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Sprinkling-Induced Foliar Injury to Pepper Plants: Effects of Irrigation Frequency, Duration and Water Composition [1]

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Summary. This study was conducted to determine the conditions and causes of foliar salt absorption and injury from sprinkler irrigation with saline water. Bell pepper plants (*Capsicum annuum* L. cv. Yolo Wonder B) grown in covered nutrient solution cultures in the greenhouse were sprinkled daily with NaCl and $CaCl_2$ waters for up to 10 weeks. Unsprinkled plants grown in nonsaline, and in one experiment, saline cultures were compared with plants sprinkled with waters containing different concentrations of NaCl and/or $CaCl_2$. Both the frequency and duration of sprinkling (up to 32 min each day) were tested.
The results showed that Ca^{2+}, Na^+, and Cl^- were readily absorbed through the leaves at rates that were essentially linear functions of salt concentration and duration of sprinkling. Increasing frequency of sprinkling increased salt uptake and injury more than increasing duration. Sprinkling with either NaCl or $CaCl_2$ waters was more toxic to pepper than mixtures of the two salts. Although $CaCl_2$ was more toxic than NaCl, low concentrations of Ca^{2+} ameliorated the detrimental effects of NaCl waters. Foliar analyses indicated that leaf injury was not correlated with Cl^- accumulation. It appeared that it was caused directly by excessive cation accumulation or indirectly by the resultant ionic imbalance.

Foliar salt uptake is a major problem in sprinkling certain crops with saline waters. Many tree and vine crops are particularly susceptible to injury when sprinkled with waters containing only a few meq/liter of Cl^- or Na^+ [4]. Although herbaceous plant species generally are more resistant, an increasing number of crops (e.g. pepper, tomato, alfalfa) are reported to be affected by sprinkler irrigation waters when Na^+ and Cl^- concentrations exceed 20 meq/l [1, 5, 7]. Cotton, which is highly tolerant of soil salinity, is injured when sprinkled during the day with waters containing more than 3000 mg/l total salts [3].

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Despite the obvious foliar injury from sprinkling some herbaceous crops with saline water, the relative contributions of root and foliar absorption were not established in the studies above because the sprinkling waters were not excluded from the root medium. Symptoms of leaf injury caused by salts absorbed through the leaves cannot be distinguished from those caused by salts accumulated through the roots.

This study was undertaken to determine the amount of salt absorbed by leaves of pepper plants sprinkled with saline water and to identify conditions that influence the rate of absorption and the onset of foliar injury.

Materials and Methods

Bell pepper plants (*Capsicum annuum* L. cv. Yolo Wonder B) were started in potting mix and then transferred to nutrient solution cultures 1 month later. Four plants were initially transplanted into 19-l crocks containing 3 mM KNO_3, 2.5 mM $Ca(NO_3)_2$, 1.5 mM $MgSO_4$, 0.17 mM KH_2PO_4, 50 μM Fe as NaFeDTPA, 23 μM H_3BO_3, 4.5 μM $MnCl_2$, 0.4 μM $ZnSO_4$, 0.15 μM $CuSO_4$, and 0.05 μM H_2MoO_4 in demineralized water. The solutions were aerated continuously and replaced weekly with fresh solution. Transpirational losses were replaced with demineralized water.

Saline culture solutions were prepared by adding a 1 : 1 mixture of NaCl and $CaCl_2$ in 3 equal increments within 1 week to obtain final concentrations of 12.2 and 63.3 meq/l. The osmotic potentials (Ψ_0) of the control and two saline treatments were 0.5, −1, and −3 bars, respectively.

Three experiments were conducted in a greenhouse. Ambient mean daytime air temperatures ranged between 23 and 29, 24 and 31, and 20 and 25 °C during experiments I, II, and III respectively. Humidity was uncontrolled and varied with prevailing ambient conditions. Air pollution was controlled by passing all incoming air through activated charcoal filters. The solution cultures were insulated with fiberglass to avoid extreme temperature fluctuations in the root media.

Before sprinkling, the plants were thinned to obtain uniform plants with 1 per crock. Waterproof plastic sheeting was sealed around each plant stem with putty (Terostat IX, Teroson GmbH, Heidelberg)[3], to prevent sprinkling waters from entering the root media. The electrical conductivity and Cl^- concentration of the culture solutions were monitored throughout the experiment to ensure that the seal remained water-tight. Sprinkling waters were sprayed over the entire plant with overhead, full-cone nozzles that delivered 0.5 l/min.

Sprinkler treatments and sampling procedures for 3 separate experiments were as follows:

Experiment I

The objectives were *1)* to determine the relative effects of sprinkling frequency and duration with Cl^- waters at two concentrations and with different cations, Ca^{2+} and Na^+, on foliar salt uptake and injury, and *2)* to compare the injury caused by salt in the root medium with that caused by foliar application. Unsprinkled plants grown in culture solutions at −0.5, −1.0, and −3.0 bars Ψ_0 were compared to sprinkled plants grown in −0.5 bar solutions. Four sprinkling waters, 0, 1.0, and 10 meq/l $CaCl_2$ and 10 meq/l NaCl, were prepared with demineralized water. Water compositions were selected to determine *1)* the effects of Cl^- concentration, *2)* the relative effects of NaCl and $CaCl_2$ waters, and *3)* the degree of foliar leaching with demineralized water. The relative effects of frequency versus duration of sprinkling were tested with 3 frequency × duration combinations, 1 × 10, 1 × 32, and 8 × 4 (no. of sprinklings per day × duration of each in minutes). The 8 × 4 plants were sprinkled hourly

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[3] Mention of company names or products is for the benefit of the reader and does not imply endorsement, guarantee, or preferential treatment by the USDA or its agents.

every day starting at 0900 h, and the 1×10 and 1×32 plants were sprinkled once daily between 1300 and 1400 h. Sprinkling was initiated June 11 when the plants were 8 weeks old (approximately 5 to 6 fully expanded leaves) and continued for 10 weeks. Each treatment had 4 replicate crocks.

Mature leaves were tagged before the sprinkling treatment and were sampled for mineral analyses monthly for the last 2 months of the experiment. Young leaves, one-third to one-half expanded were sampled monthly for analysis of both entire leaves and of the separated injured margins and remaining uninjured interior.

Experiment II

The objective was to determine the relative toxicity of Na^+ and Ca^{2+} in waters sprinkled on pepper foliage. All plants were grown in nonsaline culture solutions. Unsprinkled control plants were compared with plants sprinkled 4 min each hour, 8 times a day with 10 meq/l Cl^- waters having $Ca^{2+} : Na^+$ ratios of 10 : 0, 3 : 7, 1 : 9, and 0 : 10. Each treatment was replicated 3 times with 4 crocks per replication.

Sprinkling was started May 26 after plants had developed 13 to 15 fully-expanded leaves (10 weeks old) and was continued for 10 weeks. Leaves 5–10 cm long were tagged before the sprinkling treatment. Subsequent leaves attaining a similar size were tagged at weekly intervals thereafter. Representative leaves from both the initial and subsequent tagging were sampled weekly for mineral analysis. Tagged leaves were also observed weekly for injury symptoms. Leaf injury indices were based on subjective judgments of the extent of tip and margin necrosis. (1 = incipient tip and/or margin necrosis; 2 = tip necrotic 1 to 5 mm, margin necrosis slight and spotty; 3 = injury intermediate between 2 and 4; 4 = leaf becoming hyponastic, tip necrotic 10 to 20 mm, margins necrotic up to 5 mm in places; 5 = injury intermediate between 4 and 6; 6 = leaf severely hyponastic, tip necrotic 20 to 40 mm, 50% of margins necrotic 5 mm or more. Leaves usually abscised before exhibiting more severe symptoms). Values reported in the Results Section are averages of 5 separate observations made over a 26-day period on various 35-day-old leaves that had been sprinkled daily following their emergence on the plant.

Experiment III

The objectives and experimental procedures were the same as in experiment II except that 25 meq/l Cl^- waters having $Ca^{2+} : Na^+$ ratios of 25 : 0, 12.5 : 12.5, 1 : 24, and 0 : 25 were tested. Ten week-old plants were sprinkled daily for 8 weeks beginning September 16.

In each experiment, mature fruit were harvested weekly. When sprinkling was discontinued, the entire plant tops were harvested and the remaining fruit and fresh plant material were weighed.

Leaves sampled for mineral analyses were washed with distilled water to remove any salt adhering to the leaf surfaces. Separate tests indicated the washing technique was effective [6]. Because of the difficulty of properly washing necrotic tissue without leaching endogenous ions, leaves were sampled at incipient injury stages before necrosis developed. Leaves with chlorotic margins were selected since this symptom preceded burning and necrosis by 1 or 2 days. Where separate analyses of the margins and the interior of the leaf were desired, a 5 mm strip around the edge of the leaf was removed. All samples were oven-dried at 65 °C and finely ground. Cations were determined on nitric-perchloric acid digests by atomic absorption spectrophotometry and Cl^- was extracted with dilute nitric acid and measured by potentiometric titration [2].

Results

Leaf margin chlorosis and tip necrosis appeared on all plants sprinkled with 10 meq/l $CaCl_2$ in Experiment I. Mature and intermediate-aged leaves from the 8×4 treatment developed marginal and interveinal hyponasty 5 days after sprinkling began and in 16 days developed severe marginal necrosis and interveinal

Table 1. Mineral analysis of young pepper leaves (Experiment I)[a]

Sprinkling water composition	Sprinkling Frequency (times/day) × Duration (min/sprinkling)									
	Cl		Na		Ca		K		Mg	
	1×32	8×4	1×32	8×4	1×32	8×4	1×32	8×4	1×32	8×4
meq/l	meq/g dry wt									
0	0.01	0.01	<0.01	0.02	0.74	0.80	1.60	1.53	0.51	0.52
1 $CaCl_2$	0.04	0.10	<0.01	0.01	0.80	1.00	1.48	1.53	0.46	0.54
10 $CaCl_2$	0.51	1.05	<0.01	0.02	1.37	1.98	1.49	1.36	0.53	0.55
10 NaCl	0.42	0.93	0.34	0.78	0.67	0.74	1.30	1.17	0.46	0.47
Unsprinkled Root media Ψ_0	Cl		Na		Ca		K		Mg	
bar										
−0.5	0.01		<0.01		0.82		1.63		0.54	
−1.0	0.16		0.01		1.06		1.52		0.40	
−3.0	0.90		0.06		1.73		1.35		0.36	

[a] Ion Concentrations are means of 3 sampling dates

Table 2. Pepper yields as influenced by sprinkling (Experiment I)

Treatment		Fruit Yield		Vegetative Shoot Fresh Weight
Sprinkling water composition meq/l	Frequency × Duration times/day × min	No. per Plant	Fresh Weight kg/plant	kg/plant
0	1×10	35	2.43	1.10
	1×32	26	1.72	1.56
	8× 4	35	2.04	1.36
1 $CaCl_2$	1×10	40	2.45	1.13
	1×32	44	2.47	1.18
	8× 4	38	2.36	1.56
10 $CaCl_2$	1×10	34	2.13	1.02
	1×32	30	2.01	1.30
	8× 4	22	1.12	1.22
10 NaCl	1×10	33	1.82	1.48
	1×32	32	1.88	1.52
	8× 4	12	0.77	1.32
Unsprinkled Root media Ψ_0 bar				
−0.5		40	2.60	1.05
−1.0		22	1.95	1.10
−3.0		24	1.08	0.80
LSD (0.05)		14	0.59	0.30

chlorosis. These leaves soon abscised. Leaves sprinkled with 1 meq/l $CaCl_2$ developed mild spotty chlorosis on the 1×10 and 1×32 treatments and more severe general chlorosis on the 8×4 treatment. NaCl was noticeably less injurious than $CaCl_2$. At 10 meq/l, NaCl caused a mottled leaf chlorosis but no tip or marginal injury except on a few older leaves.

Leaves sprinkled with demineralized water appeared normal and similar to unsprinkled leaves grown on nonsaline cultures. Unsprinkled leaves from plants grown in cultures at -1.0 and -3.0 bar Ψ_0 were light to moderately chlorotic with slight tip and marginal necrosis.

The effects of sprinkling on leaf mineral composition are shown in Table 1. Both Cl^- and Na^+ were absorbed foliarly and Cl^- absorption appeared to be a linear function of concentration with about a 10-fold increase in uptake between 1 and 10 meq/l waters. Frequency, but not duration, of sprinkling also affected uptake. Leaf concentrations of both Cl^- and Na^+ increased about 2-fold as the frequency was increased from 1 to 8 times per day. No differences were evident between the 10 and 32 min sprinkling times, therefore the 1×10 data are not presented. Foliar uptake of Ca^{2+} was comparable to that of Cl^-; it too increased with increasing solution concentration and frequency of sprinkling. Leaf Mg^{2+} and K^+ were little affected by sprinkling expect possibly for some loss with the NaCl water. A comparison of leaf K^+ concentrations from sprinkled and unsprinkled treatments indicated that no appreciable leaching occurred with demineralized water or $CaCl_2$ waters. The negligible Na^+ concentrations in the unsprinkled plants show that Na^+, unlike Ca^{2+} and Cl^-, was not translocated from the roots to the leaves.

Although Experiment I was not designed to obtain yield response curves, an analysis of variance indicated that both water composition and frequency$\times$duration had significant effects on fruit number and on fresh weights of fruit and shoot. High frequency sprinkling (8×4) with 10 meq/l $CaCl_2$ and NaCl waters decreased fruit production as much or more than the -3.0 bar Ψ_0 root treatment (Table 2). Vegetative growth was affected much less than fruit yield by salinity in both sprinkling waters and root media.

Sprinkling with 10 meq/l Cl^- waters (Experiment II) caused leaf injury symptoms similar to those observed in the first experiment. The degree of injury depended on the $Ca^{2+}:Na^+$ ratio (Fig. 1). $CaCl_2$ alone was more toxic than NaCl but in low concentrations (1–3 meq/l) it reduced NaCl-induced leaf injury. Yield of fresh fruit was markedly decreased by sprinkling and the greatest decreases were caused by the single-salt waters.

Analysis of the leaves revealed that the degree of leaf necrosis among treatments was not related to an increase in Cl^- concentrations. In fact, leaf margins from the $CaCl_2$-sprinkled plants, which were injured most, had the lowest concentration of Cl^- of the salt sprinkled treatments (Fig. 2). Since the leaves were analyzed at incipient injury, it is unlikely that Cl^- was either translocated out of the tissue or was leached during washing. The uninjured central portion of the leaves always contained less Cl^- than the margins (*ca.* 40% less) but the relationship between tissue Cl^- concentration and the $Ca^{2+}:Na^+$ treatments was the same for the interior as for the margins. Na^+ content of the leaves increased linearly with Na^+ concentration in the sprinkling water but never

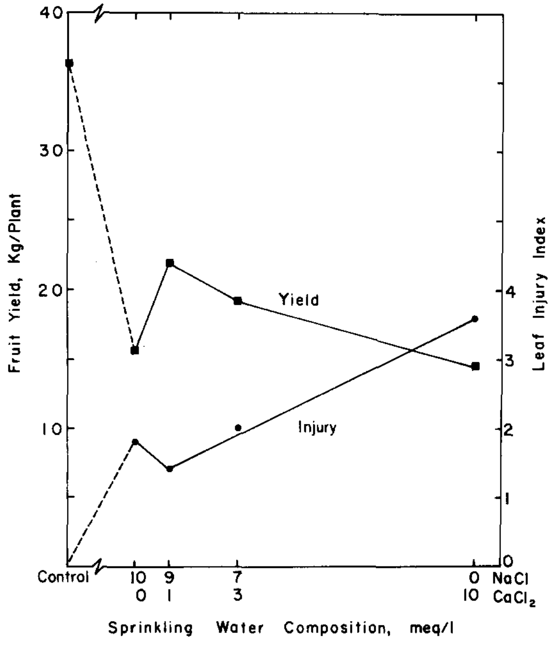

Fig. 1. The effect of 10 meq/l Cl^- sprinkling waters having various $Ca^{2+}:Na^+$ ratios on yield and foliar injury of pepper plants as compared with that of an unsprinkled control. All plants were grown in nonsaline culture solutions. (For leaf injury index, see Materials & Methods)

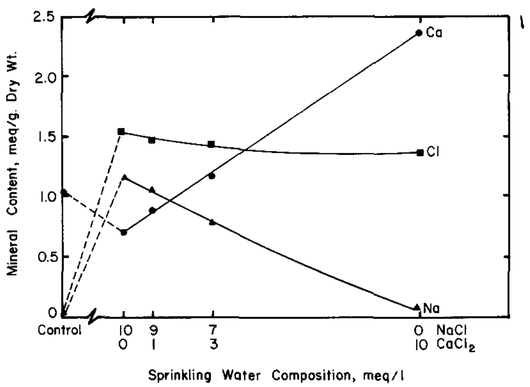

Fig. 2. Concentration of Ca^{2+}, Na^+, and Cl^- in margins of approximately 25-day-old leaves from unsprinkled control plants and plants sprinkled 6 weeks with 10 meq/l Cl^- waters having various $Ca^{2+}:Na^+$ ratios. All plants were grown in nonsaline culture solutions

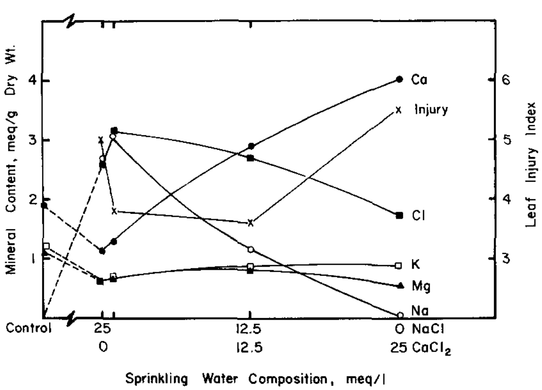

Fig. 3. Mineral composition of leaf margins from unsprinkled control plants and plants sprinkled approximately 40 days with 25 meq/l Cl^- waters having various $Ca^{2+}:Na^+$ ratios. All plants were grown in nonsaline culture solutions

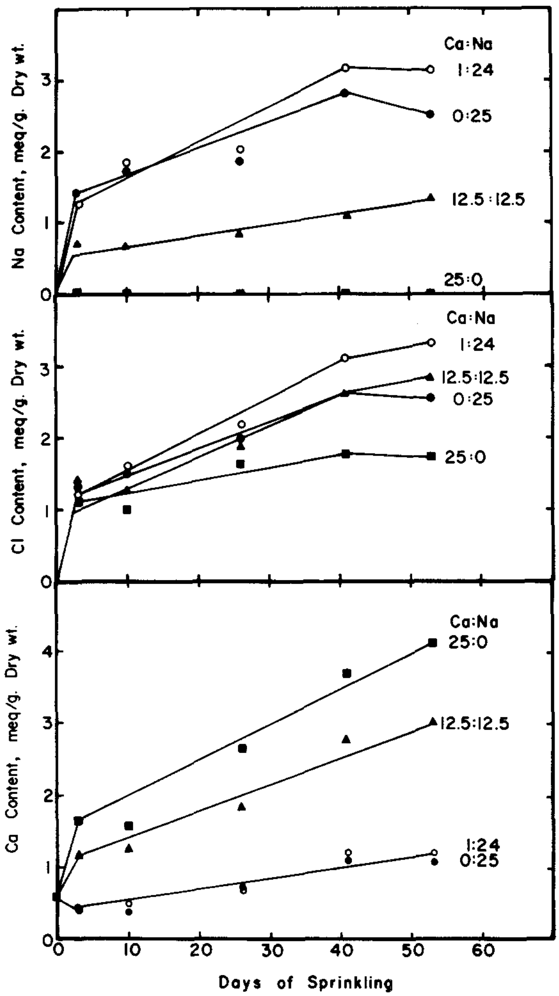

Fig. 4. Time course of Ca^{2+}, Na^{+}, and Cl^{-} accumulation in leaf margins of plants sprinkled up to 53 days with 25 meq/l Cl^{-} waters having various Ca^{2+}: Na^{+} ratios. Plants were grown in nonsaline culture solutions

equalled Cl^{-} content. The increase in Ca^{2+} content was greater than that of Na^{+} and with the 10 meq/l $CaCl_2$ treatment, the Ca^{2+} concentration exceeded that of Cl^{-}. Of course the uptake of Ca^{2+} included both that taken up through the roots from the nutrient solution and that through the leaves from sprinkling waters, but only the latter produced the high concentration that was associated with injury.

Sprinkling with 25 meq/l Cl^{-} waters (Experiment III) caused more severe injury than with the 10 meq/l water but the relation between leaf necrosis and the $Ca^{2+}:Na^{+}$ ratio of the waters was the same. Single salts were more injurious than mixtures, and $CaCl_2$ was more toxic than NaCl (Fig. 3).

As in Experiment II, leaf necrosis was negatively correlated with leaf Cl^{-} concentrations, i.e., Cl^{-} concentrations in the leaf margins were lowest in the $CaCl_2$ treatments where injury was most severe (Fig. 3). The relationship between CA^{2+} and Na^{+} uptake and the $Ca^{2+}:Na^{+}$ ratios of the waters was similar to that in Experiment II, but the total amounts accumulated were higher. Sprinkling with 25 meq/l water reduced K^+ and Mg^{2+} contents of the leaves but there were only small differences among the various Ca^{2+} : Na^+ treatments.

The time course of salt uptake into leaf margins indicated that Na^+, Cl^-, and Ca^{2+} (except at 1 meq/l) were rapidly absorbed the first 3 days and then at a lower but essentially linear rate for about 40 days (Fig. 4). After that, uptake of Na^+ and Cl^- tended to decrease. This latter period was associated with the onset of leaf desiccation and necrosis.

Discussion

Pepper plants are susceptible to foliar injury when sprinkled with saline irrigation waters [1]. Results of this study showed that injury can be directly caused by foliar absorption and accumulation of salt. Ca^{2+}, Na^+, and Cl^- were readily absorbed through leaves at rates that were essentially linear functions of salt concentration. Salts were steadily accumulated in leaves for about 5 weeks after their emergence on plants that were sprinkled daily. After that, the rate of accumulation decreased and in some cases where leaf injury and necrosis were apparent, Na^+ and Cl^- concentrations in the leaves decreased.

Frequency of sprinkling also influenced the rate of salt accumulation. Increasing the frequency from 1 to 8 times per day but with the same total duration of sprinkling doubled the rate of salt accumulation. In contrast, 3-fold differences in the duration of once-per-day sprinkling had no measurable effect on accumulation rates. Since foliar ion absorption can continue after sprinkling is stopped as long as the leaves are wet, frequent, short irrigations provide a much longer opportunity for absorption than indicated by the length of irrigation itself. Furthermore, the rate of ion absorption, being a function of salt concentration, increases rapidly as the water film on the leaf evaporates and the salt is concentrated. Consequently, the more often the wetting-drying cycle occurred, the greater was the foliar accumulation of salt. Once the salts are completely dry on the leaf, however, absorption stops until they are rewetted again [6]. Although crops are never irrigated as often as in this experiment, these conditions are not extraordinary. Some irrigation systems with slowly rotating sprinklers expose plants to repeated wetting and drying cycles within a single irrigation.

The actual cause of leaf injury and necrosis is not entirely clear from the results. Leaf injury observed on unsprinkled plants grown in saline culture solutions occurred without any appreciable translocation of Na^+ to the leaves. Injury, therefore, appeared to be related to excessive accumulations of Cl^- or Ca^{2+}. With sprinkled plants, however, accumulation of Cl^- was not correlated with the degree of injury observed. While Cl^- may have been partly responsible for the injury, it certainly does not seem to be the primary cause of injury from the single-salt waters. The highly toxic effects of $CaCl_2$ water may have resulted directly from the marked accumulation of Ca^{2+} or indirectly from the ionic imbalance it caused. However, the beneficial effects of low concentrations of Ca^{2+} are worth noting. A mixture containing 1 meq/l $CaCl_2$ and 24 meq/l NaCl was noticeably less toxic than 25 meq/l NaCl. This was true despite slightly higher Ca^{2+}, Na^+, and Cl^-

concentrations in the tissue itself (Fig. 3). The toxicity of NaCl water may reflect a deficiency in Ca^{2+} for maintaining membrane integrity [8].

Since most irrigation waters contain a mixture of salts, the severe injury caused by the single-salt waters in this study would not be expected. However, these studies indicate that frequent sprinkling with mixed-salt waters having concentrations as low as 10 meq/l (electrical conductivity = 1.0 deciSiemen/meter) can cause foliar injury on pepper plants.

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