CONTROL OF PLANT PARASITIC NEMATODES WITH FURFURAL – A NATURALLY OCCURRING FUMIGANT

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ABSTRACT

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The efficacy of furfural (2-furfuraldehyde) as a nematicide was studied in greenhouse and microplot experiments. Mixing furfural with soil at rates of 0.1–1.0 ml/kg prior to transferring soil to greenhouse pots suppressed initial populations of *Meloidogyne arenaria* and *Pratylenchus brachyurus*. The number of root galls induced by *Meloidogyne arenaria* in 'Summer Crookneck' squash (*Cucurbita pepo*) after 8 weeks was reduced proportionately to the rate of furfural applied to the soil before planting. Similar results were obtained for *M. incognita, Heterodera glycines*, and other species when soybean (*Glycine max*) was used as a host. Furfural also was effective as a nematicide when its vapor was allowed to diffuse through a soil column. In microplots, preplant injection of furfural was simulated by pouring it into a 25-cm-deep trench that was immediately covered with soil. When furfural was applied to microplots at rates of 53–159 ml/m² soil, initial populations of *M. arenaria* and *P. minor* were reduced and yields of 'Clemson Spineless' okra (*Hibiscus esculentum*) were increased. No further yield increases were obtained at higher rates. Results indicate that furfural could have practical applications in the control of phytoparasitic nematodes.

Key words: chemical control, fumigants, *Hibiscus esculentum, Meloidogyne arenaria*, natural products, nematicides, root-knot nematode, okra, *Paratrichodorus minor, Pratylenchus brachyurus*, vegetables.

RESUMEN

Rodríguez-Kábana, R., J. W. Kloepper, C. F. Weaver y D. G. Robertson. 1993. Control de nematodos fitoparásitos con furfural – un fumigante de origen natural. Nematrópica 23:63–73.

Se estudió la eficacia del furfural (2-fururaldehído) como nematicida en experimentos de invernadero y microparcelas. Mezclando furfural con suelo a dosis de 0.1–1.0 ml/kg se redujeron las poblaciones iniciales de *Meloidogyne arenaria* y *Pratylenchus brachyurus*. Transcurridas 8 semanas, el número de agallas inducidas por *Meloidogyne arenaria* en calabacín (*Cucurbita pepo*) var. 'Summer Crookneck' fue reducido proporcionalmente a las dosis de furfural aplicadas al suelo en pre-siembra. Se obtuvieron resultados similares para *M. incognita, Heterodera glycines* y otras especies cuando se utilizó soja (*Glycine max*) como planta hospedadora. Furfural fue asimismo efectivo como nematicida cuando se provocó la difusión de su vapor a través de una columna de suelo. En microparcelas, se simuló la inyección de furfural en pre-siembra mediante su vertido en una zanja de 25 cm de profundidad que fue inmediatamente cubierta con suelo. Aplicaciones de furfural en microparcelas a dosis de 53–159 ml/m² redujeron las poblaciones iniciales de *M. arenaria* y *Paratrichodorus minor* e incrementaron los rendimientos de quimbombó (*Hibiscus esculentum*) var. 'Clemson Spineless.' No se observaron mejoras en los rendimientos a dosis mayores. Los resultados indican que el furfural podría tener aplicación práctica en el control de nematodos fitoparásitos.

Palabras clave: control químico, fumigantes, hortalizas, *Hibiscus esculentum, Meloidogyne arenaria*, nematicidas, nematodo nodulador, *Paratrichodorus minor, Pratylenchus brachyurus*, productos naturales, quimbombó.

INTRODUCTION

Furfural (2-furfuraldehyde) is a liquid found in many essential oils from plants, and is present in fruit juices, alcoholic beverages, and bread. It is used in small amounts in the food industry in flavor compositions (2,7). It was first described by Dobereiner in 1832 (7) and large scale commercial production was started in 1922 (8). Furfural originates from heat

treatment of many carbohydrates and it is obtained industrially by the reaction of H_2SO_4 with pentosan-containing agricultural residues such as corn cobs, sugarcane bagasse, cottonseed hulls, oat or rice hulls, *etc.* (8). Furfural is insecticidal (7). Raeder *et al.* (9) in 1925 and Flor (5) in 1926 first studied the fungicidal properties of furfural, reporting control of *Rhizoctonia solani* in potato (*Solanum tuberosum*). More recently, Canullo *et al.* (3) demonstrated that soil treatments with furfural control southern blight (*Sclerotium rolfsii*) in lentil (*Lens culinaris*) while stimulating development of *Trichoderma* spp. and bacteria antagonistic to *S. rolfsii*. Because of its relatively low price and widespread commercial production (7,8), furfural was included in an on-going study on the value of low molecular weight volatile compounds as nematicides. The objective of the following research was to evaluate the nematicidal efficacy of furfural under greenhouse and microplot conditions.

MATERIALS AND METHODS

Greenhouse Experiments

Sandy loam soils were collected from peanut (*Arachis hypogaea*) and soybean (*Glycine max*) fields. The peanut field was naturally infested with *Meloidogyne arenaria* (Neal) Chitwood and *Pratylenchus brachyurus* (Godfrey) Filipjev & Schuurmans Stekhoven; populations of *M. arenaria* exceeded 50 juveniles/100 cm^3 soil. The soybean field was infested with *M. incognita* (Kofoid & White) Chitwood, *Heterodera glycines* Ichinohe, *Helicotylenchus dihystera* (Cobb) Sher, and *P. brachyurus*. Also present in both soils were appreciable numbers of non-parasitic nematodes in the orders Rhabditida and Dorylaimida. The soils had a pH = 6.0–6.3, organic matter content < 1.0% (w/w), and cation exchange capacity < 10 meq/100 g soil. Soil from the peanut field was composed of 74.4% sand, 15.4% silt, and 10.2% clay. The soybean soil had similar textural composition. Soil was screened (< 1 mm) to remove large particles and debris, then amended 50:50 (v:v) with siliceous builder's fine (< 0.1 mm) sand. The moisture content of the amended soil was 15% (60% field capacity).

In each experiment, soil was apportioned in 1-kg amounts in 3-L polyethylene bags. The appropriate dosage of technical grade furfural (QO Chemicals, Inc., West Lafayette, Indiana) or 1,3-D (1,3-dichloropropene) was added directly to the soils in the bags, and after thorough mixing, soil was transferred immediately to 1-L capacity cylindrical plastic pots on a greenhouse bench. The soil was maintained moist for 1 week when a 100-cm^3 sample was collected from each pot for nematological analyses using the salad bowl incubation technique (10). The remaining soil in the pots was mixed and the appropriate host plant was planted. In all experiments there were eight replications (pots) per treatment arranged in a randomized complete block design. Controls consisted of soil treated in a similar manner but without addition of furfural.

Plants were allowed to develop for 6–8 weeks, after which they were carefully separated from the soil and examined. Root galls caused by *Meloidogyne* spp. and the females and cysts of *H. glycines* were counted. Root galling was assessed using Zeck's scale (12), where 0 = no galls and 10 = maximal galling. Shoot heights and shoot and root fresh weights were determined. The 72-hr salad bowl incubation technique was used to extract nematodes from roots and from 100-cm^3 soil samples.

Experiment I: Furfural was applied at doses of 0, 1.0, and 3.0 ml/kg to soil from the peanut field. The host plant, 'Sum-

mer Crookneck' squash (*Cucurbita pepo*), was planted at a rate of 5 seeds per pot.

Experiment II: Furfural was applied at rates of 0, 0.1, 0.5, and 1.0 ml/kg to soil from the soybean field. 'Davis' soybean, the host plant, was planted at the rate of 5 seeds per pot.

Experiment III: The nematicidal efficacy of furfural was compared with that of 1,3-D (Telone^{R} II) using soil from the peanut field. The materials were added at doses of 0, 0.1, 0.2, 0.5, 0.75, and 1.0 ml/kg soil. Squash was used as the host as in Experiment I.

Experiment IV: The nematicidal efficacy of liquid furfural applied directly to soil was compared with that of furfural vapor diffusing through a soil column. Soil from the peanut field was used. Liquid furfural was applied to soil in plastic bags at rates of 0, 0.2, 0.5, 1.0, 1.5, and 2.0 ml/kg soil and the treated soil was transferred to pots as in Experiment I. These same doses of furfural were also delivered into a fumigation apparatus (Fig. 1) that consisted of a wide-mouth, square glass bottle, where the furfural was delivered, joined by an air-tight connector to a 9-cm-diam cylinder containing 0.5 kg soil. A fiberglass screen (1 mm mesh) covered by glass filter paper retained the soil. The injection port was sealed with silicone rubber immediately after delivery of furfural into the chamber. Soil in the apparatus and in the pots was left undisturbed for one week and then was planted with squash as in Experiment I.

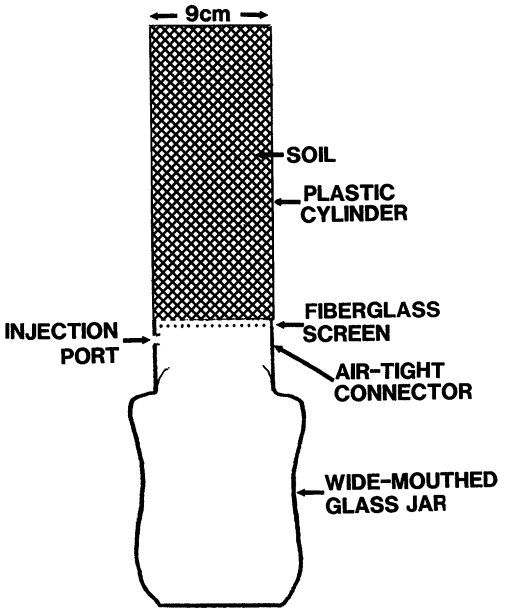

Fig. 1. Fumigation chamber attached to 9-cm-diam plastic cylinder filled with soil to study the nematicidal activity of furfural vapor.

Microplot Experiment

A microplot experiment was established at the Old Agronomy Farm at the Auburn University campus at Auburn. Microplots in the experiment were 929 cm^2 delimited by square Terra-Cotta chimney flutes embedded in the soil to a depth of 50 cm with 10 cm of the flute's wall above ground level. Soil in the microplots was from a soybean field near Elberta, Alabama, infested with *M. arenaria* and *Paratrichodorus minor* Siddiqi. Microplots had been planted to soybean 1 year prior to the experiment and to a hairy vetch (*Vicia villosa*) cover crop during the winter. Furfural was applied 3 July at rates of 0, 5, 10, 15, 20, 40, and 60 ml/microplot. The material was delivered to the bottom of a narrow (2–3 cm wide) trench cut diagonally across the microplot to a depth of 25 cm with a square shovel. Following delivery, the trench was covered by pushing in soil from the trench sides. The soil surface was tamped lightly and the microplot surface was moistened immediately after delivery of furfural to assure a good seal.

Microplots were kept moist, and after 1 week, soil samples were collected from each microplot by taking two 2.5-cm-diam

soil cores to a depth of 25 cm with a standard probe. Cores were taken approximately 5 cm from each side of the center of the microplot on the diagonal line perpendicular to the location of the treatment trench. Cores for each microplot were composited, and a 100-cm^3 subsample was used for nematode analysis. Later the same day, two 2-week-old 'Clemson Spineless' okra (*Hibiscus esculentum*) seedlings were transplanted into each microplot. There were eight replications (microplots) per treatment arranged in a randomized complete block design. Controls included untreated microplots and microplots treated with aldicarb (Temik 15G) at 9 kg a.i./ha (broadcast basis). Aldicarb was applied at planting time after taking preplant soil samples, by spreading the granules evenly on the soil surface and incorporating them to a depth of 2–3 cm.

Microplots were equipped with a drip irrigation system, and water was applied as needed. Weed control was by hand, and fertilization and control of foliar insects was according to standard recommendations (1,4). Yield data were obtained by harvesting fruit as they grew to marketable size and recording the total number and weight of fruit harvested. Two weeks before termination of the experiment, a composite soil sample was collected from each microplot for nematological analysis as described previously. The experiment was terminated on 23 October when the plants were removed carefully from each microplot. Stalks were weighed and the roots were evaluated for galling using Zeck's root-knot index scale.

Statistical Analyses

Data from all experiments were analyzed according to standard procedures for analyses of variance (6,11). Fisher's least significant differences were calculated when F values were significant. Unless otherwise stated differences referred to were significant to the 5% or lower probability level.

RESULTS

Greenhouse Study

Experiment I: No *M. arenaria* juveniles were recovered from soil treated with 1.0 or 3.0 ml furfural/kg soil; control samples averaged 193 juveniles/100 cm^3 soil. There were no root galls caused by *M. arenaria* in plants from soil treated with furfural and these plants had heavier roots and shoots than those from the control (Table 1).

Experiment II: Numbers of plant-parasitic nematodes in preplant soil samples decreased proportionately to furfural

Table 1. Experiment I. Effect of furfural on fresh weights of shoots and roots of 'Summer Crookneck' squash (*Cucurbita pepo*), numbers of root galls caused by *Meloidogyne arenaria*, and root-knot index values.

Furfural rate (ml/kg soil)	Shoot weight (g)	Root weight (g)	Galls per gram root	Root-knot index (0–10)[z]
0.0	2.58	0.24	32.8	3.2
1.0	3.07	0.39	0.0	0.0
3.0	3.14	0.44	0.0	0.0
FLSD ($P = 0.05$)	0.48	0.10	6.8	0.5

[z]Based on Zeck's scale (15) of 0–10, where 0 = no galls and 10 = maximal galling.

Table 2. Experiment II. Effect of furfural on the number of nematodes in soil and root samples from a greenhouse experiment with soybean (*Glycine max*) planted 1 week following application of the chemical to the soil.

Type of sample	Fufural rate (ml/kg)	Number of nematodes extracted[x]				
		Meloidogyne incognita	*Heterodera glycines*	*Pratylenchus brachyurus*	*Helicotylenchus dihystera*	Non-parasitic
Soil preplant[y]	0.0	41	206	21	48	186
	0.1	23	52	28	34	354
	0.5	3	0	0	0	67
	1.0	0	0	0	0	3
FLSD ($P = 0.05$)		5	34	6	18	66
Soil at 8 weeks	0.0	55	87	11	20	253
	0.1	120	225	3	34	252
	0.5	7	287	0	0	277
	1.0	0	1	0	0	127
FLSD ($P = 0.05$)		75	129	6	15	67
Roots at 8 weeks[z]	0.0	123	21	215	110	378
	0.1	744	53	273	190	415
	0.5	10	24	8	93	186
	1.0	0	0	0	0	19
FLSD ($P = 0.05$)		152	46	76	65	108

[x]Nematodes extracted from samples after 72-hr incubation with the salad bowl method (12).
[y]Soil sample size = 100 cm^3.
[z]Nematode numbers in root samples are on the basis of the entire root systems.

dosage (Table 2). Numbers of non-parasitic nematodes increased in response to the 0.1-ml rate but were lower in soils treated with the two higher rates than in untreated soil.

The numbers of *M. incognita* juveniles, *P. brachyurus*, and *H. dihystera* in soil at the final sampling were lower than in the control in soils treated with doses of 0.5 ml/kg or higher (Table 2). The numbers

Table 3. Experiment II. Fresh weights of shoots and roots, root-knot index, and number of root-galls caused by *Meloidogyne incognita* in soybean (*Glycine max*) plants from a greenhouse experiment on the nematicidal properties of furfural.

Furfural rate (ml/kg soil)	Shoot height (cm)	Shoot weight (g)	Root weight (g)	Galls per gram root	Root-knot index (0–10)
0.0	38.0	1.92	0.59	31	4.5
0.1	32.4	1.40	0.94	33	4.8
0.5	35.7	3.00	2.70	1	2.1
1.0	27.8	2.10	2.71	0	0.0
FLSD ($P = 0.05$)	3.2	0.69	0.47	12	1.4

of non-parasitic nematodes and juveniles of *H. glycines* were suppressed at the 1.0-ml rate (Table 2).

Numbers of plant parasitic nematodes in the roots either increased or were not affected by the the 0.1-ml dose of furfural (Table 2); the 0.5-ml rate suppressed numbers of *M. incognita* juveniles and of *P. brachyurus*, but did not affect numbers of *H. dihystera* or *H. glycines* juveniles. The 1.0-ml dose reduced populations of all nematodes in the roots (Table 2).

The number of root galls caused by *M. incognita* and values for the root-knot index were not affected by the 0.1-ml dose but were reduced by the higher rates (Table 3).

Shoot height was reduced by the 0.1 and 1.0-ml treatments and the roots and shoots of soybean from soils that received 0.5 ml/kg were heavier than those of the control or the 0.1-ml treatment (Table 3).

Experiment III: In this experiment, mixing 1,3-D with soil in plastic bags had no effect on the numbers of *M. arenaria* juveniles extracted by the salad bowl method 1 week afterward (Table 4). In contrast, furfural killed the juveniles or prevented egg hatch proportionately to the amount of the chemical applied; no juveniles were detected in soils treated with 0.5 ml/kg or higher rates. Furfural applications also reduced numbers of non-parasitic nematodes in soil (Table 4). This was also true for 1,3-D but the effect was not as pronounced as with furfural.

At the final sampling, the number of *M. arenaria* juveniles extracted from soil declined proportionately with the furfural rate between 0 and 0.5 ml/kg soil (Table 4), and no juveniles were detected in soil treated with the higher rates (0.75 and 1.0 ml/kg). Numbers of juveniles in soils treated with 1,3-D were decreased by all rates of application when compared with the control; however, numbers of juveniles extracted at the 0.75 and the 1.0 ml/kg rates were significantly greater than those at the 0.5 ml/kg rate.

Numbers of non-parasitic nematodes in the control at the end of the experiment were similar to those at planting

Table 4. Experiment III. Comparison of the effects of furfural and 1,3-D on soil populations of *Meloidogyne arenaria* juveniles and non-parasitic nematodes in a greenhouse experiment with 'Summer Crookneck' squash (*Cucurbita pepo*).

	Nematodes per 100 cm³ soil[x]							
	Preplant[y]				Final[z]			
	M. arenaria		Non-parasitic		*M. arenaria*		Non-parasitic	
Rate (ml/kg soil)	Furfural	1,3-D	Furfural	1,3-D	Furfural	1,3-D	Furfural	1,3-D
0.00	95	95	222	222	32	32	174	174
0.10	67	86	169	232	12	4	232	259
0.20	17	63	160	137	6	12	207	215
0.50	0	78	48	93	0	2	512	136
0.75	0	104	1	153	0	14	737	204
1.00	0	56	0	116	0	22	703	245
FLSD ($P = 0.05$)	38		51		9		187	

[x]Nematodes were extracted from soil after incubation for 72 hrs with the salad bowl incubation method (12).
[y]Preplant samples were taken 1 week after treatment of soil with the chemicals and the same day squash was planted.
[z]Final sampling was 8 weeks after planting of squash.

Table 5. Experiment III. Comparison of the effects of furfural and 1,3-D on root populations of *Meloidogyne arenaria* juveniles and *Pratylenchus brachyurus*, and on root-knot index values and numbers of galls caused by *M. arenaria* in the roots of 'Summer Crookneck' squash (*Cucurbita pepo*) grown for 8 weeks in soil treated with the chemicals.

Rate (ml/kg soil)	Nematodes in roots[y]				Galls per gram root		Root-knot Index (0–10)[z]	
	M. arenaria		*P. brachyurus*					
	Furfural	1,3-D	Furfural	1,3-D	Furfural	1,3-D	Furfural	1,3-D
0.00	488	488	185	185	58	58	6.1	6.1
0.10	382	204	123	97	51	37	6.0	4.5
0.20	204	104	67	158	22	38	5.1	4.2
0.50	2	304	8	141	0	45	0.0	4.4
0.75	8	437	2	122	1	86	0.5	5.1
1.00	1	501	1	103	0	79	0.0	4.6
FLSD ($P = 0.05$)	87		38		9		0.5	

[y]Nematodes were extracted from roots after incubation for 72 hr with the salad bowl incubation method (12).
[z]Root-knot index based on Zeck's scale (15) of 0–10, where 0 = no galls and 10 = maximal galling.

(Table 4). In soils treated with furfural at rates ≥ 0.5 ml, populations of non-parasitic nematodes increased by 2–3-fold. 1,3-D had no effect on numbers of these nematodes.

Numbers of *P. brachyurus* and of *M. arenaria* juveniles in the roots diminished with increasing furfural rates (Table 5). There was no clear pattern of response between 1,3-D rates and numbers of *P. brachyurus* in the roots 9 weeks after application. The effect of 1,3-D on *M. arenaria* juveniles in the roots (Table 5) was similar to that observed for juveniles in the soil; populations declined at doses up to 0.20 ml and increased proportionately to 1,3-D rate above 0.20 ml/kg.

Changes in root-knot index values and in the numbers of root galls caused by *M. arenaria* in response to either chemical

Table 6. Experiment III. Comparison of the effects of furfural and 1,3-D on shoot height and fresh weights of shoots and roots of 'Summer Crookneck' squash (*Cucurbita pepo*) grown for 8 weeks in soil treated with the chemicals.

Rate (ml/kg soil)	Shoot height (cm)		Shoot weight (g)		Root weight (g)	
	Furfural	1,3-D	Furfural	1,3-D	Furfural	1,3-D
0.00	18.5	18.5	4.65	4.65	1.27	1.27
0.10	19.4	19.9	5.14	4.38	1.11	0.92
0.20	20.6	19.5	4.39	3.78	0.98	0.81
0.50	19.9	19.6	5.21	4.38	0.85	0.94
0.75	20.1	20.6	5.23	4.92	1.26	0.91
1.00	19.8	19.1	5.29	3.64	1.02	0.86
FLSD ($P = 0.05$)	n.s.		1.35		n.s	

n.s. = statistically not significant.

(Table 5) followed a pattern of change similar to that observed for juveniles of the nematode in the roots.

Application of the chemicals had no significant effect on fresh root weight or shoot height (Table 6). No treatment with either chemical improved shoot weights above the control (Table 6); however, all furfural treatments but one (0.20 ml/kg rate) resulted in plants with heavier shoots than those from soils treated with 1,3-D at the 1.0 ml/kg rate.

Experiment IV: Mixing liquid furfural with soil was more effective for control of nematodes than was vapor treatment at the two lowest rates (Table 7). However, both methods of application resulted in almost complete suppression of the nematodes when rates ≥ 0.5 ml were used. Root-knot indices and numbers of root galls caused by *M. arenaria* were generally lower in treatments receiving liquid furfural than in those that were vapor treated (Table 7).

Plants from soils treated with the 2.0-ml rate in the vapor apparatus were taller and had heavier shoots than all other plants in the experiment (Table 8). Although there were other differences among treatments, no pattern of response to either dosage or application method was detected for these variables. There were no differences in fresh root weights among the treatments.

Microplot Experiment

The effect of furfural was more pronounced on *P. minor* and *M. arenaria* juveniles than on non-parasitic nematodes (Table 9). For the most part, the effects of furfural were transient. At the October sampling numbers of *P. minor*, and of *M. arenaria* juveniles in furfural-treated soil had recovered or had increased above

Table 7. Experiment IV. Comparison of the nematicidal efficacy of furfural previously applied directly to soil as a liquid, or as a vapor applied by connecting a container of furfural to the bottom of a soil column, in a greenhouse experiment with 'Summer Crookneck' squash (*Cucurbita pepo*) and soil infested with *Meloidogyne arenaria*.

Method of application	Rate (ml/kg)	Preplant population[y]		Final population of *M. arenaria*		Galls per gram of root	Root knot index[z]
		M. arenaria	Non-parasitic	Soil	Roots		
Liquid	0.0	141	181	83	186	93	4.9
	0.2	7	49	0	2	16	2.2
	0.5	0	1	0	1	0	0.0
	1.0	0	0	0	0	0	0.0
	1.5	0	0	0	0	0	0.0
	2.0	0	0	0	0	0	0.0
Vapor	0.0	153	188	84	186	71	5.0
	0.2	49	133	32	55	28	3.1
	0.5	10	41	39	126	45	3.3
	1.0	0	7	1	1	6	0.9
	1.5	1	11	0	0	1	0.4
	2.0	0	3	0	0	0	0.0
FLSD ($P = 0.05$)		14	24	32	75	9	1.1

[y]Nematodes extracted from soil and roots after 72 hr incubation with the salad bowl incubation method (12). Numbers represent nematodes in 100 cm^3 soil or in total mass of roots.

[z]Root-knot index based on Zeck's scale (15) of 0–10 where 0 = no galls and 10 = maximal galling.

Table 8. Experiment IV. Comparison of furfural liquid mixed directly into soil and application as a vapor underneath a soil column, for effects on growth of 'Summer Crookneck' squash (*Cucurbita pepo*) in soil infested with *Meloidogyne arenaria*.

Application rate (ml/kg soil)	Shoot height (cm)		Shoot weight (g)	
	Liquid	Vapor	Liquid	Vapor
0.0	18.6	20.1	2.6	3.0
0.2	19.3	18.9	2.2	2.5
0.5	20.4	17.2	2.8	2.3
1.0	17.2	17.6	2.2	2.7
1.5	17.1	20.5	2.8	8.6
2.0	18.2	25.0	2.4	8.2
FLSD ($P = 0.05$)	1.7		1.4	

numbers found in control plots (Table 9); differences among treatments in numbers of non-parasitic nematodes were not significant. The aldicarb treatment had a depressive effect on numbers of *M. arenaria* juveniles in the October soil samples; however, the treatment did not affect numbers of *P. minor*. Root-knot indices (Table 9) had a response pattern to furfural generally similar to that observed for *M. arenaria* juveniles in the October soil samples.

The number of fruits and the weights of fruits (Table 10) increased in response to furfural rate in the range of 0–20 ml with no additional increases in values in response to higher dosages. Stalk weight increased throughout the range of treatment. Aldicarb increased yields, number of fruits, and stalk weights to levels comparable to the best furfural treatments.

Table 9. Effect of furfural applications on preplant and final nematode populations and on root-knot indices in a microplot experiment with 'Clemson spineless' okra (*Hibiscus esculentum*) and soil infested with *Meloidogyne arenaria* and *Paratrichodorus minor*.

Furfural Rate (ml/microplot)	Nematodes per 100 cm^3 soil[y]						Root-knot index[z]
	Preplant			Final			
	M. arenaria	*P. minor*	Non-parasitic	*M. arenaria*	*P. minor*	Non-parasitic	
0	35	36	122	87	94	381	3.0
5	7	15	102	68	67	366	3.0
10	6	4	57	93	42	391	3.5
15	2	3	46	95	15	511	4.5
20	5	8	66	273	30	501	5.3
40	3	0	48	287	19	476	4.8
60	0	12	39	59	60	452	4.9
FLSD ($P = 0.05$)	25	11	38	75	23	189	1.8

[y]Nematodes extracted from soil after 72 hr incubation with the salad bowl method (12).
[z]Root-knot index according to Zeck's scale (15) of 0–10 where 0 = no galls and 10 = maximal galling.

Table 10. Effect of furfural application on fresh weight of fruit and stalks, and on the number of fruit of 'Clemson spineless' okra (*Hibiscus esculentum*) in microplots containing soil infested with *Meloidogyne arenaria* and *Paratrichodorus minor*.

Furfural rate (ml/microplot)	Weight of fruit (g)	Number of fruit per plant	Stalk weight (g)
0	23	1.6	41.8
5	62	3.8	60.9
10	89	4.5	85.3
15	145	6.9	116.6
20	162	7.4	106.5
40	119	6.3	135.6
60	155	6.8	144.6
FLSD ($P = 0.05$)	57	2.5	42.2

DISCUSSION

Several nematicides, including methyl isothiocyanate (MIT), MIT precursors (metham sodium, dazomet), methyl bromide, and chloropicrin are recommended for use in the range of 60–1200 kg/ha (1). These rates are roughly equivalent to 0.03–0.5 g/kg soil, assuming that the weight of soil in a hectare to a 15-cm depth (furrow slice) is 2.242×10^6 kg. The density of furfural at 25 °C is 1.1545 g/ml. Therefore, the furfural application rates used in our greenhouse experiments (0.11–3.46 g/kg soil) and the two lowest rates in the microplot experiment (5.8 and 11.5 g/microplot) were within the range of rates used for several commercial nematicides. At these rates, furfural was an effective nematicide in soil. Since furfural is relatively inexpensive it might be competitive with other, commercially available broadspectrum materials.

Furfuraldehyde was superior to 1,3-D as a nematicide when the chemicals were mixed with soil in plastic bags. This effect could have resulted from differences in vapor presssures of the two materials. The vapor pressure of 1,3-D (28 mm Hg at 20 °C) is 14 times that of furfuraldehyde (2 mm Hg at 20 °C) (9,10). Another factor affecting nematicidal activity is water solubility. At 20 °C, the solubility of 1,3-D in water is approximately 0.1% (w/w) and that of furfuraldehyde is 8.3% (9,10). Although these properties suggest that furfural would be used best by spraying an aqueous solution directly into soil followed by mixing, it is evident from our results that the vapor alone can work.

The method of application we used to deliver furfuraldehyde in the microplot experiment was possibly not optimal for nematicidal efficacy. The nematicidal action was short-lived, and maximal nematicidal activity and yield response were obtained with rates between 10 and 20 ml/plot. It is possible that with improved application methods furfural rates could be reduced considerably. Furfural's solubility in water might permit application through drip or other irrigation systems to prolong treatment. Our future research on furfural will focus on determining the best way of applying the chemical under field conditions.

In conclusion, results from this study showed that furfural can have considerable nematicidal activity in soil. Its physical and chemical properties suggest potential for commercial formulation and application. These factors combined with its relative safety to humans (8), low price, and its ready degradation by soil microorganisms (3), suggest that furfural should be considered for development as a broadspectrum nematicide-microbiocide.

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