# VIEWPOINT

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## Application of Nematicides Via Drip Irrigation[1]

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*Key words:* irrigation, management, nematicide, chemical control.

Use of drip, or trickle, irrigation in agriculture has increased rapidly during the past 20 years. In 1970 approximately 50,000 ha in the United States were under drip irrigation, by 1985 the area had increased to over 300,000 ha (6). Irrigation has been used to deliver fertilizers and pesticides (8,9,14,18,27,28), and there are increasing numbers of studies on the application of nematicidal compounds or other pest control agents via drip irrigation (1–5,12,13,16,19,20,22,24,25,32). Most of these reports, however, do not detail the mechanical considerations of delivering nematicides through drip irrigation.

In the following we discuss application of nematicides through drip irrigation, mentioning potential problems and considerations that are important for successful application. We focus on the use of drip irrigation for delivery of nematicides in research, and refer to our research experience with nematicides delivered by drip irrigation systems in Hawaiian pineapple. The technical (soil physics and engineering) aspects of drip irrigation are not discussed here, as reviews on these topics are available (6,8,9,21,29).

*Concepts and history:* Drip or trickle irrigation delivers relatively low volumes of water as drops, streams, or sprays through holes or emitters located at intervals along plastic water delivery lines (9,27). The basic concepts involved in drip irrigation can be traced back to experiments on subirrigation and drainage in Germany in the 1860s (29). Since that time many developments and refinements have occurred, the most important being the development of the plastic industry after World War II (27). Drip irrigation was introduced to the United States in the 1960s and currently is used in growing many different crops. In Hawaii drip irrigation is used extensively, following introduction into sugarcane and pineapple production systems during the early 1970s.

Drip irrigation can be implemented in various ways including surface, subsurface, bubbler, sprays (9), or traveling drip systems (21). The objective is to provide the plant root zone with sufficient water to meet evapo-transpiration demands.

A major advantage of the system is that it supplies only the volume of water required by the plant directly to the root zone. Additional advantages (9,27) include the following:

1) It makes maximum beneficial use of the available water supply.

2) The grower controls water infiltration rates.

3) Water is supplied to plants on the basis of phenological requirements.

4) Disease incidence is reduced through decreased wetting of plant leaves.

5) Weed growth is reduced by decreasing the area of soil supplied with water.

6) Drip irrigation systems can be easily adapted to automated control.

7) Saline water may be used.

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8) The system provides a vehicle for application of fertilizer and pesticides.

Drip irrigation is an economically sound method for applying water because costs are minimized. This is quite important in areas where water costs are rising rapidly.

The relationship between moisture stress and nematode induced damage to crop plants is reasonably well established, and some researchers have demonstrated the influence of irrigation on nematode population dynamics and plant growth (11). Drip irrigation serves to provide the plant with optimal water conditions, thus reducing the influence of nematode stress. Additionally, when drip irrigation is used as a delivery system for fertilizer, nematicides, and (or) other pesticides, the efficacy of the pesticide is often maximized in relation to dosage, allowing the effective use of lower rates (15,16). Lower rates of application decrease the likelihood of groundwater contamination.

*Nematode management:* During the past several decades, nematode control on commercial crops has been primarily chemical in nature and has consisted largely of soil fumigants applied by chisel injection. Although it is possible to have fumigant failures because of poor soil preparation, injection methods, or soil moisture or temperature conditions, the nature of the treatment—the diffusion of a volatile gas through soil pores—has had a considerable margin for error. This margin allows fumigant application under less-than-ideal conditions by the researcher or grower.

Applying nematicides (volatile or nonvolatile) by drip irrigation depends on water movement and hence is quite different from injecting volatile soil fumigants that diffuse as a gas. Awareness of factors influencing the success of a water application is essential because poor application technique will yield poor results.

*Nematicide characteristics:* All nematicides, regardless of application methods used, should be handled carefully and in accord with label instructions. Applicators should be aware of the mammalian toxicity of the nematicides applied and the symptoms of poisoning, and they should be familiar with emergency procedures and capable of performing them in case of accidents during application.

Nematicides differ chemically, and these differences are important in timing, application rates, and the design of application methods. Before considering application of a nematicide through drip, it is desirable to know the parent compound, its chemical characteristics, its half-life in a particular soil, and its mobility in relation to the organic matter content and pH of the soil. Knowledge of the breakdown products, or metabolites, of the parent compound and their behavior in soil is also desirable.

For example, the half-life of fenamiphos in Hawaiian soils is 3–5 days; it adsorbs strongly to organic matter. Consequently its movement is limited. The nematicidal metabolite, fenamiphos sulfoxide, is highly mobile with a half-life of 45–70 days (17). Excessive water applied through irrigation or rainfall will quickly move this metabolite out of the top 30 cm of soil (26). Fenamiphos sulfone, the breakdown product of the sulfoxide, is less mobile. The data base on adsorption and penetration of various nematicides in different soil types needs to be developed further because such information will be important as a guide to application rates and frequency of irrigation.

*Nematicide movement in soil:* Critical factors determining the success of a nematicide application in the field by drip irrigation are the wetted surface area and the wetting depth. Management of the wetting depth, which assures penetration of the compound to the root zone, requires knowledge of the physics of a particular soil. Simplified equations have been developed that allow estimation of distribution patterns of nematicides in relation to discharge rate, desired pesticide concentration, and irrigation time (15). Applying the equations requires knowledge of the soil hydraulic conductivity and soil sorptivity. Soil profile heterogeneity, due to cultivation or biological activity, was not included in the development of the equations. This is a problem when applying the equations to field conditions because soils contain macropores such as earthworm burrows or canals left by decaying roots, resulting in a wetting depth greater than that predicted (16). The equations represent an excellent starting point for estimating the parameters involved in applying nematicides through drip.

We have utilized two-dimensional profile sampling, laterally and vertically from the drip tube beneath an emitter, to assess the distribution of nematicides in pineapple beds (Fig. 1). A nematicide that demonstrates good lateral movement in one soil type may be much more mobile vertically in a different soil. Depending on the depth and growth pattern of the root system being protected, differential nematicide mobility may be important.

If a soil fumigant, such as 1,3-D, is applied as an emulsifiable formulation by drip irrigation, it moves through the soil pores in the water front, as opposed to movement as a gas when applied by chisel injection. The success of a water application of 1,3-D is influenced by the amount of water used in the application and the moisture content of the soil at the time of application. Injection of 1,3-D must be relatively quick and followed by a large amount of irrigation water—at least 1 acre-inch to move the nematicide into the root zone.

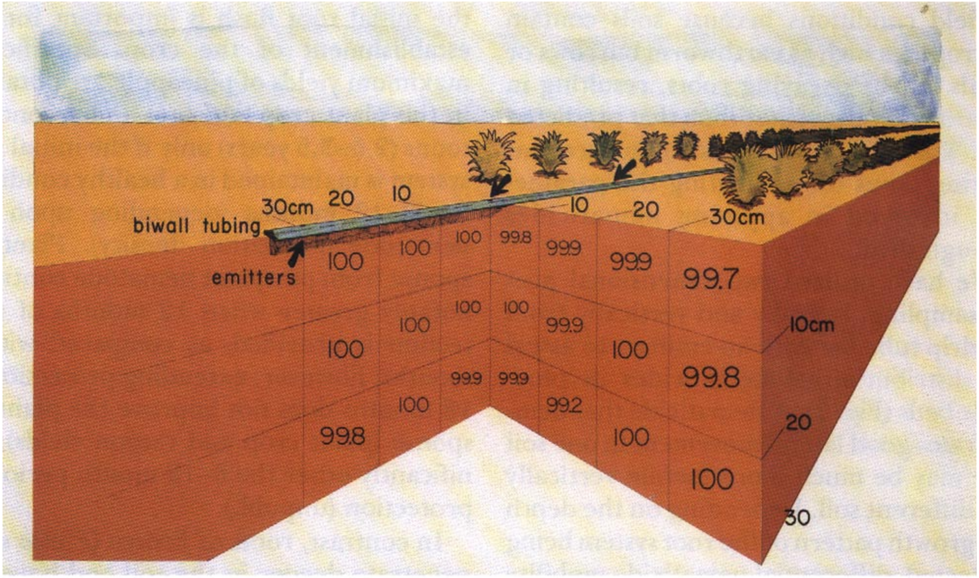
*Period of protection:* The critical period for protection of plant root systems by nematicides applied through drip irrigation varies with the crop plant. An important consideration is awareness of the characteristics of the root system with respect to rooting depth and root growth patterns.

In pineapple, the soil roots originate from the base of a vegetative seed piece—the crown, slip, or sucker. The primary roots maintain initial plant growth, establish the mother stem, and subsequently produce sucker growth and ratoon crops. The root system penetrates to a depth of approximately 45 cm, depending on soil conditions. The loss of these primary roots through nematode infection early in the season is highly detrimental to subsequent stem growth and yield. The protection of the initial root flush is important for the establishment of the crop. Specifically, maximum yields of pineapple are obtained in the plant crop and first and second ratoons (2.5–3.5 years) only if the initial root system is maintained in a healthy condition for 8–12 months (depending upon the nematode population density). Plant response from postplant nematode control is notably greater when 12 months of protection is provided, as compared with 6 months; however, extending protection to 18 months does not improve the plant response (plant crop and ratoon yields) significantly other the 8–12 month period of protection (unpubl.).

In contrast, roots of Protea (*Protea* spp.) penetrate deeper in the soil and have annual flushes of growth. A nematicide applied postplant by drip irrigation to Protea will not affect existing infections of *Meloidogyne incognita* (Kofoid & White) Chitwood, as females and juveniles may remain inside galled tissue. Thus, original infection sites provide inoculum indefinitely. Appropriately timed applications of nematicide may protect flushes of new roots, however, thus allowing the new roots to maintain plant growth. For Protea then, periodic postplant treatments are required for the duration of the plant's life, which may be many years.

Maintaining low concentrations of carbosulfan, carbofuran, aldoxycarb, or oxamyl in the root zone of tomato through multiple applications via drip irrigation provided protection against *M. incognita* as measured by root galling (13). The application schedule determined the efficacy of the nematicides with respect to yield. Four applications of oxamyl, aldoxycarb, and carbofuran applied at 0.37 kg a.i./ha beginning at planting and 3, 6, and 14 days later (2.22 kg a.i./ha total) resulted in significant yield increases (13).

In Hawaii oxamyl applied at 3.4, 6.7, and 13.4 kg a.i./ha through a biwall tubing with emitters 30.5 cm apart reduced populations of *Rotylenchulus reniformis* Linford & Oliveira 70.5, 76.3, and 91.5%, respectively, 4 weeks after a single application (3).



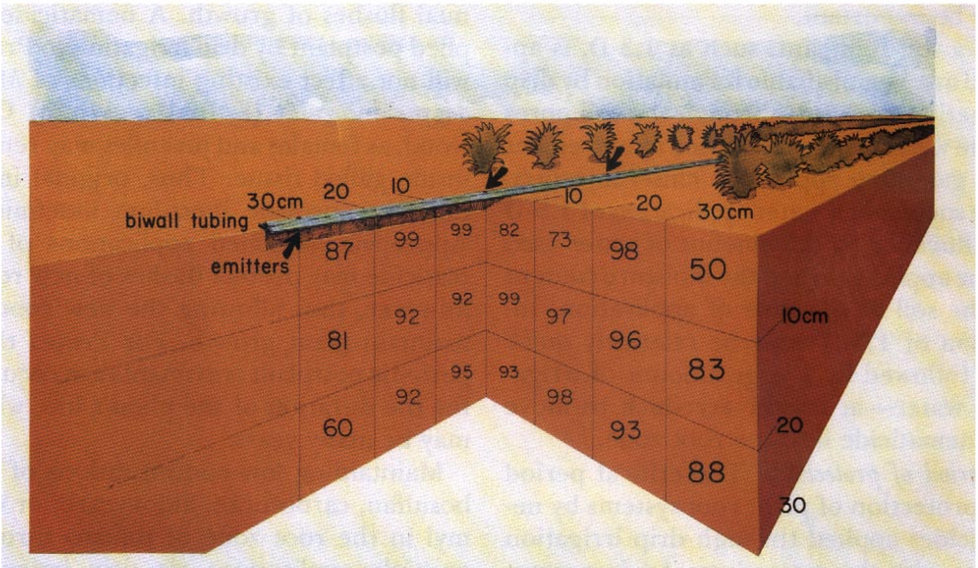




FIG. 1 (TOP). Reduction percentage of populations of *Rotylenchulus reniformis* Linford & Oliveira relative to a nontreated water control after four monthly applications of oxamyl applied at 3.4 kg a.i./ha via drip irrigation (total of 13.4 kg a.i./ha).

FIG. 2 (BOTTOM). Reduction percentage of populations of *Rotylenchulus reniformis* Linford & Oliveira relative to a nontreated water control 4 months after oxamyl was applied at 13.4 kg a.i./ha in one at-planting application via drip irrigation.

Four monthly applications of oxamyl at 3.4 kg a.i./ha reduced the average nematode population density in the soil profile 99% (Fig. 1). Less effective control was obtained with a single application of 13.4 kg a.i./ha at planting (Fig. 2). The estimated half-life of oxamyl applied through flood irrigation is 1–4 days, with penetration ca. 152 cm deep (18).

Metham sodium can be applied successfully by drip irrigation. It should be applied throughout the irrigation period with no water applied postapplication. Overman (19) found that a single preplant (14 days preplant) injection of metham sodium at a rate of 224 kg/ha through a drip irrigation system significantly reduced root galling and increased tomato yields. Incremental injections of metham sodium equally spaced over a period of 9 weeks significantly reduced root galling, but did not significantly increase tomato yields. Roberts and Matthews (24) found metham sodium applied preplant through drip irrigation superior to conventional fumigation with 1,3-D in controlling *M. incognita* on tomato.

*Duration of application:* There are two basic approaches to the time allotted for nematicide injection during an irrigation run: the nematicide can be injected rapidly, followed by a determined amount of water; or the nematicide can be applied continuously during the irrigation run. In most cases we have applied nematicides over the irrigation run, allowing sufficient time after the injection period to clear the nematicide from the lines.

*Control treatments:* Experiments designed to assess the efficacy of nematicides applied through drip irrigation should include an irrigated control treatment. Drip irrigation by itself may have a substantial influence on plant growth, and not taking this into account may result in erroneous interpretations of the efficacy of a nematicide. The nematicide may appear more effective than it is.

The importance of including an irrigated control treatment was shown when trickle irrigation alone reduced populations of *Xiphinema americanum* Cobb and *Pratylenchus penetrans* Filipjev & Shuurmans Stekhoven associated with peach roots (11). Pineapple plants may tolerate a specific nematode density more readily under irrigated than under nonirrigated conditions. In a test of the efficacy of 1,3-D and fenamiphos as applied through drip irrigation, irrigation alone significantly increased pineapple yields (Table 1) (Apt, unpubl.). If a nonirrigated control had not been included, the affect of the nematicide application would have been overestimated.

TABLE 1. Effect of drip irrigation and nematicide application on yield of pineapple in soil heavily infested with *Rotylenchulus reniformis.*

| Treatment† | Average fruit weight (kg) | Metric tons per ha |
|---|---|---|
| Untreated control | 1.31 d | 88.44 d |
| Irrigated (Irr.) control | 1.50 c | 101.08 c |
| Irr. + 1,3-D | 1.91 ab | 129.11 ab |
| 1,3-D | 1.60 c | 107.74 c |
| Irr. + fenamiphos (1.7) | 1.85 b | 124.66 b |
| Irr. + fenamiphos (3.4) | 1.86 b | 125.35 b |
| Irr. + 1,3-D + fenamiphos (1.7) | 2.07 a | 139.83 a |
| Irr. + 1,3-D + fenamiphos (3.4) | 2.00 ab | 135.31 ab |

Means within a column followed by the same letter are not significantly different ($P$ = 0.05) according to Duncan's multiple-range test.

† Irrigation = 65,450 liters/ha weekly (¼ acre-inch). 1,3-D = 336 liters/ha, injected preplant. Fenamiphos (1.7) = 1.7 kg a.i./ha monthly, for 12 months by drip. Fenamiphos (3.4) = 3.4 kg a.i./ha monthly, for 12 months by drip.

*Nematode identification:* Proper utilization of drip irrigation requires that the nematode target be correctly identified and its life cycle and ecology understood. Some nematode species have life history characteristics that can be used to advantage in a drip irrigation program. For example, the success of drip applications of a nematicide for control of *R. reniformis* is due in part to knowledge of the nematode's life cycle and the influence of soil moisture thereon. Water applied via drip irrigation apparently induces quiescent eggs to hatch, resulting in active, susceptible juvenile stages being present in the soil when a nematicide is applied (unpubl.).

*Determination of efficacy:* Assessment of efficacy of nematicides is often taken for granted. Nematode extraction procedures that rely on nematode activity, such as Baermann funnels and mist chambers, and methods that extract passive nematodes, such as centrifugation-flotation, may yield different results, especially if a nematicide is nematistatic. A comparison of Baermann funnel counts with centrifugation-flotation counts may provide insight into the effect of nematicides on the activity of nematodes in the soil. Extraction efficiency also should be determined so that results can be com-

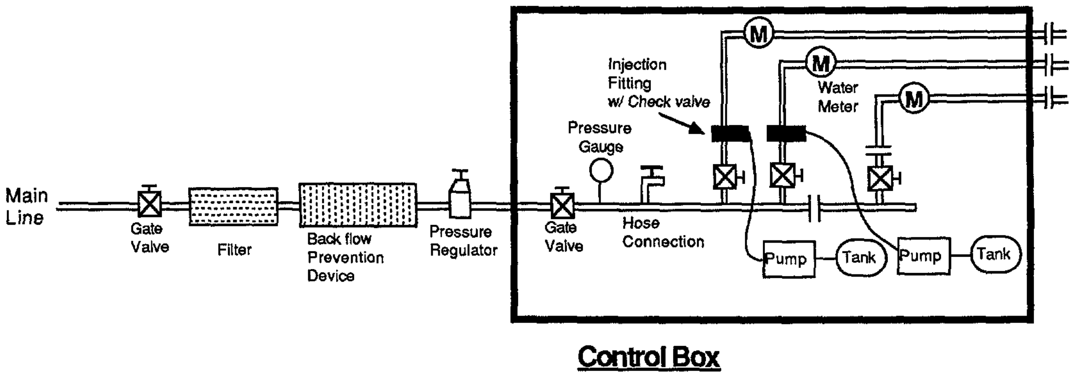



FIG. 3. Detailed schematic of the control box used in research on Hawaiian pineapple for nematicide application through drip irrigation. Water enters through the main line and the gate valve. Nematicides are pumped from separate tanks into injection fittings, with subsequent flow to each treatment monitored by a water meter (not to scale).

pared by researchers investigating the efficacy of nematicides in different locations.

*Drip irrigation system design:* The design of drip irrigation systems depends on the root system of the crop and the particular cultural practices employed for a given crop. The efficient distribution of water in relation to root growth depends on the drip irrigation system design; however, economics may compromise an ideal design. For example, pineapples are planted in two-row beds with the beds on 122-cm centers. The pineapple industry in Hawaii uses a single drip tube in the center of each bed. Ideally two tubes per bed in the plant row could be used to give maximum distribution of water and nematicides; however, this would be too costly and also would interfere with the planting operation. The drip tube in pineapple culture is placed on the surface of the soil, or slightly below the soil surface (1–3 cm) to hold it in place, and is covered by black-plastic mulch. The plastic mulch provides for water retention, increased soil temperatures, and suppressed weed growth.

*Drip tubing:* There are different types of drip tubes, including dual-chambered emission type and continuous extruding type. In selecting the appropriate type, consultation with agricultural engineers is advisable. The distance between emitters will influence the soil volume protected. The optimal size of the protected area is determined by planting density, the rooting pattern of the crop, and the nematode involved. In pineapple, emitters are 30.5 cm apart along the length of the drip tube. Emission of water is continuous with an extruding type of tubing.

A potential problem in all drip irrigation systems is the partial or complete clogging of emitters. This leads to decreased and irregular application and can be a tremendous problem in experiments assessing nematicide efficacy. Filtering the water supply to the drip irrigation system is necessary to remove particulate contamination in the irrigation water and reduce clogging (Fig. 3).

High salt content in water may lead to clogging. We noticed that streams from emitters slowly decreased over time—weeks to months—when dual-chambered emission tubing was used in pineapple fields. No visible plugging was found, but it was determined that salt was deposited around the emitter on the inside of the tube and was very slowly sealing off the emitters. The salt deposit was visible only when the tubing was dry. Periodic inspection of flow rates is advisable.

Ants and rodents are often attracted to drip tubes, especially during dry periods. Ants may enlarge the emitters and rodents may cut the tubing. In either case, it is necessary to be alert for abnormal flow rates—a disadvantage of the drip irrigation system. A metered line will indicate an abnormally high or low flow rate.

In arid regions where water sources are somewhat saline, it is advisable to periodically apply more water than will be used by the plants. This allows leaching of accumulated salts away from the root zone (27).

*Injection systems:* Factors that must be considered when designing an injection system are 1) method and rate of injection, 2) concentration of the solution, 3) tank capacity, and 4) prevention of contamination of the water supply (9). Three principle methods for injecting chemicals into drip systems are available, including metering pumps, venturi pumps, and pressure differential systems.

In our research on pineapple, an electric diaphragm metering pump was used for injection (Figs. 3, 4). In isolated field locations a gas-powered generator may be used as the power source. The pump has a maximum output of 240 ml/minute which can be reduced as needed. The metering pump allows great precision in the injection of nematicides into the water flow. We have always diluted the formulated nematicide in a holding tank and the diluted material, rather than the concentrate, is metered into the line (Figs. 4, 5). The product is diluted to improve the accuracy of treatment distribution among replications.

Because of the corrosive properties of some nematicides, use of corrosion resistant O-ring seals in the metering pump is necessary. Another solution is to use a Venturi or simple pressure differential system for injection. A PVC canister pressure differential system for injecting nematicides into drip irrigation systems has been developed (12,13). The unit is effective, light weight, and can be transported easily from plot to plot. Another simple and inexpensive nematicide injection system consisting of a syringe connected to a battery driven high-torque rotisserie motor has been reported (23). The unit is also light weight, easily transported, and suitable for small-scale field research.

*Monitoring flow rates:* The flow rate of irrigation water will affect the amount of a pesticide applied through a drip irrigation system. Therefore, the water flow rate

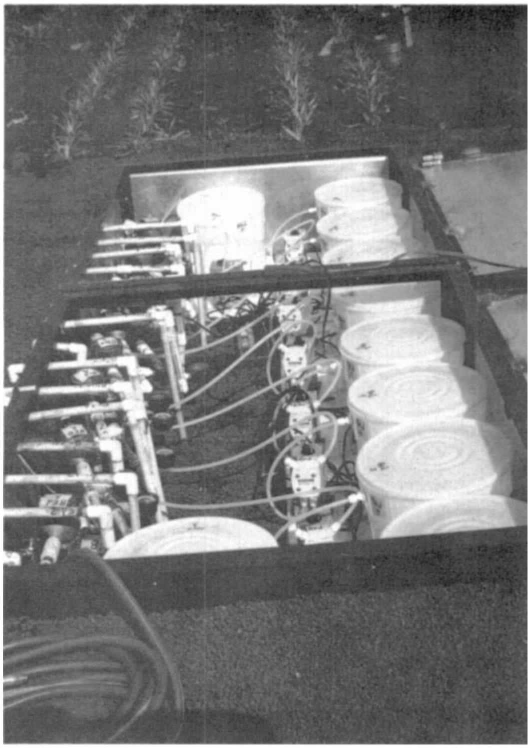


FIG. 4. Control box used in our research on nematicide application through drip irrigation in Hawaiian pineapple. Individual tanks and pumps for nematicides are at the right; injection fittings and water meters are at left. Steel control box provides protection against damage by heavy equipment or vandalism.

should be monitored closely because accurate application rates of the nematicide, and the reporting thereof, cannot be overstated (10). In our pineapple research, the water flow is metered with a quality water meter on all treatments (Fig. 3).

*Backflow prevention:* Vacuum breakers and gate (shut-off) valves should be used for every replicate of a treatment (Fig. 5). The vacuum breaker serves two purposes: 1) When the water is shut off, it prevents a vacuum in the line that can pull soil into emitters and block them, and 2) it can allow the pressure to be determined using a pressure gauge (Fig. 6). The gate valve makes it possible to adjust pressure that is too high or too low. This is important if some replicates of an experiment lie on a slope. Adjustment of all replications in a treatment to the same pressure insures a greater accuracy of nematicide distribution.

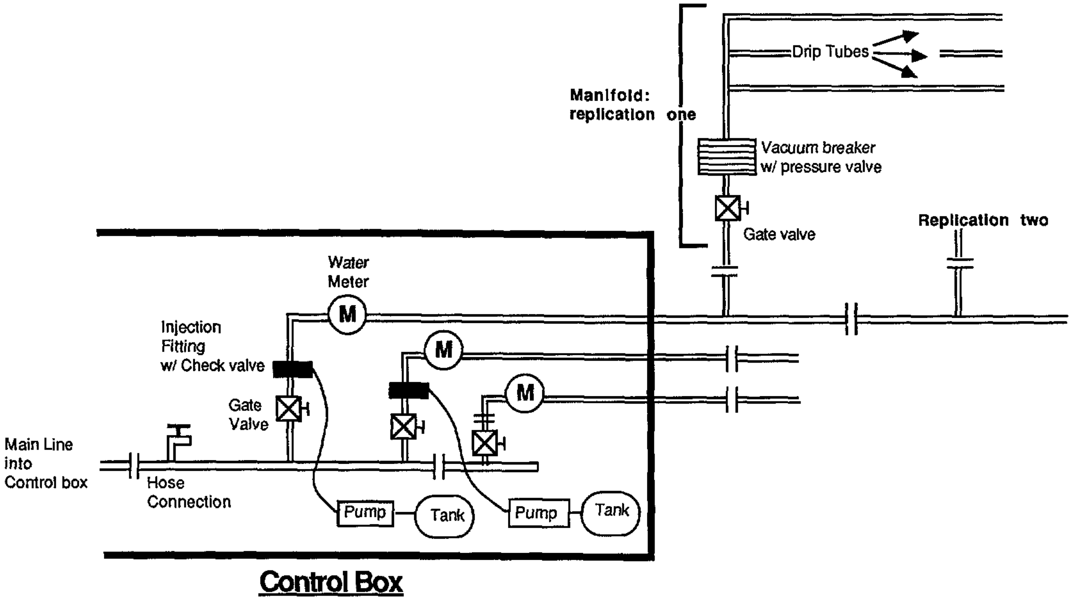



FIG. 5. Detailed schematic of control box connection to treatment manifold for nematicide application through drip irrigation in research on Hawaiian pineapple. Each manifold serves one replication, with each replication consisting of three beds, one drip tube per bed.

*Environmental contamination:* The potential for groundwater contamination is a major concern with soil application of nematicides (31). Many instances of groundwater contamination have been recorded in the past 8 years (7). In 1980 ethylene dibromide (EDB) and 1,2-dibromo-3-chloropropane (DBCP) were discovered contaminating Hawaii's groundwater (7). Although the concentrations were low, the public outcry was vigorous. Similar situations have arisen with other nematicides in many regions of the United States (31). As previously mentioned, drip irrigation application of nematicides can minimize environmental contamination by facilitating precise control of nematicide placement and quantity of nematicide delivered.

*Nematode resistance and nematicide degradation:* The potential for nematodes developing resistance to nematicides is still largely unknown. Recent studies (33–36) have demonstrated, however, that exposing populations of nematodes to nonfumigant nematicides may result in behavioral changes (observed with *Xiphinema index* Thorne & Allen) or decreased sensitivity to a nematicide (observed with *M. incognita* and *Pratylenchus vulnus* Allen & Jensen). The development of resistance to nonfumigant nematicides in the field (with *X. index* and *M. incognita*) has also been observed (37).

Application of nematicides over long periods at relatively low concentrations in repeated applications via drip irrigation is a potentially strong selection pressure for resistance. Application of nematicides through drip irrigation results in root systems and nematode populations being confined to limited soil volumes and there is a smaller portion of the nematode gene pool "escaping" the nematicide by residing in nontreated areas, as does occur with other methods of application (30). This may enhance the development of resistance because there is a limited nonexposed gene pool to dilute the increasing frequency of resistance genes. This may not be a problem in deeply rooted crops where soil moisture is adequate for nematode movement throughout the soil profile.

Frequent application of nematicides at low concentrations via drip irrigation is also a strong selection for populations of microorganisms capable of degrading specific

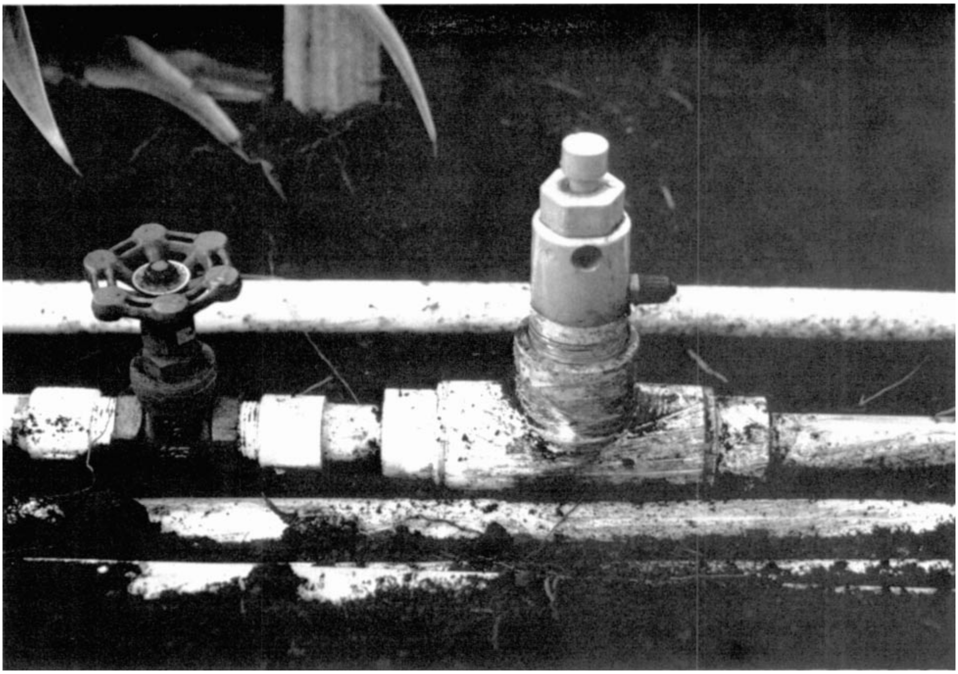


FIG. 6. Gate valve for an individual manifold, with a vacuum breaker equipped with a pressure valve for checking water pressure to an individual treatment replication (right).

nematicides (30). The increasing frequency of such micro-organisms in the root zone will decrease the concentration, and hence efficacy, of the nematicide in the soil profile.

*Future directions:* Drip irrigation application of nematicides is being used more and more frequently; however, further research is required to optimize the efficacy of this system. An increased understanding of root growth in relation to plant growth and yield is required for many crops, as is the influence of nematode populations on root growth. Information on the dynamics of root growth in relation to nematode parasitism will allow additional refinement of application strategies for available nematicides, thereby increasing their efficacy.

In the future, application of biological control agents through drip irrigation is also a distinct possibility (4). One of the problems preventing field application of biological control agents is obtaining a sufficient quantity of the agent and then delivering the agent to the rhizosphere. Application through drip irrigation could minimize the mass of the agent required and assure delivery to the rhizosphere. Consequently, drip irrigation can be used in integrated crop management systems to facilitate delivery of pesticides and biological control agents to the rhizosphere.

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