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Influence of Adjuvants on Foliar Absorption of Nitrogen and Phosphorus by Soybeans

Larry A. Stein[1] **and J. Benton Storey**[2]
Department of Horticultural Sciences, Texas A&M University, College Station, TX 77843

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Abstract. **Adjuvants at various concentrations were evaluated for phytotoxicity and capacity to enhance foliar absorption of N and P. Some adjuvants among the following classes were phytotoxic to soybean (*Glycine max* Merr.) leaves at concentrations of 0.25% and 0.5% active ingredient on a volume or weight/volume basis: sulfonates, alcohols, ethyoxylated hydrocarbons, esters, sulfates, and amines. Many adjuvants in the following classes: alcohols, sulfonates, ethoxylated hydrocarbons, polyethylene glycols, carbohydrates, proteins, and phosphates were not phytotoxic at concentrations as high as 1.0%. Sometimes increasing phytotoxicity occurred at increasing concentrations, but the humectants, such as glycerol and propylene glycol, were not phytotoxic at concentrations of 10.0%. Selected adjuvants were mixed with a foliar fertilizer (12.0N–1.7P–3.3K–0.5S) and evaluated for enhancement of foliar absorption of N and P. The average increases in percentage of N and P for the glycerol, lecithin, and Pluronic L-121 (an ethyoxylated hydrocarbon), and foliar fertilizer combinations, respectively, were 8.9%, 2.2%, and 2.5% for N and 34.2%, 27.6%, and 20.8% for P over the foliar fertilizer control, respectively, for the 3 adjuvants.**

Foliar sprays often are used to fulfill micronutrient needs of plants (19). Although foliar fertilizers may not adequately supply all of the required macronutrients (6, 19), foliar sprays are important as supplemental sources (19). Properly timed foliar applications of nutrients may overcome nutrient deficiencies if demand exceeds root uptake (2, 18). As a result, various commercial foliar fertilizers have been formulated to supply nutrient ions at critical times. The results from the use of these sprays have been quite erratic, and, in some studies, yields have increased (2), whereas in others, yields have remained the same or have decreased (15, 17). Possible reasons for erratic results include poor retention, poor penetration, improper formulations, and rapid drying of the solution. Leaf burn (8) may lessen the value of foliar fertilization due to reduction of leaf area available for photosynthesis and yield (16).

Adjuvants are added to increase the effectiveness of spray solutions. The most frequently used adjuvants are surfactants, which decrease surface tension, and humectants, which keep solutions moist for longer periods of time. Adjuvants should overcome some of the problems associated with erratic results. This work was initiated to find adjuvants that would increase the foliar absorption of N and P.

Materials and Methods

Plant materials. Field-grown 'Lee', 'Amsoy', and 'Bragg' soybeans were used as test plants in the phytotoxicity studies. Soybeans were grown in the field in Summer 1980 and 1981. Soils were treated with 330 $kg \cdot ha^{-1}$ of fertilizer (13.0N–7.3P–10.8K) or were inoculated with *Rhizobium japonicum*, Strain 110, in a peat base, and fertilized with P at 50 $kg \cdot hr^{-1}$ and K at 25 $kg \cdot ha^{-1}$ banded in the row prior to planting. Plants were watered by trickle irrigation.

Greenhouse-grown 'Bragg' soybeans were used in all studies with foliar sprays for enhanced N and P uptake. Plants were grown in sand culture in a glass greenhouse in which environmental conditions ranged from 60% to 90% RH and 21° to 35°C. Three plants were grown per 15-cm pot and were watered automatically 3 times daily with a modified Steiner (3) nutrient solution applied directly to the sand. Each pot received about 600 ml of nutrient solution per day. Pots were drenched weekly with *O,O*-dimethyl *S* [2-(methylamino-2-oxoethyl] phosphorodithioate (dimethoate), a systemic insecticide, at the rate of 5 ml per 30 liters of water to prevent thrip damage.

Phytotoxicity. The uppermost, fully opened soybean leaves from mature, flowering cultivars of 'Amsoy', 'Lee', or 'Bragg' were taken at random for treatment. Leaves were cut at the petiole near the stem and sealed in polyethylene bags for transport to the laboratory. Petioles of the leaves were recut under water, placed in 250 ml of distilled water, and allowed to equilibrate for 1 hr before treatment. A 10-μl drop of solution, composed of the undiluted foliar fertilizer and the specified weight or volume of adjuvant, was applied to the middle adaxial surface of the leaflet, slightly to the right of the midvein. Drops were monitored for spread and outlined before drying with a permanent marker pen. The pen marks were found to be nontoxic when applied to control leaves.

A wide range of concentrations of adjuvants was screened because adjuvant properties can change drastically above, below, or at the critical micelle concentration (CMC) (9). The CMC occurs when an adjuvant reaches a critical level in an aqueous system and forms molecular aggregates. Maximum lowering of surface tension occurs at the CMC (9). Six or 8 concentrations of 45 adjuvants (Table 1) were screened at 3 leaves per treatment. Leaves were examined and rated for burn 4 days after treatment using the following rating scale: X = concentration not tested; 1 = no effect; 2 = slight surface burn on the treated area with no cell collapse; 3 = slight to heavy surface burn on the treated area with a few areas of cell collapse; 4 = heavy surface burn on the treated area with much cell necrosis and collapse; and 5 = total cell necrosis and collapse on the treated area.

Enhanced N and P studies. Initially 26 adjuvants [including (see Table 1): glycerol, sorbitol, Aerosol OT-75 and MA-80, L-77, Al-1575, carboxymethylcellulose, Carbowax-200, gelatin, lecithin, pectin, starch, Compex, First Prize Soil Condi-

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[1] Extension Horticulturist, Texas A&M Research and Extension Center, Stephenville.
[2] Professor.

Table 1. Chemical class, ionic form, and source of selected adjuvants used in studies.

Adjuvant	Class	Ionic form[z]	Source[y]
Glycerol	Alcohol	NA	14
Propylene glycol	Alcohol	NA	16
Sorbitol	Alcohol	NA	13
Regulaid	Alcohol	N	12
Tronic	Alcohol	A/N/C	12
Armeen 18 D	Amine	C	5
Uran-75	Amine (urea-ammonium nitrate)	NA	1
Urea	Amine	NA	9
Carboxymethylcellulose	Carbohydrate	NA	15
Starch	Carbohydrate	NA	14
Pectin	Carbohydrate	NA	15
Atlox 1045	Ester	N	11
Jet-Wet	Ethoxylated hydrocarbon	N	7
Pluronic L-121	Ethoxylated hydrocarbon	N	6
Tergitol NP-9	Ethoxylated hydrocarbon	N	17
Saturall	Ethoxylated hydrocarbon	N	8
Wex	Ethoxylated hydrocarbon	N	8
Span 20	Ethoxylated hydrocarbon	N	11
Tween 80	Ethoxylated hydrocarbon	N	11
Tween 85	Ethoxylated hydrocarbon	N	11
Bio-88	Ethoxylated hydrocarbon	N	12
Bio-Film	Ethoxylated hydrocarbon	A/N	12
Buffer-X	Phosphate	A/N	12
Gafac PE-510	Phosphate	A	10
Gafac RS-710	Phosphate	A	10
Lecithin	Phosphate	Z	15
Carbowax	Polyethylene glycols	NA	17
Gelatin	Protein	NA	14
L-77	Silicone	N	17
Compex	Sulfate	A	12
Dimethylsulfoxide	Sulfate	NA	9
Fomark	Sulfate	A	12
Aerosol AY-65	Sulfonate	A	2
Aerosol OT-S	Sulfonate	A	2
Aerosol OT-75	Sulfonate	A	2
Aerosol MA-80	Sulfonate	A	2
Atlas G-3300	Sulfonate	A	2
Ultrawet AOK	Sulfonate	A	4
Ultrawet K	Sulfonate	A	4
Al-1575	Sodium dodecyl benzyene sulfonate	A	11
Atplus 300F	Ethoxylated ester	N	11
Atplus 401	Activator adjuvant for MSMA concentrates with coupling agents	A	11
Atplus 522	Activator adjuvant for sodium chlorate concentrates with coupling agents	A	11
Atplus 526	Concentrated blend of fatty acids, fatty acid esters, and alkoxylated polyhydric alcohol fatty acid esters	N	11
First Prize	Bacillus thuringensis and pyerthin	N	3
Amway L.O.C.	Primary alcohol alkoxylate	N	3

[z]A = anionic, C = cationic, N = nonionic, Z = zwitterionic, A/N = anionic/nonionic blends, A/N/C = anionic/nonionic/cationic blends, NA = not applicable.

[y]1 = Allied Chemical, Morristown, N.J.; 2 = American Cyanamid, Houston, Texas; 3 = Amway, Ada, Mich.; 4 = Arco Chemical, Houston, Texas; 5 = Armak Industrial Chemicals, Chicago, Ill.; 6 = BASF Wyandotte, Wyandotte, Mich.; 7 = C.J. Martin Co., Nacogdoches, Texas; 8 = Conklin, Shakopee, Minn.; 9 = Fischer Scientific, Fair Lawn, N.J.; 10 = GAF, Charlotte, N.C.; 11 = ICI Americas, Wilmington, Del.; 12 = Kalo Laboratories, Kansas City, Mo.; 13 = Lonza, Fair Lawn, N.J.; 14 = J.T. Baker Chemical, Phillipsbury, N.J.; 15 = Sigma; 16 = Texaco Chemical, Bellaire, Texas; 17 = Union Carbide, New York, N.Y.

tioner, Atplus 300-F, Atlas G-3300, Gafac PE-510, Pluronic L-121, RS-710, Tergitol NP-9, Tween 80, Regulaid, Ultrawet, Ultrawet AOK, Span 20, and Tween 85, which were not phytotoxic at 0.5% concentrations or below] were tested for enhancement of N and P content of soybean plants. Armeen 18-D and Uran-75 were used because they enhanced uptake of Fe (7) and Zn (13). Adjuvants were mixed at 0.05% (v/v or w/v) with a foliar fertilizer (FF). The foliar fertilizer containing 12.0N–1.7P–3.3K–0.5S by weight was manufactured by Allied Chemical, Morristown, N.J. under the trade name Folian. Urea sup-

Table 2. Nitrogen and P content of 3-week-old 'Lee' soybean plants treated with adjuvant-foliar fertilizer solutions containing 0.05% of various adjuvants at 430 μl per pot compared to runoff sampled 3 days after treatments.

Adjuvant mixed with FF	Composition of shoots[z] Percent N (dry wt) 430 μl	Percent N Runoff	Percent P (dry wt) 430 μl	Percent P Runoff	Phytotoxicity[y] 430 μl	Phytotoxicity Runoff
			Expt. A			
Control[x]	4.5 b[z]	4.5	0.50 b	0.42 d	1.0 a	1.0 b
FF[w]	4.7 b	5.3 c	0.51 b	0.83 a	1.3 a	4.0 a
Glycerol	5.9 a	5.3 c	0.80 a	0.61 bc	1.3 a	4.0a
Sorbitol	4.7 b	5.5 bc	0.54 b	0.56 cd	2.0 a	4.0 a
Aerosol OT-75	4.8 b	5.8 ab	0.51 b	0.78 ab	2.5 a	5.0 a
L-77	4.5 b	5.9 a	0.37 b	0.94 a	2.0 a	5.0 a
			Expt. B			
Control[x]	4.5 c	4.5 f	0.34 a	0.37 c	1.0 a	1.0 b
FF[w]	4.9 abc	5.7 e	0.34 a	0.62 d	2.0 a	4.0 a
Lecithin	5.0 a	6.7 ab	0.40 a	1.04 b	1.8 a	5.0 a
Pectin	5.0 a	6.3 cd	0.41 a	0.78 c	1.8 a	4.0a
Starch	4.9 abc	6.4 bc	0.34 a	0.79 c	1.5 a	4.0a
Compex	4.9 abc	6.5 bc	0.35 a	0.98 b	2.0 a	4.5 a
First Prize	4.9 abc	6.8 a	0.33 a	1.21 a	1.8 a	5.0 a
Uran 75	4.6 bc	6.4 bc	0.24 b	0.96 b	2.0a	4.0 a

[z]Means within columns and experiment separated by Duncan's multiple range test, $P = 5\%$.
[y]Visual rating of phytotoxicity.
[x]Unsprayed control.
[w]Foliar fertilizer control.

Table 3. Nitrogen, P, and chlorophyll content of 3-week-old 'Bragg' soybean plants treated with 430 μl per pot of foliar fertilizer containing selected adjuvants on 18 June 1981 and sampled 4 days after treatment.

Treatment	Plant composition[z] Chlorophyll per gram of tissue	Percent N (dry wt)	Percent P (dry wt)
	Glycerol experiment		
Control[y]	3.05 b	3.9 b	0.24 b
FF[x]	3.09 b	4.0 ab	0.24 b
Glycerol + FF[w]	3.33 a	4.1 a	0.30 a
	Lecithin experiment		
Control[y]	3.05 b	3.9 b	0.25 b
FF[x]	3.09 ab	4.0 ab	0.24 b
Lecithin + FF[w]	3.32 a	4.1 a	0.30 a
	Pluronic L-121 experiment		
Control[y]	3.05 b	3.9 b	0.25 ab
FF[x]	3.09 b	4.0 ab	0.24 b
Pluronic L-121 + FF[w]	3.46 a	4.1 a	0.27 a

[z]Means within experiments and columns separated by Duncan's multiple range tests, $P = 5\%$.
[y]Unsprayed control.
[x]Foliar fertilizer control.
[w]Foliar fertilizer used in combination with specified compound.

plied 10.8% and $(NH_4)_2HPO_4$ supplied 1.2% of the 12% N. All of the 1.7% P came from $(NH_4)_2HPO_4$, and the 0.5% S came from K_2SO_4. Part of the 3.3% K came from K_2SO_4 and the remainder from KCl. Four pots, or 12 plants per adjuvant, were sprayed with an aerosol sprayer that delivered 430 $\mu l \cdot s^{-1}$ for 4 sec or about 1 sec/pot, which simulated an aerial application of 90 $liters \cdot ha^{-1}$ of canopy area. The canopy of the plants in the experiments reported in this paper covered 16 cm of the 76 cm row width, so 21% was used to calculate the actual area covered by the canopy. (The calculation was as follows: 430 $\mu l \cdot s^{-1}$ × 4 sec/12 plants = 1720 μl/12 plants = 143 μl/plant. Plant population for soybeans in commercial plantings in the Brazos River flood plain near the Texas A&M Univ. campus was 131,868/ha by count of 6 random 100-m, 76-cm rows. Ninety thousand milliliters of spray solution/ha per 131,868 plants = 682.5 μl/plant × 0.21 canopy coverage of space in 76-cm rows = 143.3 μl/plant.) The 90 $liters \cdot ha^{-1}$ rate was the commercial rate for undiluted foliar fertilizer that these treatments sought to emulate. A 2nd set of plants was sprayed to runoff with about 470 $liters \cdot ha^{-1}$. Pots were covered with aluminum foil to prevent excess solutions from entering the pot. Applications were made in the greenhouse before 9:00 AM on each spray date.

The 17 adjuvants that increased N and P in the initial screening were tested for their capacity to increase the N and P concentrations of plants and included: glycerol, lecithin, Pluronic L-121, Armeen 18-D, Aerosol OT-75, Compex, First Prize Soil Conditioner, Regulaid, L-77, Atplus 300-F, Gafac PE-510, Ultrawet AOK, Ultrawet K, Span 20, Gafac RS-710, Atlas G-3300, and Carbowax-200. Treatments were made as before, and 6 pots (18 plants) were sprayed per treatment per adjuvant and concentration.

For all experiments, the plants were cut at the sand level 72 hr after treatment, and the fresh weights were determined. Each sample consisted of 3 plants. Samples were washed for 5 sec sequentially in 0.1% detergent in water, running tap water, 1.0% HCl, and 3 separate baths of distilled water to remove spray residues (15).

Samples were dried, weighed, and ground in a Wiley mill to pass a 20-mesh screen. Two hundred fifty milligrams of sample were block-digested for 2 hr at 380°C with 3.2 g of catalyst (15 g K_2SO_4 to 0.7 g HgO), 7 ml of H_2SO_4, and 5 ml of 30% H_2O_2 (Industrial Method No. 3698-75 A/A, Technicon Industrial Systems, Tarrytown, N.Y.). Portions from each tube were analyzed for total N and P using a Technicon Autoanalyzer II (Industrial Method No. 334-74-W/B).

The apical leaflet from the uppermost, fully opened leaf from each of the 3 plants in each sample was selected for chlorophyll determination. Leaflets were cut and sealed in polyethylene bags to prevent moisture loss and inserted in paper bags to prevent light degradation of chlorophyll. Storage time at 12°C did not exceed 48 hr for any sample. One 1.3-cm diameter disk was cut from the middle of each of the 3 leaflets adjacent to the midrib. Disks were weighed and then ground in a mortar and pestle using 10 cc of sand, 15 ml 80% acetone (v/v), and 0.015 g of $CaCO_3$. The homogenate was centrifuged, and the supernatant was read at 645 and 663 nm. Chlorophyll was expressed as milligrams per gram of fresh weight as calculated by Arnon's formulas (1). Treatment means were compared for significance by Duncan's multiple range test.

Results and Discussion

Phytotoxicity. The following adjuvants were not phytotoxic at concentrations of 0.01% a.i. (v/v or w/v) and above, including: Atplus 522, Al-1575, Carbowax 200, glycerol, CMC, propylene glycol, sorbitol, gelatin, lecithin, Pluronic L-121, starch, pectin, Ultrawet AOK, and Ultrawet K. Atplus, 300-F, Tween 85, First Prize, Gafac PE-510, Amway L.O.C., and Atlas G-3300, Atplus 526, Regulaid, and Aerosol MA-80 did not cause leaf burn at 1.0% and below. Gafac RSP-710, Aerosol OT-75, Tronic, Span 20, and L-77 were safe at 0.50% and below. Atlox 1045 A, Tween 80, DMSO, Bio-Film, urea, Tergitol NP-9, Aerosol AY-65, Jet-Wet, Compex, Buffer-X, Uran 75, and Aerosol OT-S were not phytotoxic at 0.25% and below. Fomark, Bio-88, Wex, Saturall, and Armeen 18-D caused no buring at 0.01%.

Enhanced N and P absorption. Glycerol (Table 2) was the only adjuvant that significantly increased the percentage of N and P over the unsprayed and the FF controls. Other adjuvants failed to increase the measured parameters over the FF control (Table 2).

If treatments were applied to runoff, Aerosol OT-75, L-77, lecithin, pectin, starch, Compex, First Prize, and Uran-75 increased the percentage of both N and P significantly, although severe burn resulted (Table 2). Generally, as the N and P concentrations increased, so did the phytotoxicity rating for the adjuvants for the runoff treatments. Chlorophyll and percentage of P were significantly increased over the untreated plants and those treated with FF by glycerol (Table 3). Lecithin significantly increased the percentage of P, and Pluronic L-121 significantly increased the chlorophyll content over the control and FF treated plants.

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