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Paper No. 994168
An ASAE Meeting Presentation

DEVELOPMENT AND EVALUATION OF AQUEOUS FOAM FOR COLD PROTECTION IN GREENHOUSES

by

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Written for Presentation at the
1999 ASAE Annual International Meeting
Sponsored by ASAE

Toronto, Ontario, Canada
July 18-21

Summary:

Aqueous foam was developed to serve as barrier to conductive, convective, and radiative heat transfer. Through the use of a bulking agent, the physical properties of gelatin-based foam were more stable, adhesive, biodegradable, and long lasting. Factors that affect the physical properties and the utilization of the foam were quantified. These included the proportions of the foam components, the mixing temperature of the pre-foam solution, the application temperature, and the rate of foam generation. The foam demonstrated the longevity necessary for practical field use. Soil temperatures beneath an insulation layer of aqueous foam were measured to determine the effectiveness of foam as soil mulch for greenhouses. The aqueous foam proved to be an effective insulator and radiation shield against the cold night sky.

Keywords: freeze and frost damage, plant cold protection, radiation shield, biodegradable aqueous foam, and mulching.

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The recurring widespread losses of agricultural commodities due to freeze/frost damage have been the driving force behind the continued research in crop protection during the last few decades. In cases where the cold period is severe and prolonged with a danger of freezing, the existing techniques are either inadequate to protect trees or too costly (Reiger, 1989). Therefore, any effective, economically viable, environmentally responsible means of protection against freeze and frost damage by elevating temperatures by only a few degrees may be of inestimable value to the agricultural industry in the United States and around the world.

There have been many cold protection techniques utilized such as artificial wind or heat generation, or the use of phase change energy from spray irrigation water. One alternative is the application of aqueous foam over crops for both freeze and frost protection. The scientific justification for the present research is twofold: (i) aqueous foam is a good insulator with relatively low thermal conductivity, (ii) and aqueous foam is an excellent radiation shield, since water is opaque to radiation.

Previous agricultural foam research demonstrated the effectiveness of aqueous foam (Batholic, 1985), while important technical challenges for field application were still unsolved. Therefore, the primary objectives of the present study were to develop stable, inexpensive, adhesive, long-lasting aqueous foam and to conduct a field study. The main hypothesis is that aqueous foam can be applied readily to any crop or soil in greenhouses and may serve as an effective barrier against convective and radiative heat loss for a desirable time period. The development and evaluation of long-lasting foam and the results of field experiments involving freeze and frost protection are presented.

MATERIALS AND METHODS

A series of experiments was performed to evaluate foam properties, while searching for foams that would last for a minimum of several days in various weather conditions, would be sufficiently adhesive to endure windy conditions on tree trunks and on canopies of freestanding tall trees, would be non-toxic to plants and environment, and would readily degrade after its useful period. There were hundreds of possible chemicals and formulations to examine. Chemicals were chosen and tested with numerous formulations based on literature survey and hypothesis.

As a standard procedure, 25 mL (0.85 fl oz) liquid foam solution was poured into a 1 L (0.26 gal) plastic beaker. The beaker was tilted, and a glass pipette with a hypodermic needle needle (0.24 mm ID, Becton-Dickinson & Co, NJ) was inserted into the liquid. A controlled stream of air was blown through the needle, and the time and solution temperature were noted.

A higher capacity foam generator incorporating a venturi similar to previous research was also constructed and used for the laboratory test (Braud and Chesness, 1970, Braud et al., 1971). Compressed air served as the energy source for creating the foam and provided the air for incorporation into bubbles. The pressure drop in the venturi was sufficient to suck the solution into the foam generator. The rate of liquid flow and airflow also had to be controlled; too much liquid in the venturi reduced foam stability, with too little liquid, the foam would not form. Later the venturi section was replaced with a micro-pump in an effort to accurately control the flow rate of the solution.

For the field test, a polyethylene plastic film-covered, hoop-supported row tunnel [1 x 2 x 0.8 m (3.3 6.6 x 2.6 ft, length x width x height] was installed above a side-by-side test consisting of foam applied to the ground as a soil mulch and foam applied to a tray of lettuce plants as a plant insulator. The tunnel provided protection from rainfall, but not from radiative heat loss; i.e., longwave transmission through the polyethylene was approximately 80% for a single, non-infrared barrier film (Giacomelli and Roberts, 1993). Thus, radiative heat loss at night could be significant under the clear, winter desert sky in Arizona.

The soil was tilled and raked smooth, and thermocouples were installed with two replications each on three soil treatment areas [30 x 60 cm (11.8 x 23.6 inch)]. The treatments included two depths of applied foam over soil — thin foam [2.5 cm (1.0 inch)], thick foam [5 cm (2.0 inch)] — and bare ground as a control. At each of these six locations, three thermocouples were located to measure the temperature of the soil near the surface [0.25 cm (0.1 inch)] and at a depth of 2.5 cm (1 inch) (see figure 1). The air temperature within the tunnel was measured at 12 cm (4.4 inch) above the bare soil. All thermocouple junctions inch the air or within the foam layers were fitted with radiation shields.

Two trays [30 x 60 cm (11.8 x 23.6 inch)] of lettuce (*Lactuca sativa L.* cv. 'Black Seeded Simpson'), containing 15 seedlings each, were placed side-by-side within the tunnel. At the time of field testing, a closed plant canopy existed within the lettuce tray. Thermocouple junctions were attached to selected leaves by inserting the thermocouple within the midrib of the adaxial face of the leaf, approximately one-third the leaf distance up from the root zone, and well within the plant canopy. Foam was applied to cover one entire tray to a depth of approximately 2 cm (0.8 inch). This test began on 29 January, 1998, and was terminated on 12 February, 1998.

Air, soil and foam temperatures were measured with 24 gage type-T thermocouples. A thermister in each terminal block (National Instrument SCXI 1100 multiplexer, SCXI 1303 isothermal terminal block, and AT-MIO-16H-9 multifunction board, Austin, Texas) was used as a reference cold junction temperature. All the thermocouple junctions that measured air and foam temperatures were shielded from radiation. Each experiment was preceded by a calibration test of the data acquisition system, with particular emphasis on the thermocouple sensors. Based on data from a series of calibration tests, the accuracy was determined to be ± 0.15 °C (± 0.27 °F), and repeatability was ± 0.05 °C (± 0.09 °F).

RESULTS AND DISCUSSION

The formulation with gelatin and sucrose was most successful among the chemical formulations we tested, and the formulation is shown in Table 1.

Table 1. The ideal foam formulation chosen for the freeze/frost field experiments based on laboratory experiments.

Ingredients	Percentage by Weight
Water	68.0
Gelatin (Dynagel 250 Bloom)	2.4
Sucrose (Sugar)	28.0
Sulfochem ALS (10% SOLIDS)	0.5
Glycerol	1.0
Potassium sorbate	0.1

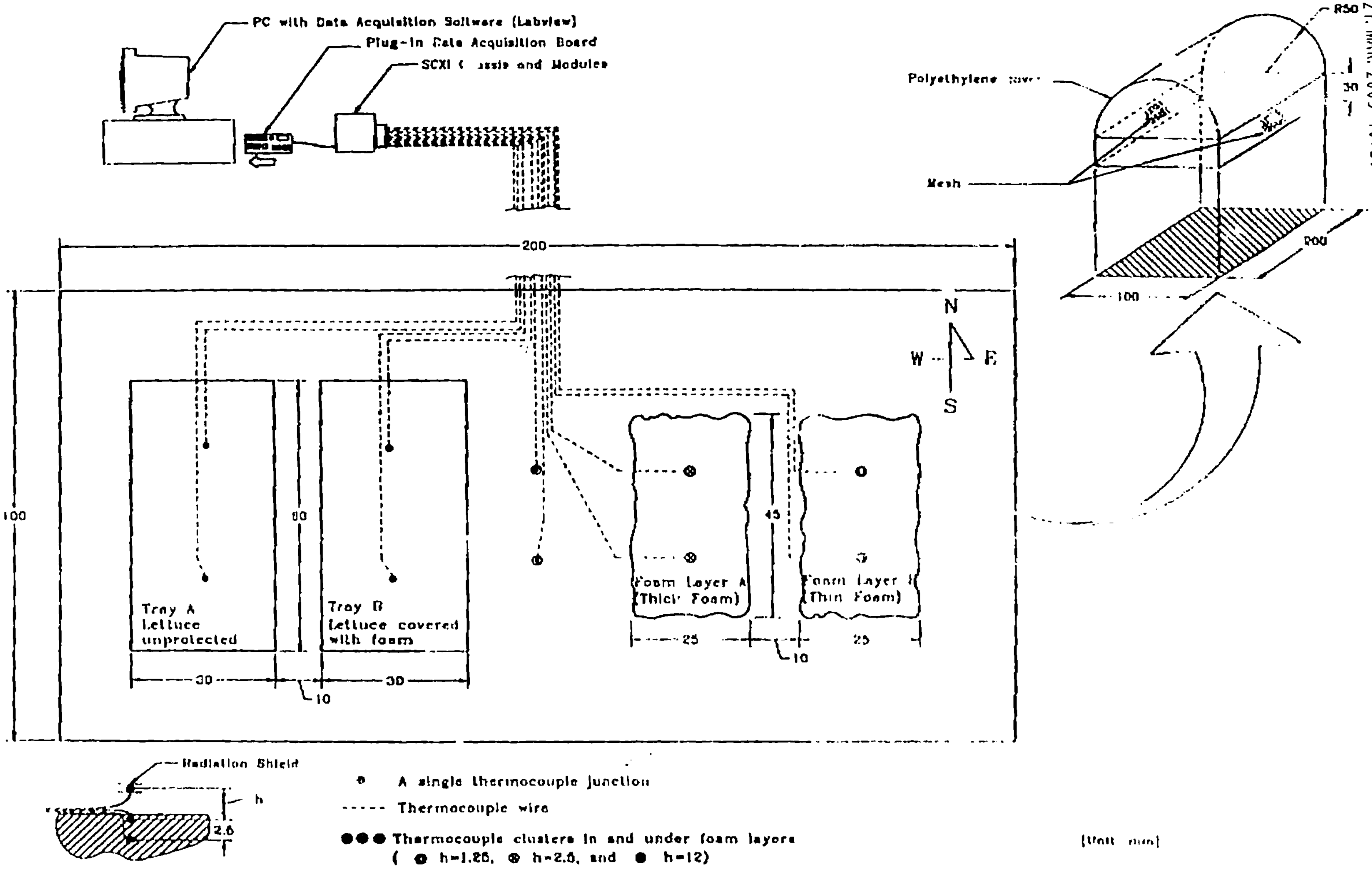

Figure 1. The size of the row tunnel and the layout of the field experiment conducted in a single-layer polyethylene plastic film covered, wire hoop-supported, row tunnel.

Foam in the 1 L (0.26 gal) beaker was placed in a constant temperature oven (Isoteme Vacuum Oven 282A, Fisher Scientific, Pittsburgh, PA) to observe its longevity under warm subtropical conditions. The temperature was set consecutively at 30, 40, 50 °C (86, 104, 122 °F), and each temperature was maintained for 48 h. No visible degradation of the foam structure was observed, although volumetric shrinkage did take place. A screen [1.3 x 1.3 cm mesh size (0.5 x 0.5 inch)] was prepared in order to study the foam shrinkage when all foam surfaces were exposed to air. Approximately 15 cm long, 5 cm wide, 3 cm thick foam (5.9 x 2.0 x 1.2 inch) was placed on the screen. The foam shrank about 10% within 24 h; and remained the same volume afterward. The volumetric loss was due mainly to the reduction in the foam thickness (depth) rather than lateral shrinkage (length or width). Higher oven temperatures accelerated the shrinkage and the drying of the foam surface; i.e. the soft and moist texture of the foam surface quickly disappeared due to evaporation. Nevertheless, the foam maintained its original shape over the screen. After the oven experiments, the foam from the oven was placed in the laboratory at 23 ± 3 °C (73.4 ± 5.4 °F) and 30 ± 15% relative humidity for more than a week. No noticeable change in shape and volume was observed during this period.

The survival of the foam under freezing and thawing conditions was also examined. Beakers filled with foam were placed in a constant temperature freezer. Temperature was set at -10 and -20 °C (14 and -4 °F) respectively. The foam immediately shrank to approximately 70% of its original volume at both -10 and –20 °C (14 and -4 °F). When the beakers were rapidly exposed to room temperature after 24 h in the freezer, the foam completely collapsed within an hour. Repeated experiments produced the same results. Alternatively, the beakers with foam were gradually thawed over 4 h; i.e., the beakers from the -10 and -20 °C (14 and -4 °F) freezers were placed in the 0 °C (32 °F) freezer for about 4 h. They were moved to a 5 °C (41 °F) refrigerator for more than 4 h; they were then exposed to room temperature. With gradual warming, the foam consistently maintained its volume and shape. The latter experiment closely simulates extreme weather conditions in nature. Thus, the foam may likely survive severe daily temperature fluctuations.

A closed wind tunnel was used to test the foam stability under windy conditions at various temperatures. The wind tunnel provided a uniform temperature and RH airflow across the test section at air speeds varying from 0 to 10 m·s^{-1} (0 to 32.8 ft/s) and at air temperatures from 0 °C to 50 °C (32 to 122 °F). Details of the wind tunnel design and evaluation are described by Leon et al. (1998).

Foam 2–4 cm (0.8-1.6 inch) thick on a horizontal Plexiglas plate maintained its structure under windy conditions, where the wind speed was set at 2, 4, 6, 8, and 10 m·s^{-1} (6.6, 13.1, 19.7, 26.2, and 32.8 ft/s), respectively. The air temperature in the wind tunnel was maintained at a constant temperature for each run. Starting from room temperature [about 21 °C (70 °F)], the air temperature was reduced to 0 °C (32 °F) using a heat exchanger and an isothermal bath. The relative humidity in the wind tunnel was within 50 ± 10%. In general, the results showed that the foam was stable at windy conditions. At 8 and 10 m·s^{-1} (26.2 and 32.8 ft/s), however, the upstream section of the fresh foam on the Plexiglas surface deformed noticeably toward the downstream. The gelatin in the foam had not gelled immediately after the foam generation. As the wind speed was reduced, the foam returned to its original shape. The foam became increasingly impervious to wind deformation as it gelled and solidified. Overall, the foam maintained its shape well at wind speeds up to 10 m·s^{-1} (32.8 ft/s).

Figure 2 presents the temperature fluctuation of air and soil at a 2.5 cm (1 inch) depth. Each temperature reading represents the average value from two locations. The daily fluctuation pattern was nearly the same as the data collected at the weather station, and the temperature readings were 5 – 10 °C (9 – 18 °F) higher during the day than the weather station data due to a moderate greenhouse effect caused by the plastic film tunnel. The soil temperature protected by the thick foam maintained the highest temperature at night, and the thin foam maintained the highest temperature during the day.

During the cold morning (from 0300 to 0700 HR) of 31 January, 1998, the soil temperature difference (ΔT) between the thick-foam protected soil and the unprotected soil was about 5 °C (9 °F), and the difference between the thick foam treatment and the air was nearly 10 °C (18 °F), as shown in Figures 2 and 3. The thin foam provided a reduced insulation effect during the same period, with about a 3 °C (5.4 °F) temperature difference. On the relatively mild morning of January 30, the effectiveness of the foam as measured by the temperature difference was reduced. On 1 February, 1998, the temperature difference between the foam-protected soil and the unprotected soil gradually increased (Figure 3) as the air temperature dropped early in the morning (Figure 2). The differences were quite consistent during cold and clear nights.

The daytime soil temperatures under the thin foam were consistently higher than under the thick foam, reaching values between 8 - 9 °C (14 - 16 °F) greater (Figure 2). The shortwave solar radiation apparently penetrated the thin foam and was absorbed at the soil surface, while the foam acted as a good insulator against convective heat loss. However, the stored thermal energy was quickly lost after sunset. Radiative loss from the soil surface to the cold clear sky could have contributed to the energy loss. The accumulation of thermal energy during the day, therefore, did not significantly alter the soil temperature during the following evening.

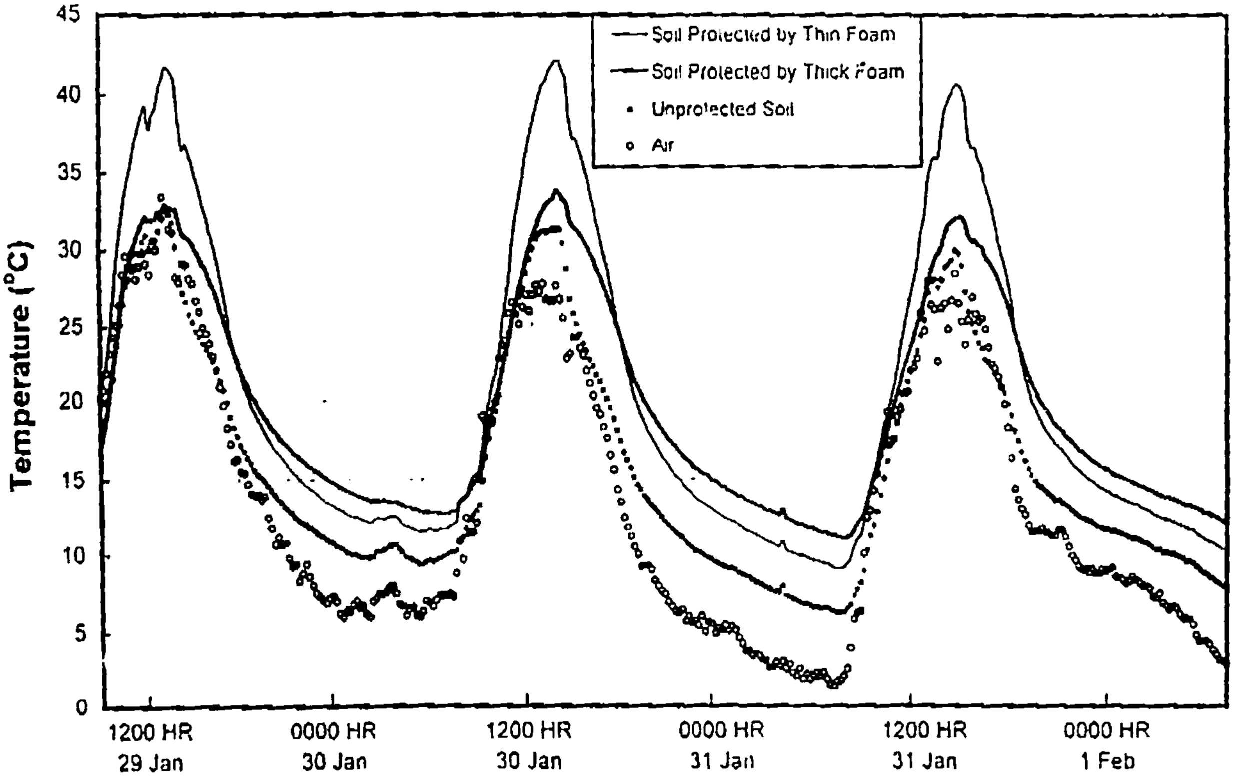

Figure 2. Soil temperature at 2.5cm (1 inch) depth.

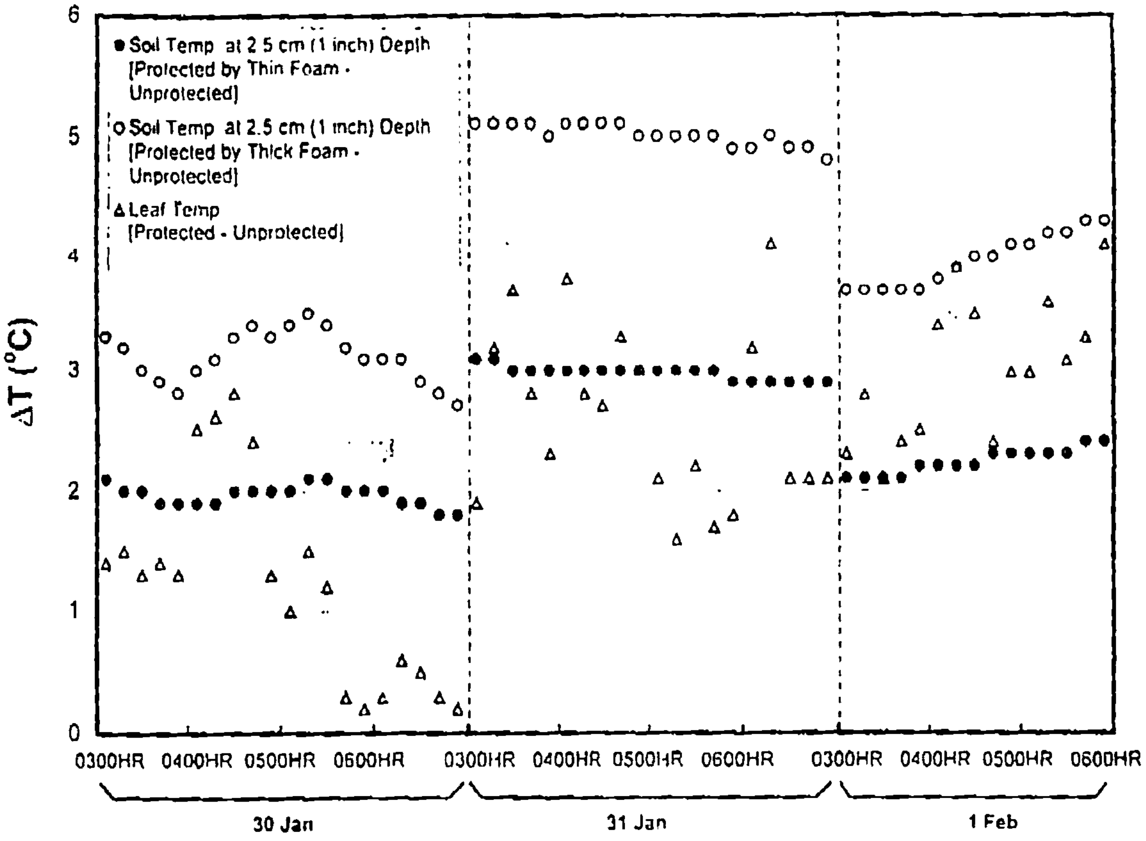

Figure 3. Temperature differences (ΔT) between protected and unprotected soils/leaves during the early morning hours (0300-0600 HR).

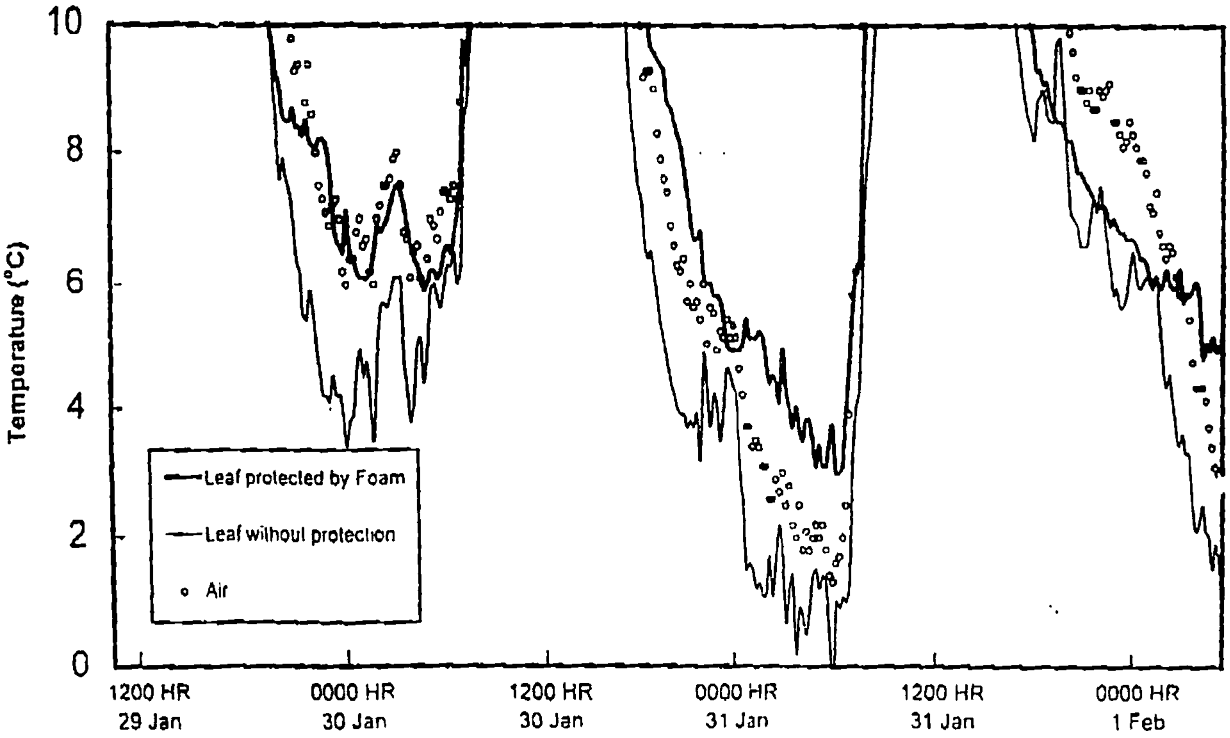

Figure 4. Temperature of the midribs of foam-covered and uncovered lettuce leaves.

Temperature of the midribs of foam-covered and uncovered lettuce leaves is shown in Figure 4. During the cloudy and warm morning of 30 January, 1998, the effect of the foam was not significant. The temperature difference between the protected and unprotected leaves was negligible (see Figure 3) due to the cloud cover. On 31 January, 1998, the temperature differences for the leaf covered with foam were about 3 °C (5.4 °F) on average and as high as 4 °C (7.2 °F) greater than the uncovered leaf. Figure 5 indicates that the leaf temperatures of the protected midrib were higher than the air temperature, because the foam layer protected the lettuce leaves from radiative loss to the cold and clear sky during the morning hours of 31 January and 1 February, 1998. Such a trend was not evident on the cloudy morning of 30 January, 1998.

CONCLUSIONS

The foam protected soil was effectively insulated and generally exhibited temperatures that were 3 and 5 °C (5.4 and 9 °F) above that of the bare soil for the thin and thick foam covers, respectively. When compared to air temperature, these values increased to 10 and 8 °C (18.0 and 16.2 °F), respectively. Radiation heat losses from the plant leaf canopy were reduced on clear nights by an application of foam directly to the leaf. Temperatures were from 3 to 4 °C (5.4 and 7.2 °F) higher than the air temperature. Leaves were not damaged after being covered with the foam for 14 days. The foam maintained its integrity and desirable properties under dry weather conditions for the entire 14 days and nights of exposure.

In conclusion, the gelatin-based, aqueous foam can be used as biodegradable soil mulch in greenhouses. The foam can potentially protect the aerial portion of both low and high profile crops from damage by below freezing air temperature, and from frost caused by radiation heat loss under clear sky night conditions. The foam can easily adhere to plant canopies, branches and trunks of freestanding tall trees, and unless washed away by water spray, the foam structure will be maintained in typical outdoor environments.

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