	25.3	20.1	23.3	29.0	23.4
		+	0	25.7	24.0	31.5	24.5	30.9	25.3	27.0
		+	+	31.9	28.0	28.2	26.3	34.5	30.4	29.9

Appendix Table 23. Ca content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent Ca (%) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	0.66	0.74	0.73	0.51	0.60	0.90	0.69
		0	+	0.82	0.75	0.76	0.91	0.77	1.04	0.84
		+	0	0.72	0.88	0.94	0.77	1.25	0.81	0.89
		+	+	1.14	0.77	0.96	0.74	0.88	0.75	0.87
	+DMSO	0	0	0.80	1.39	1.34	0.69	0.83	1.06	1.02
		+	0	0.90	1.46	0.90	0.82	0.83	0.84	0.96
		+	0	0.92	0.89	0.85	0.78	0.84	0.76	0.84
		+	+	0.68	0.77	0.75	0.71	0.75	0.73	0.73
Low	-DMSO	0	0	1.30	0.83	0.77	1.11	0.51	0.78	0.88
		0	+	1.04	0.79	1.15	0.56	0.56	0.56	0.77
		+	0	0.54	0.70	0.65	0.73	0.52	0.70	0.64
		+	+	0.52	0.79	0.58	0.69	0.60	0.61	0.63
	+DMSO	0	0	0.49	0.98	0.69	0.54	0.56	0.63	0.65
		0	+	0.70	0.58	0.60	0.60	0.73	0.78	0.67
		+	0	0.71	0.52	0.79	0.92	0.60	0.53	0.68
		+	+	0.64	0.61	0.50	0.47	0.55	0.85	0.60

Appendix Table 24. Mn content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent Mn (ppm) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	83	114	90	95	108	121	102
		0	+	85	128	134	154	152	135	131
		+	0	138	125	168	106	148	115	133
		+	+	110	117	115	148	112	158	127
	+DMSO	0	0	168	151	154	158	124	162	152
		0	+	125	168	134	118	143	128	136
		+	0	148	100	96	120	114	101	113
		+	+	96	125	122	110	106	125	114
Low	-DMSO	0	0	178	129	118	145	94	123	131
		0	+	148	100	137	115	147	92	123
		+	0	116	130	138	112	80	106	114
		+	+	90	113	110	171	143	114	124
	+DMSO	0	0	88	128	108	88	146	97	109
		0	+	138	140	122	125	136	126	131
		+	0	144	92	122	110	109	106	114
		+	+	119	112	107	109	111	169	121

Appendix Table 25. P content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent P (%) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	0.534	0.567	0.500	0.467	0.483	0.450	0.500
		0	+	0.500	0.500	0.500	0.435	0.435	0.534	0.484
		+	0	0.517	0.551	0.500	0.435	0.351	0.500	0.476
		+	+	0.451	0.567	0.517	0.450	0.500	0.451	0.489
	+DMSO	0	0	0.483	0.375	0.435	0.400	0.435	0.418	0.424
		0	+	0.483	0.400	0.467	0.517	0.483	0.534	0.481
		+	0	0.567	0.467	0.500	0.483	0.400	0.483	0.483
		+	+	0.514	0.551	0.467	0.418	0.483	0.451	0.481
Low	-DMSO	0	0	0.338	0.418	0.375	0.325	0.500	0.400	0.393
		0	+	0.325	0.375	0.288	0.435	0.387	0.567	0.396
		+	0	0.435	0.338	0.375	0.338	0.500	0.451	0.406
		+	+	0.451	0.351	0.363	0.400	0.400	0.435	0.400
	+DMSO	0	0	0.451	0.375	0.363	0.517	0.467	0.467	0.440
		0	+	0.400	0.387	0.435	0.451	0.400	0.387	0.410
		+	0	0.418	0.435	0.375	0.375	0.418	0.451	0.412
		+	+	0.375	0.387	0.400	0.387	0.467	0.375	0.399

Appendix Table 26. Mg content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent Mg (%) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	0.352	0.389	0.431	0.369	0.356	0.476	0.396
		0	+	0.428	0.459	0.429	0.669	0.429	0.541	0.493
		+	0	0.398	0.437	0.484	0.441	0.686	0.490	0.489
		+	+	0.550	0.405	0.500	0.420	0.487	0.411	0.462
	+DMSO	0	0	0.408	0.578	0.650	0.405	0.379	0.547	0.495
		0	+	0.495	0.678	0.476	0.452	0.381	0.410	0.482
		+	0	0.440	0.488	0.421	0.443	0.421	0.439	0.442
		+	+	0.371	0.385	0.470	0.412	0.412	0.432	0.414
Low	-DMSO	0	0	0.650	0.419	0.399	0.576	0.401	0.468	0.486
		0	+	0.605	0.410	0.511	0.396	0.379	0.350	0.442
		+	0	0.320	0.372	0.352	0.467	0.395	0.432	0.390
		+	+	0.306	0.368	0.341	0.438	0.404	0.402	0.377
	+DMSO	0	0	0.360	0.481	0.385	0.402	0.404	0.395	0.405
		0	+	0.370	0.333	0.373	0.401	0.449	0.471	0.399
		+	0	0.387	0.292	0.432	0.578	0.408	0.374	0.412
		+	+	0.366	0.360	0.309	0.340	0.409	0.435	0.370

Appendix Table 27. K content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent K (%) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	2.71	3.13	2.61	2.74	2.80	2.74	2.79
		0	+	2.93	2.95	2.66	3.04	2.99	3.19	2.96
		+	0	2.84	3.06	2.79	2.79	3.08	2.84	2.90
		+	+	2.73	3.19	2.85	2.74	3.17	2.73	2.90
	+DMSO	0	0	2.63	3.05	2.51	2.71	2.68	2.95	2.75
		0	+	2.62	2.80	2.70	3.29	2.80	3.05	2.88
		+	0	3.16	2.61	2.64	2.93	2.37	3.00	2.79
		+	+	2.59	3.04	2.87	2.59	3.10	2.98	2.86
Low	-DMSO	0	0	3.25	2.77	2.66	3.40	2.98	2.89	3.01
		0	+	2.91	2.69	2.70	2.91	2.84	2.76	2.80
		+	0	3.09	2.99	2.84	2.91	2.96	2.76	2.93
		+	+	2.90	2.89	2.41	3.10	3.13	2.91	2.89
	+DMSO	0	0	2.80	2.85	2.99	2.86	3.14	2.94	2.93
		0	+	2.92	2.67	3.04	2.81	2.80	3.03	2.88
		+	0	3.06	2.81	2.96	2.89	2.95	2.61	2.88
		+	+	2.68	2.73	2.84	2.99	2.93	2.73	2.82

Appendix Table 28. Zn content of terminal foliage of Solanum tuberosum grown under two soil P conditions and subjected to eight foliar treatments (Study VI). Values represent Zn (ppm) on a dry weight basis.

Soil P Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High	-DMSO	0	0	51.2	41.3	30.7	51.6	39.9	34.7	41.5
		0	+	38.7	35.0	30.1	40.0	32.0	38.5	35.7
		+	0	36.1	44.0	26.1	37.9	18.9	32.8	32.6
		+	+	31.0	44.0	26.8	35.0	37.9	31.6	34.4
	+DMSO	0	0	30.5	27.1	23.1	34.5	40.0	26.7	30.3
		0	+	33.1	25.9	26.8	38.7	51.6	38.5	35.8
		+	0	42.1	28.9	30.7	34.5	33.8	52.0	37.0
		+	+	41.5	49.7	49.1	30.6	45.8	30.9	41.2
Low	-DMSO	0	0	25.8	61.5	30.2	38.0	34.6	24.7	35.8
		0	+	25.8	34.1	20.1	32.9	30.0	37.8	30.1
		+	0	40.1	26.6	30.8	24.8	30.1	37.6	31.7
		+	+	38.1	26.8	30.8	30.0	30.5	37.9	32.4
	+DMSO	0	0	37.8	26.6	30.6	30.8	30.6	37.8	32.3
		0	+	30.4	28.8	34.4	27.6	24.4	34.4	30.0
		+	0	30.3	35.0	26.9	24.9	30.2	38.3	30.9
		+	+	33.8	30.2	38.7	33.8	30.8	26.5	32.3

Appendix Table 29. Yield of pods of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent fresh weight (lbs) of pods from 125 plants.

Soil Fertility Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	25.8	27.3	22.7	26.6	24.7	25.5	25.4
		0	+	24.5	25.5	22.9	24.4	22.0	24.9	24.0
		+	0	23.4	20.9	21.4	24.1	20.2	25.6	22.6
		+	+	23.5	21.3	23.9	24.0	22.1	22.0	22.8
	+DMSO	0	0	24.5	21.9	23.0	22.5	21.5	26.4	23.3
		0	+	23.8	23.3	23.3	23.7	24.3	23.0	23.6
		+	0	22.7	21.4	22.1	24.6	22.6	24.3	22.9
		+	+	24.2	21.2	23.9	25.8	18.9	25.1	23.2
Low P-K	-DMSO	0	0	15.8	20.4	17.8	16.5	20.6	21.1	18.7
		0	+	15.1	20.9	18.3	17.9	21.2	19.8	18.9
		+	0	18.1	19.3	20.7	18.7	19.6	19.9	19.4
		+	+	16.0	19.4	18.9	16.2	22.0	19.7	18.7
	+DMSO	0	0	18.6	21.6	18.4	17.5	19.8	20.1	19.3
		0	+	17.8	19.8	20.7	16.8	22.2	20.9	19.7
		+	0	21.0	22.0	19.7	19.7	21.0	21.9	20.9
		+	+	17.1	21.0	20.2	17.6	22.3	19.3	19.6

Appendix Table 30. Ca content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent Ca (%) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	1.42	1.69	1.43	1.49	1.84	1.59	1.58
		0	+	1.55	1.69	1.50	1.48	1.69	1.54	1.58
		+	0	1.45	1.34	1.26	1.81	1.75	1.63	1.54
		+	+	1.58	1.66	1.45	1.53	1.69	1.62	1.59
	+DMSO	0	0	1.45	1.41	1.71	1.49	1.71	1.63	1.57
		0	+	1.38	1.51	1.58	1.59	1.65	1.41	1.52
		+	0	1,53	1.44	1.41	1.43	1.57	1.76	1.52
		+	+	1.59	1.50	1.44	1.50	1.45	1.60	1.51
Low P-K	-DMSO	0	0	1.71	1.87	1.57	1.39	1.69	1.38	1.60
		0	+	1.66	1.75	1.51	1.39	1.60	1.61	1.57
		+	0	2.00	1.85	1.74	1.69	1.76	1.69	1.79
		+	+	1.96	1.78	1.78	1.72	1.61	1.53	1.73
	+DMSO	0	0	2.03	1.64	1.79	1.71	1.68	1.49	1.72
		0	+	1.91	1.78	1.69	1.81	1.85	1.58	1.77
		+	0	1.82	1.53	1.60	1.84	1.83	1.52	1.69
		+	+	1.74	1.81	1.58	1.77	1.79	1.79	1.75

Appendix Table 31. Mn content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent Mn (ppm) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	29	44	32	34	29	34	34
		0	+	30	43	27	34	28	37	33
		+	0	30	29	20	33	28	34	29
		+	+	31	33	21	33	29	32	30
	+DMSO	0	0	28	28	17	31	29	37	28
		0	+	22	40	22	32	30	32	30
		+	0	32	29	26	34	31	39	32
		+	+	30	31	20	34	31	35	30
Low P-K	-DMSO	0	0	29	42	31	23	35	38	33
		0	+	29	29	36	23	29	34	30
		+	0	31	27	28	40	27	32	31
		+	+	35	33	28	36	31	35	33
	+DMSO	0	0	29	24	25	34	29	35	29
		0	+	21	40	22	34	31	38	31
		+	0	28	34	25	42	26	37	32
		+	+	28	33	25	44	29	40	33

Appendix Table 32. P content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent P (%) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	0.387	0.300	0.351	0.313	0.288	0.325	0.327
		0	+	0.363	0.313	0.325	0.313	0.325	0.351	0.332
		+	0	0.387	0.375	0.387	0.338	0.300	0.325	0.352
		+	+	0.375	0.338	0.387	0.325	0.275	0.300	0.333
	+DMSO	0	0	0.387	0.351	0.313	0.313	0.288	0.351	0.334
		0	+	0.375	0.325	0.351	0.300	0.313	0.325	0.331
		+	0	0.387	0.363	0.387	0.313	0.325	0.313	0.348
		+	+	0.351	0.375	0.363	0.313	0.313	0.313	0.338
Low P-K	-DMSO	0	0	0.300	0.312	0.288	0.250	0.300	0.313	0.294
		0	+	0.275	0.288	0.300	0.262	0.250	0.275	0.275
		+	0	0.288	0.275	0.288	0.275	0.211	0.275	0.269
		+	+	0.288	0.300	0.288	0.237	0.250	0.313	0.279
	+DMSO	0	0	0.288	0.275	0.262	0.275	0.250	0.300	0.275
		0	+	0.313	0.300	0.288	0.237	0.211	0.288	0.273
		+	0	0.288	0.288	0.288	0.262	0.211	0.325	0.277
		+	+	0.275	0.262	0.288	0.250	0.200	0.313	0.265

Appendix Table 33. Mg content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent Mg (%) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	0.387	0.450	0.452	0.407	0.441	0.428	0.428
		0	+	0.429	0.435	0.453	0.438	0.411	0.452	0.436
		+	0	0.395	0.378	0.405	0.448	0.444	0.442	0.419
		+	+	0.459	0.414	0.422	0.439	0.407	0.447	0.431
	+DMSO	0	0	0.429	0.378	0.470	0.440	0.442	0.445	0.434
		0	+	0.405	0.410	0.448	0.449	0.435	0.402	0.425
		+	0	0.469	0.410	0.454	0.404	0.390	0.452	0.430
		+	+	0.444	0.381	0.449	0.407	0.387	0.404	0.412
Low P-K	=DMSO	0	0	0.454	0.521	0.378	0.480	0.471	0.448	0.459
		0	+	0.397	0.500	0.410	0.471	0.449	0.481	0.451
		+	0	0.470	0.489	0.410	0.448	0.467	0.481	0.461
		+	+	0.468	0.506	0.381	0.457	0.460	0.453	0.454
	+DMSO	0	0	0.482	0.476	0.437	0.470	0.484	0.453	0.467
		0	+	0.468	0.501	0.425	0.467	0.467	0.442	0.462
		+	0	0.436	0.432	0.442	0.496	0.484	0.415	0.451
		+	+	0.427	0.495	0.509	0.463	0.475	0.470	0.473

Appendix Table 34. K content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent K (%) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	1.68	1.70	1.66	1.91	2.09	1.60	1.77
		0	+	1.46	1.66	1.87	1.76	2.45	1.76	1.83
		+	0	2.79	1.91	1.88	2.14	1.98	1.55	2.04
		+	+	1.76	1.91	2.03	1.79	1.84	1.81	1.86
	+DMSO	0	0	1.92	2.06	1.69	1.79	2.20	1.63	1.88
		0	+	2.04	1.83	1.70	1.86	1.63	1.87	1.82
		+	0	1.67	1.80	1.79	1.89	2.06	1.71	1.82
		+	+	1.65	1.81	1.76	1.67	1.82	1.91	1.77
Low P-K	-DMSO	0	0	1.38	1.42	1.29	1.14	1.82	1.71	1.46
		0	+	1.01	1.40	1.46	1.36	1.83	1.64	1.45
		+	0	1.35	1.46	1.59	1.59	1.42	1.70	1.52
		+	+	1.32	1.48	1.61	1.15	1.52	1.90	1.50
	+DMSO	0	0	1.21	1.46	1.44	1.55	1.51	1.49	1.44
		0	+	1.77	1.28	1.49	1.25	1.46	1.66	1.49
		+	0	1.10	1.40	1.35	1.69	1.59	1.66	1.47
		+	+	1.27	1.56	1.93	1.57	1.59	2.03	1.66

Appendix Table 35. Zn content of terminal foliage of Phaseolus vulgaris grown under two soil fertility levels (P and K) and subjected to eight foliar treatments (Study VII). Values represent Zn (ppm) on a dry weight basis.

Soil Fertility Level		Treatment Zn	Treatment Mn	Replication I	II	III	IV	V	VI	Mean
High P-K	-DMSO	0	0	22.7	12.4	18.2	18.2	14.7	19.1	17.6
		0	+	19.5	12.1	16.6	16.9	15.5	21.5	17.0
		+	0	21.9	15.4	18.7	18.4	15.3	21.3	18.5
		+	+	21.8	13.2	18.5	17.8	16.5	18.5	17.7
	+DMSO	0	0	23.6	13.0	12.0	15.3	16.3	19.1	16.6
		0	+	20.0	14.8	15.7	16.9	17.4	18.3	17.2
		+	0	21.0	14.6	24.3	16.7	15.3	19.0	18.5
		+	+	20.4	15.0	24.0	15.5	14.4	19.8	18.2
Low P-K	-DMSO	0	0	20.1	22.6	14.8	18.3	21.9	24.9	20.4
		0	+	17.5	22.1	15.4	16.7	30.2	18.7	20.1
		+	0	22.0	23.0	14.6	18.6	24.7	20.1	20.5
		+	+	21.9	23.0	24.0	15.1	28.0	24.9	22.8
	+DMSO	0	0	23.8	21.5	16.6	17.1	27.6	24.6	21.9
		0	+	23.8	23.6	16.9	14.4	24.9	23.2	21.1
		+	0	22.6	23.6	18.5	21.7	24.0	24.9	22.6
		+	+	26.5	18.0	18.9	20.2	18.2	30.3	22.0

Appendix Table 36. Total number of stems of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Each value represents the total number of stems per plot (14 feet; 12 parent tubers).

Soil P Level	Treatment	Replication I	II	III	IV	V	VI	Mean
High	Control	54	50	56	49	56	51	53
	0.001% DMSO	43	54	48	51	52	50	50
	0.01% DMSO	48	58	47	39	51	63	51
	0.1% DMSO	53	62	58	52	43	51	53
	0.5% DMSO	44	55	43	49	45	45	47
	1.0% DMSO	51	52	60	49	59	53	54
	5.0% DMSO	63	67	49	44	59	68	58
	10.0% DMSO	53	54	60	56	69	58	58
Low	Control	66	52	56	61	45	66	58
	0.001% DMSO	55	53	61	64	54	59	58
	0.01% DMSO	56	64	55	49	55	55	56
	0.1% DMSO	50	61	54	56	59	61	57
	0.5% DMSO	65	45	47	55	50	55	53
	1.0% DMSO	50	56	70	64	56	58	59
	5.0% DMSO	57	66	61	66	58	65	62
	10.0% DMSO	65	48	67	70	62	73	64

Appendix Table 37. Total number of tubers of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Each value represents the total number of tubers per plot (14 feet; 12 parent tubers).

Soil P Level	Treatment	Replication I	II	III	IV	V	VI	Mean
High	Control	149	156	146	162	159	153	154
	0.001% DMSO	149	161	152	165	155	157	157
	0.01% DMSO	157	141	152	130	163	163	151
	0.1% DMSO	158	177	161	148	141	152	156
	0.5% DMSO	141	159	160	142	168	161	155
	1.0% DMSO	161	150	171	188	143	161	162
	5.0% DMSO	168	178	169	163	170	172	170
	10.0% DMSO	161	164	154	162	165	152	160
Low	Control	172	155	162	160	135	173	160
	0.001% DMSO	169	158	151	166	156	151	158
	0.01% DMSO	165	159	157	152	152	158	157
	0.1% DMSO	122	171	133	169	159	142	149
	0.5% DMSO	164	139	162	157	159	140	153
	1.0% DMSO	153	152	184	159	161	164	162
	5.0% DMSO	175	183	168	185	166	172	175
	10.0% DMSO	157	167	180	176	185	178	174

Appendix Table 38. Total weight of tubers of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Each value represents the total weight (lbs) of tubers per plot (14 feet; 12 parent tubers).

Soil P Level	Treatment	Replication I	II	III	IV	V	VI	Mean
High	Control	43.1	45.3	49.6	58.5	65.6	60.1	53.7
	0.001% DMSO	46.0	48.5	66.5	48.9	59.7	50.2	53.3
	0.01% DMSO	54.0	59.7	50.4	53.7	52.1	66.0	56.0
	0.1% DMSO	43.6	69.7	50.0	58.1	51.2	55.1	54.6
	0.5% DMSO	41.8	47.5	56.1	41.1	61.6	61.2	51.5
	1.0% DMSO	64.9	66.5	59.4	53.7	63.7	59.8	61.3
	5.0% DMSO	69.7	73.5	68.4	64.7	66.7	56.6	66.6
	10.0% DMSO	57.4	54.4	58.5	68.6	54.9	60.4	59.0
Low	Control	56.0	47.8	51.4	70.0	64.1	56.5	57.6
	0.001% DMSO	52.0	60.7	48.7	60.8	43.0	60.6	54.3
	0.01% DMSO	54.4	49.7	57.5	47.8	61.6	74.0	57.5
	0.1% DMSO	61.9	52.6	50.6	54.7	46.8	42.7	51.5
	0.5% DMSO	52.1	57.9	56.1	74.0	55.0	43.8	56.5
	1.0% DMSO	69.5	57.8	56.2	67.5	50.5	46.1	57.9
	5.0% DMSO	79.7	60.0	66.3	56.9	60.2	61.7	64.1
	10.0% DMSO	60.0	67.1	59.4	72.0	68.6	78.4	67.6

Appendix Table 39. Number of marketable size (U.S. No. 1) tubers of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Each value represents the total number of U.S. No. 1 tubers per plot (14 feet; 12 parent tubers).

Soil P Level	Treatment	Replication I	II	III	IV	V	VI	Mean
High	Control	74	72	69	82	73	68	73
	0.001% DMSO	67	66	81	68	85	64	72
	0.01% DMSO	68	72	75	88	83	72	76
	0.1% DMSO	61	63	81	69	73	80	71
	0.5% DMSO	56	66	89	78	64	81	72
	1.0% DMSO	91	80	81	68	79	97	83
	5.0% DMSO	97	101	84	92	81	88	91
	10.0% DMSO	71	80	75	68	76	79	75
Low	Control	88	73	75	67	83	73	77
	0.001% DMSO	87	75	93	81	69	70	79
	0.01% DMSO	93	87	78	85	88	85	86
	0.1% DMSO	88	83	66	98	81	92	85
	0.5% DMSO	89	94	94	85	77	88	88
	1.0% DMSO	87	91	91	106	103	89	95
	5.0% DMSO	110	80	94	92	116	101	99
	10.0% DMSO	82	86	84	60	77	111	83

Appendix Table 40. Weight of marketable size (U. S. No. 1) tubers of Solanum tuberosum grown under two soil P conditions and subjected to eight DMSO pre-plant immersion treatments (Study VIII). Each value represents the weight (lbs) of U. S. No. 1 tubers per plot (14 feet; 12 parent tubers).

Soil P Level	Treatment	Replication I	II	III	IV	V	VI	Mean
High	Control	29.3	28.5	31.8	38.2	46.5	42.1	36.0
	0.001% DMSO	31.2	32.3	47.1	35.3	46.4	30.8	37.2
	0.01% DMSO	37.3	30.8	33.5	28.5	35.1	40.3	34.3
	0.1% DMSO	25.0	39.9	30.7	39.7	32.6	34.5	33.7
	0.5% DMSO	25.7	28.4	45.2	34.2	44.0	44.4	37.0
	1.0% DMSO	45.9	40.4	37.1	33.9	45.1	41.9	40.7
	5.0% DMSO	50.3	51.7	40.9	45.4	48.3	48.3	47.5
	10.0% DMSO	47.2	37.2	43.1	38.3	38.2	35.9	40.0
Low	Control	40.0	32.2	32.1	42.5	48.1	39.3	39.0
	0.001% DMSO	35.9	43.0	33.1	54.8	31.2	31.1	38.2
	0.01% DMSO	37.5	36.3	40.2	35.3	42.2	47.1	39.8
	0.1% DMSO	45.2	32.6	37.5	33.6	31.7	34.1	35.8
	0.5% DMSO	38.5	39.7	38.7	43.9	41.2	36.1	39.7
	1.0% DMSO	43.6	34.9	44.4	43.2	38.8	39.8	40.8
	5.0% DMSO	53.0	42.6	45.2	49.8	44.0	47.2	47.0
	10.0% DMSO	42.7	50.2	42.1	49.6	51.0	44.7	46.7