Techniques

Effects of Microwave Oven Treatment on Microorganisms in Soil

R. S. Ferriss

Department of Plant Pathology, University of Kentucky, Lexington 40546-0091.
Journal Series Paper 82-11-233 of the Kentucky Agricultural Experiment Station, Lexington 40546.
I thank J. M. Baker for general technical assistance, R. L. Anderson for statistical consultation, R. A. Chapman for nematode assays, J. M. Vincent and C. W. Rice for nitrogen analyses, and A.-C. McGraw for assistance in assays of mycorrhizal fungi.
Accepted for publication 4 August 1983.

ABSTRACT

Ferriss, R. S. 1984. Effects of microwave oven treatment on microorganisms in soil. Phytopathology 74:121-126.

Procedures were developed for routine microwave (MW) radiation treatment of soil to eliminate or reduce populations of soilborne plant pathogens. Shredded, naturally-infested soil in plastic bags was exposed to full power in an MW oven. Assays on selective media indicated that the effects of MW treatment on populations of soil microorganisms increased with increasing treatment time, decreased with increasing amounts of soil, and decreased with increasing soil water content between 16 and 37% (weight water/dry weight soil). No pronounced effect of soil type was noted for five mineral soils. Treatment of 1 kg soil at 7–37% water content for 150 sec eliminated populations of *Pythium*, *Fusarium*, and all nematodes except *Heterodera glycines* in all soils tested. Marginal survival of *Rhizoctonia*, cysts of *H. glycines*, and vesicular-arbuscular mycorrhizal fungi was observed in some soils at this treatment rate. Treatment of 4 kg of soil for 425 sec gave comparable results. Compared with autoclaving (1 hr on each of 2 days in succession) or methyl bromide-chloropicrin (98-2) fumigation (0.454 kg/45 kg soil), MW treatment released less nutrient into the soil solution, had less effect on soil prokaryotes, and resulted in less recolonization of soil by *Fusarium* and other fungi. MW treatment was found to be a convenient and rapid method of eliminating soilborne pathogens from soil without excessive detrimental effects.

Additional key words: soil disinfestation, soil pasteurization, soil sterilization.

Procedures commonly used to eliminate or reduce populations of plant pathogens in soil include autoclaving, ionizing radiation, fumigation with various materials, and aerated steam (19). Compared with these procedures, the treatment of soil with microwave (MW) radiation has received less attention. In early work, the temperature response of small amounts of soil and clay to microwave treatment was interpreted to indicate that variations in clay and water content of soil would make MW treatment of little practical use in the control of soilborne plant pathogens (2). MW treatment of soil reduced damping-off of *Trifolium incarnatum*, but had little effect on nodulation of plants by *Rhizobium* populations in the soil (7). *Meloidogyne incognita* was eliminated from soil by treatment in an MW oven for short periods of time (20); however, larvae in cysts of *Heterodera glycines* were found to be extremely tolerant to MW treatment (3). In field tests, a specially constructed MW treatment device eliminated populations of *Rotylenchulus reniformis* in the upper 5 cm of soil, but had little effect on populations at 15 cm (12). Other investigations have indicated that MW treatment of soil can inhibit nitrification and sulfur oxidation (26), and that no heating occurs during MW treatment of very dry soil (2,25). In general, the effects of MW treatment on microorganisms appear to be related to heating (25); however, some metabolic effects not related to heating may occur (2,6). Although the results of this previous research have established that MW treatment can have significant effects on populations of soil microorganisms, broadly applicable methods for routine MW treatment of soil have not been described.

The objectives of this research were to evaluate factors influencing the survival of microorganisms in soil treated in a commercial MW oven, to use this information to develop procedures for MW treatment of soil, and to compare MW effects with some other commonly used methods of soil treatment. A preliminary report has been published (8).

MATERIALS AND METHODS

Soils collected from five locations in Kentucky were stored in polyethylene bags at room temperature until treated or assayed. Soybeans were either growing or had been grown the previous season at all locations. Chemical characteristics of the nontreated soils are presented in Table 1.

Soil to be treated in the MW oven was placed in a 0.04-mm (1.5

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. § 1734 solely to indicate this fact.

mil) polyethylene or polypropylene bag (Markson Scientific, Inc., Del Mar, CA 92014). An opened bag of soil was placed centrally in the cavity (volume = 40.8 L) of an MW oven (Kenmore model 99601, Sears Roebuck & Co., Chicago, IL 60684), and the bag was exposed to full power (625 W heating power, 2,450 MHz) for the treatment time. Some breakage of polyethylene, but not polypropylene, bags occurred with larger amounts of soil and longer treatment times. After treatment, bags were closed and the soil was allowed to cool to room temperature before it was sampled. Soil temperature 1 min and 60 min after treatment was measured with a mercury thermometer inserted approximately 10 cm into the soil mass. The temperature increase of 1,000 ml of deionized water in a 2-L Pyrex beaker exposed to full power for 2 min indicated 653 W heating power (5). For fumigation, approximately 45 kg of soil was placed in a polyethylene bag in a 76-L (20-gallon) garbage can, and 0.454 kg of methyl bromide-chloropicrin (98-2) was released into the bag. For autoclaving, 2 kg of soil was placed in a 2-L flask and autoclaved for 1 hr at 121 C either once or on two successive days.

For assays of microorganisms, carbohydrates, and amino acids in soils, a 25- or 50-g (wet weight) soil sample was comminuted with 100 ml of autoclaved deionized water in a Waring blender, a dilution series was prepared, and appropriate dilutions were plated on the following media: for *Pythium*, 17 g Difco cornmeal agar, 25 mg ampicillin, 100 mg pentachloronitrobenzene, 10 mg rifampacin, 10 mg rose bengal, and 5 mg pimaricin in 1 L of water (17); for *Fusarium*, modified PCNB medium (21); for total fungi, 39 g Difco potato-dextrose agar, 1 ml tergitol NP-10 (Union Carbide Corp., New York), 100 mg streptomycin sulfate, and 20 mg chlortetracycline HCl in 1 L of water (24); and for total prokaryotes (bacteria and actinomycetes), 0.3% tryptic soy agar (16). For assay of *Rhizoctonia*, the initial suspension was screened on a 125-μm sieve, the residue was suspended in 15 ml of 3.0% agar at 50 C, and the agar-soil mixture was cut into 100 blocks after solidification. Blocks were plated on a medium containing 0.18 g enzymatic digest of casein, 1.0 g KH_2PO_4, 0.5 g $MgSO_4 \cdot 7H_2O$, 0.12 g tannic acid, 0.7 g neomycin sulfate, 95 mg pyroxychlor, 0.5 mg benomyl, and 15.0 g agar in 1 L of water (9,10). For assays of carbohydrates and amino acids in the soil solution, the initial suspension was centrifuged at 10,000 *g* for 10 min, the supernatant was filtered through Whatman No. 1 filter paper, and assays were performed on the filtrate. Amino acid and total carbohydrate concentrations were determined by ninhydrin (18) and anthrone (14) procedures, respectively. Unless otherwise noted, all assays except those for *Pythium* were performed <24 hr after treatment. Assays for *Pythium* were performed 2–3 days after treatment unless otherwise noted.

To determine NH_4-N and NO_3-N concentrations, a 10-g soil sample was extracted in 1 N KCl, and nutrient concentrations were measured with an auto analyzer (Technicon Industrial Systems, Tarrytown, NY 10591) using the phenol-hypochlorite reaction for NH_4-N (23) and *N*-1-napthylethylene-triamine for NO_3-N (15).

Other chemical and physical characteristics of the soils were determined on air-dry samples by the University of Kentucky Soil Testing Laboratory.

For evaluation of plant growth in soil, approximately 150 cc of soil was placed in a 165-ml, 4-cm top diameter plant growth tube (Leach "Super Cell," Ray-Leach Cone-tainer Nursery, Canby, OR 97013), and three soybean (*Glycine max* (L.) Merr. 'Williams') or

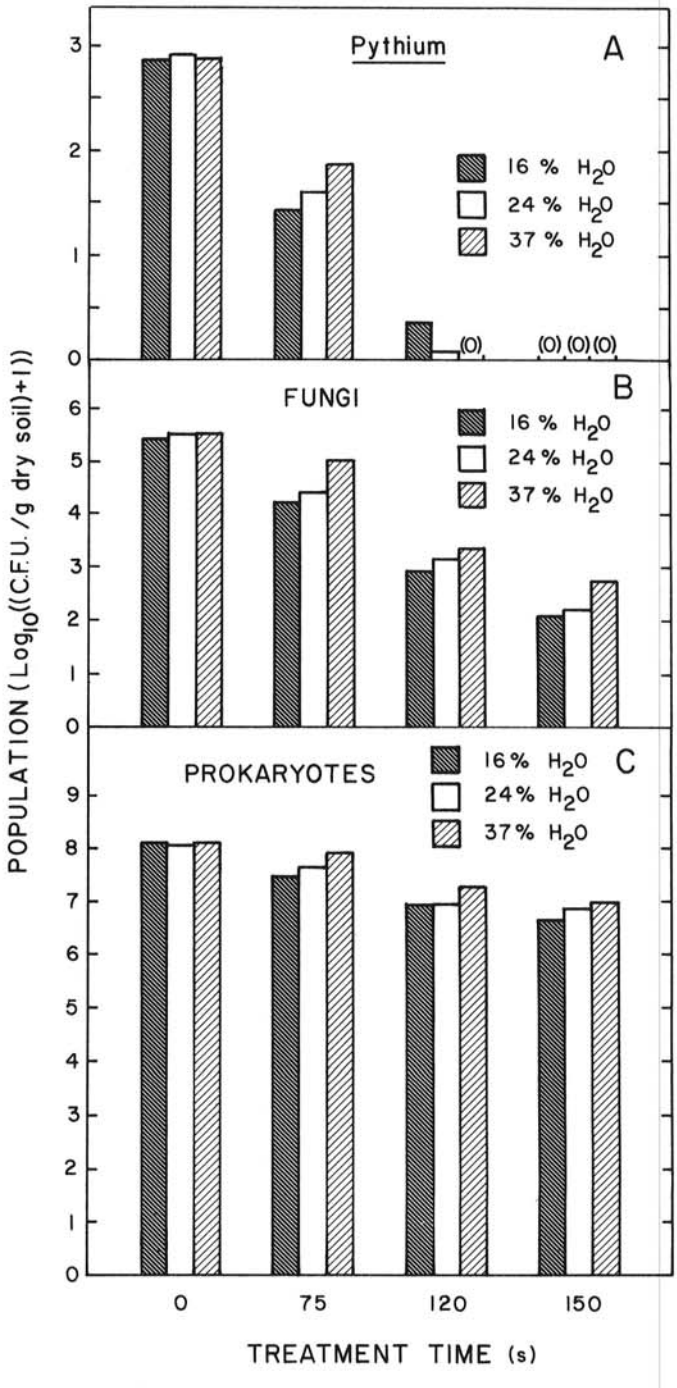

Fig. 1. Populations of soil microorganisms in colony-forming units per gram dry soil 1 day after treatment of 1 kg soil at three moisture contents (weight water/dry weight soil) for 0, 75, 120, or 150 sec in a microwave oven. Populations are means of three replicate samples. **A,** *Pythium*. **B,** Total fungi as enumerated on amended potato-dextrose agar. **C,** Total prokaryotes.

TABLE 1. Chemical characteristics of soils used in microwave soil treatment experiments

Designation	Source[a]	Soil type	pH	Nutrient concentration (μg/g dry soil)						
				Total N	P	K	Ca	Mg	Zn	Mn
1	Fayette Co.	Maury silt loam	6.4	1,706	18	112	1,685	82	1.5	2.3
2	Fayette Co.	Maury silt loam	6.2	1,792	255	122	1,963	102	3.4	1.3
3	Carlisle Co.	Robinsonville silt loam	7.7	1,000	31	113	2,043	396	14.3	0.2
4	Carlisle Co.	Robinsonville loamy sand	7.7	274	21	56	1,105	120	4.1	0.5
5	Webster Co.	Belknap silt	6.9	721	25	88	1,345	86	1.9	0.7

[a] All locations are in Kentucky.

sorghum-sudangrass hybrid (*Sorghum bicolor* (L.) Moench × *S. sudanense* (L.) 'FFR66') seeds were planted. Plants were grown in a greenhouse at 20–25 C and were thinned to one per container 1 wk after planting. Fresh root and shoot weights were determined 7 wk after planting. Four containers of each plant species were prepared for each soil tested. To assay colonization of roots by vesicular-arbuscular (VA) mycorrhizal fungi, 0.5 g (fresh weight) of roots was removed from each plant 7 wk after planting. The sample was cleared, stained in 0.05% trypan blue in lactophenol (22), and the proportion of root length colonized was determined by a grid line intersect method (11).

For assays of nematode populations, 180-g soil samples were sieved through a 250-μm sieve for recovery of cysts of *Heterodera glycines*, and through a 37-μm sieve for recovery of other nematodes.

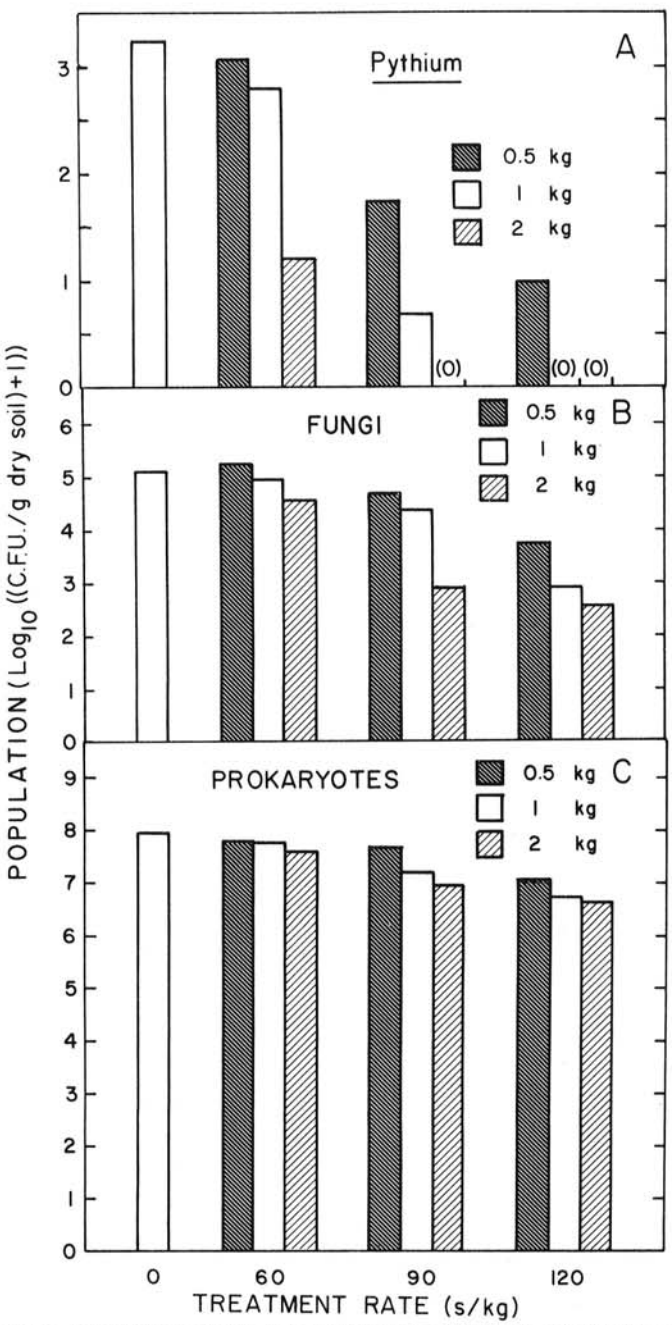

Fig. 2. Populations of soil microorganisms in colony-forming units per gram dry soil 1 day after treatment of 0.5, 1.0, or 2.0 kg soil in a microwave oven for treatment times equivalent to treatment rates of 0, 60, 90, or 120 sec per kilogram of soil. Populations are means of three replicate samples. **A,** *Pythium*. **B,** Total fungi as enumerated on amended potato-dextrose agar. **C,** Total prokaryotes.

RESULTS

Effects of soil water content and MW treatment time on microbial populations and soil temperature. Bags containing 1.0 kg (wet weight) of soil 1 were adjusted to 16, 24, or 37% H_2O (weight water/dry weight soil) by air drying (16%) or addition of deionized water (37%), and were treated for 75, 120, or 150 sec. Populations of *Pythium*, total fungi, and total prokaryotes were reduced by MW treatment at all water contents, and were reduced more in drier than in wetter soil treated for the same length of time (Fig. 1). Populations of *Pythium* were not detected in soil treated for 150 sec. Analysis of variance indicated a significant ($P < 0.05$) effect of treatment time on populations of all microorganisms assayed, and a significant ($P < 0.05$) effect of soil moisture on populations of total fungi and total prokaryotes (Table 2). There were no significant ($P < 0.05$) interactions between treatment time and soil moisture. Soil temperature immediately after treatment correlated positively with treatment time and negatively with soil water content (Table 3). The rate of soil cooling after treatment was greater for drier soil.

Effect of soil weight and MW treatment time on microbial populations and soil temperature. Bags containing 0.5, 1.0, or 2.0 kg of soil 2 at 21% H_2O were treated for periods of time equivalent to treatment rates of 60, 90, or 120 sec per kilogram of soil (wet weight) under the working hypothesis that the effect of MW treatment on soil microorganisms is proportional to treatment time divided by soil weight (eg, for 2.0 kg soil the 60 sec/kg treatment rate consisted of treatment for 120 sec) (4). For each treatment rate, soil temperature immediately after treatment was correlated positively with soil weight (Table 3). The rate of cooling after treatment was not related to soil weight. For each treatment rate, populations of *Pythium*, total fungi, and total prokaryotes decreased with increasing soil weight (Fig. 2). Analysis of variance indicated a significant ($P < 0.05$) effect of treatment rate and soil weight on populations of all microorganisms, and significant interactions between treatment rate and soil weight for total fungi (Table 4).

In another series of experiments, 0.5-, 1.0-, 2.0-, 4.0-, or 8.0-kg bags of soil 1 at 21–24% H_2O were treated for various treatment times (*unpublished*). For each soil weight, the population of total fungi was correlated negatively ($P = 0.05$) with treatment time. Populations of *Pythium* were eliminated by MW treatment of 0.5-, 1.0-, 2.0-, and 4.0-kg bags of soil for at least 100, 120, 180, and 425 sec, respectively. Populations of *Pythium* were not eliminated consistently from 8.0-kg bags of soil by treatment for 800 sec (the longest treatment time applied.)

Effects of MW treatment time and autoclaving on soil nutrients, plant growth, and colonization of plant roots by VA mycorrhizal fungi. Bags containing 1.0 kg of soil 1 at 23% H_2O were treated for 120, 150, 180, 240, or 360 sec in the MW oven. For comparison, the same soil was autoclaved for 1 hr once. Concentrations of amino acids, carbohydrates, and Mn in the soil solution were increased

TABLE 2. Analysis of variance for effects of microwave oven treatment time and soil moisture content on populations of microorganisms in soil[a]

Source of variation	Degrees of freedom	Probability of greater F value		
		Pythium	Total fungi	Total prokaryotes
Treatment time	2	<0.0001	<0.0001	<0.0001
Linear effect	1	<0.0001	<0.0001	<0.0001
Quadratic effect	1	<0.0001	0.0050	0.2567
Moisture	2	0.0611	<0.0001	0.0041
Linear effect	1	0.0608	<0.0001	0.0014
Quadratic effect	1	0.1091	0.0426	0.3779
Treatment time × moisture	4	0.0555	0.5702	0.6460
Mean square error	17			

[a] Means for data are presented in Fig. 1. Analysis was conducted after deletion of data for nontreated soil.

TABLE 3. Temperature of soil 1 min and 1 hr after treatment in a microwave oven[a]

Soil wet weight (kg)	Soil water content (%)	Treatment time (sec)	Treatment rate (sec/kg)	Experiment[c]	Temperature (C)[b] after: 1 min	60 min	Difference (C)
1.0	16	75	75	1	65	36	29
1.0	24	75	75	1	57	38	19
1.0	37	75	75	1	47	36	11
1.0	16	120	120	1	76	41	35
1.0	24	120	120	1	73	39	34
1.0	37	120	120	1	60	43	17
1.0	16	150	150	1	91	42	49
1.0	24	150	150	1	85	42	43
1.0	37	150	150	1	72	48	24
0.5	21	30	60	2	50	34	16
1.0	21	60	60	2	52	37	15
2.0	21	120	60	2	60	42	18
0.5	21	45	90	2	57	33	24
1.0	21	90	90	2	70	42	28
2.0	21	180	90	2	73	46	27
0.5	21	60	120	2	68	35	33
1.0	21	120	120	2	80	42	38
2.0	21	240	120	2	85	53	32

[a] A weighed amount of soil at known water content (weight water/dry weight soil) in a polyethylene or polypropylene bag was treated at full power in a microwave oven for the indicated treatment times.
[b] Temperature was determined by using a mercury thermometer inserted approximately 10 cm into the soil mass.
[c] Soils 1 and 2 (Table 1) were used in experiments 1 and 2, respectively.

($P = 0.05$), compared with nontreated soil by MW treatment for 240 sec or longer, 120 sec or longer, and 360 sec, respectively (Table 5). Concentrations of NO_3-N, NH_4-N, P, K, Zn, Ca, and Mg were not significantly affected by MW treatment. Autoclaving increased ($P = 0.05$) concentrations of amino acids, carbohydrates, NH_4-N, P, and Mn in the soil solution compared with nontreated soil or soil that received the longest MW treatment (360 sec). Concentrations of K, Zn, Ca, and Mg were not affected by autoclaving. Fresh root weights of 7-wk-old soybean and sorghum-sudangrass plants grown in soil which had received MW treatment of 150 sec or longer were greater ($P = 0.05$) than those of plants grown in nontreated soil (Table 6). Soybean shoot fresh weight was not affected by MW treatment of soil. Soybean shoot fresh weight was less ($P = 0.05$) for plants grown in autoclaved soil compared with those grown in nontreated or MW-treated soil. Sorghum-sudangrass shoot fresh weight was increased ($P = 0.05$) by all MW treatments. Shoot fresh weight of sorghum-sudangrass grown in autoclaved soil was greater ($P = 0.05$) than that of plants grown in nontreated soil. Colonization of sorghum-sudangrass roots by VA mycorrhizal fungi was less ($P = 0.05$) for plants grown in any treated soil compared with nontreated soil. MW treatment times of 150 sec or more essentially eliminated mycorrhizal fungus infection.

Effect of MW treatment on microorganisms in four Kentucky soils. Bags containing 1.0 kg of soils 1, 3, 4, or 5 were treated in the MW oven for 150 sec. In all soils, MW treatment eliminated detectable populations of *Pythium* and *Fusarium* (Table 7). In one soil each, populations of *Rhizoctonia* and VA mycorrhizal fungi were reduced ($P = 0.05$), but not eliminated, by MW treatment. Some cysts of *Heterodera glycines* were recovered after MW treatment of two soils. Viability of these cysts was not evaluated; however, in another experiment a small number (less than 1% of that in nontreated soil) of viable juveniles were recovered from cysts recovered from an MW treated (1 kg at 14% water content for 240 sec) soil which had a high natural population of *H. glycines* (*unpublished*).

Comparison of the effects of MW treatment, autoclaving, and fumigation on soil nutrients and microorganisms. Soil 1 at 22% water content was fumigated, autoclaved twice, or 1.0-kg bags of soil were MW treated for 150 sec. One day after autoclaving and MW treatment and 5 days after release of the fumigant, soil samples were placed uncovered on surface-sterilized trays on a greenhouse bench and were allowed to aerate for 24 hr. After aeration, soil samples were adjusted to 25% water content (approximately −0.25 bars soil matric potential) with deionized water, placed in polyethylene bags, and incubated at 25 C in the dark. Five days after aeration, concentrations of carbohydrates and amino acids in soil ranked fumigated > autoclaved > MW-treated > nontreated (Table 8). Populations of *Pythium* were not detected in any treated soil at either 5 or 28 days after aeration. Populations of *Fusarium* in all treated soils were below 100 colony-forming units per gram 5 days after aeration; at 28 days after aeration, however, populations had increased ($P = 0.05$) in autoclaved and fumigated, but not MW treated, soil (Table 8). Populations of total fungi were less ($P = 0.05$) in MW-treated compared with fumigated or autoclaved soil at both 5 and 28 days after aeration and increased ($P = 0.05$) in all treated soils between 5 and 28 days after aeration. At 28 days after aeration, populations of total fungi were predominantly *Penicillum* in MW-treated soil, *Trichoderma* in autoclaved soil, and *Trichoderma* and *Mucor* in fumigated soil. Total prokaryote populations were less ($P = 0.05$) in autoclaved or fumigated soil than in nontreated or MW-treated soils 5 days after aeration. At 28 days, the total prokaryote population in fumigated soil was less ($P = 0.05$) than in the other soils. At 28 days, actinomycetes comprised 7, 2, 75, and 27% of the total prokaryote population in untreated, MW-treated, autoclaved, and fumigated soil, respectively.

TABLE 4. Analysis of variance for effects of microwave treatment rate and soil weight on populations of microorganisms in soil[a]

Source of variation	Degrees of freedom	Probability of a greater F value: *Pythium*	Total fungi	Total prokaryotes
Treatment rate	2	0.0012	<0.0001	<0.0001
Linear effect	1	0.0005	<0.0001	<0.0001
Quadratic effect	1	0.1393	0.7187	0.8607
Soil weight	2	0.0098	<0.0001	0.0005
Linear effect	1	0.0034	<0.0001	0.0002
Quadratic effect	1	0.4592	0.4881	0.0808
Treatment rate × soil weight	4	0.5439	0.0188	0.0800
Mean square error	17			

[a] Means for data are presented in Fig. 2. Analysis was conducted after deletion of data for nontreated soil.

DISCUSSION

The effects of MW treatment of soil on soil microorganisms were related to treatment time, the amount of soil treated, and soil water

content. For amounts of soil from 0.5 to 4.0 kg, the treatment rate (time per unit weight of soil) required to achieve a given effect on soil microorganisms or soil temperature decreased with increasing soil weight. Thus, the working hypothesis that the effects of treatment rate are the same regardless of weight of soil treated must be rejected. This relationship may have been due to more efficient interception of MW radiation by larger amounts of soil. For 8 kg of soil, results were inconsistent, possibly because of uneven heating of the soil mass. Such uneven heating probably also occurs with lesser amounts of soil; however, for these lesser amounts, the temperature of different sections of the soil may equilibrate before the soil cools to below a temperature lethal to the microorganisms. For the soil water content range tested (from 7 to 37%), soil water content had a minimal, although significant, effect on MW treatment effects. Longer treatment times were required to achieve a given temperature increase in wetter soil, but wetter soil cooled more slowly after treatment. These two contrasting effects may have interacted to moderate the effect of soil water content on the effects of MW treatment on soil microorganisms. For the soils used in these experiments, soil type had little effect on the results of MW treatment. This observation may be related to the mechanism of soil heating by MW treatment: soil water is heated by the MW radiation, and this heat is transferred to other soil components by conduction (25). Because the range of specific heat capacities for mineral soils is relatively narrow (13), little soil-type effect would be expected for mineral soils. However, the treatment times needed to achieve given effects on microbial populations in organic soils may differ from those for mineral soils. The effect of oven manufacturer on treatment effects was not investigated. However, standard MW ovens do not vary greatly in the time needed to heat a specific amount of water to boiling (1) and thus few differences between ovens would be expected.

TABLE 5. Effect of microwave (MW) treatment time and autoclaving on nutrient concentrations in soil

Treatment	Amino acids (μm gly equiv./g dry soil)	Carbohydrates (μM glu equiv./g dry soil)	NH_4^+ (μg/g dry soil)	P (μg/g dry soil)	Mn (μg/g dry soil)
None	0.000 d[z]	0.075 d	5.4 b	21.0 b	1.53 cd
MW - 120 sec[y]	0.060 cd	0.337 c	4.2 b	21.3 b	1.30 cd
MW - 150 sec	0.000 d	0.469 bc	4.8 b	21.3 b	1.05 d
MW - 180 sec	0.002 d	0.597 b	3.6 b	21.0 b	1.35 cd
MW - 240 sec	0.162 bc	0.600 b	7.8 b	21.0 b	1.75 c
MW - 360 sec	0.247 b	0.619 b	4.2 b	20.3 c	2.70 b
Autoclaved 1 hr	0.444 a	1.204 a	20.5 a	25.0 a	16.43 a

[y] Microwave oven treatment of a 1-kg bag of soil at 23% H_2O for 120 sec at full power.
[z] Means are of two replicate samples and are not significantly different ($P = 0.05$) within the same column according to Duncan's multiple range test if followed by the same letter.

TABLE 6. Effects of microwave (MW) treatment and autoclaving on plant growth and root colonization by vesicular-arbuscular mycorrhizal fungi

Treatment	Soybean[w]		Sorghum × Sudan grass		Mycorrhizal[x] fungus colonization (%)
	Fresh shoot weight (g)	Fresh root weight (g)	Fresh shoot weight (g)	Fresh root weight (g)	
None	5.4 a[y]	2.9 bc	0.9 d	1.4 c	37.5 a
MW - 120 sec[z]	6.7 a	4.5 ab	3.2 c	2.8 c	16.4 b
MW - 150 sec	5.8 a	5.2 a	4.4 a	5.2 b	0.7 c
MW - 180 sec	5.6 a	5.5 a	4.7 ab	5.9 b	0.4 c
MW - 240 sec	6.3 a	5.7 a	4.8 ab	6.1 b	0.3 c
MW - 360 sec	6.6 a	5.3 a	5.1 ab	6.0 b	0.4 c
Autoclaved 1 hr	3.5 b	2.3 c	5.5 a	8.6 a	0.6 c

[w] All variables evaluated after plants had been grown in the greenhouse for 7 wk.
[x] Percentage of root length colonized by vesicular-arbuscular mycorrhizal fungi as determined on a stained root sample by using a grid line intersect method.
[y] Means are of four replicate plants and are not significantly different ($P = 0.05$) within the same column according to Duncan's multiple range test if followed by the same letter.
[z] Microwave oven treatment of a 1-kg bag of soil at 23% H_2O for 120 sec at full power.

TABLE 7. Effects of microwave (MW) treatment of four Kentucky soils on soil microorganisms

Soil	MW treatment	Water content (%)	Population (CFU/g dry soil)[a]			Nematodes (no./g dry soil)	Mycorrhizal[b] fungus colonization (%)
			Pythium	*Fusarium*	*Rhizoctonia*		
1	−	17	1,630*[c]	10,800*	0.09	5.8*	30.2*
	+[d]	17	0	0*	0	0	0.1
3	−	14	1,850*	8,600*	0.80*	2.2*	9.4*
	+	14	0	0	0.10	0	0.0
4	−	7	52*	2,000*	0.30*	0.9*	9.3*
	+	7	0	0	0	0.001	0.0
5	−	17	1,500*	3,100*	0.44*	3.9*	16.3*
	+	17	0	0	0	0.004	0.0

[a] Population in colony-forming units (CFU) per gram dry soil determined by using selective media.
[b] Percentage of sorghum × Sudan grass root length colonized by vesicular-arbuscular mycorrhizal fungi 7 wk after planting as determined on a stained root sample using a grid line intersect method.
[c] Asterisks (*) = mean for nontreated soil significantly different ($P = 0.05$) from corresponding mean for treated soil.
[d] Microwave oven treatment of a 1-kg bag of soil for 150 sec at full power.

TABLE 8. Effects of autoclaving, fumigation, and microwave treatment on soil nutrients and populations of soil microorganisms

Treatment	Amino acids (μM gly equiv./ g dry soil)	Carbohydrates (μM glu equiv./ g dry soil)	Population (log_{10}((CFU/g dry soil)+1)) at time after treatment[y]					
			Fusarium		Fungi		Prokaryotes	
			5 days	28 days	5 days	28 days	5 days	28 days
None	0.000 d[z]	0.02 c	4.27 a	4.15 a	5.31 b	5.46 b	8.19 a	7.82 ab
Microwave oven	0.024 c	0.07 bc	0.00 d	0.46 d	2.15 e	5.25 b	7.90 ab	8.06 ab
Autoclave	0.036 b	0.14 b	1.68 c	4.24 a	4.02 c	6.26 a	6.54 d	7.77 bc
Fumigation	0.070 a	0.24 a	1.51 c	3.26 b	3.02 d	6.01 a	6.42 d	7.44 c

[y]CFU = colony-forming units as determined using selective media, 5 and 28 days after aeration following treatment.
[z]Means of two replicate samples followed by the same letter not significantly different ($P = 0.05$) for the same variable by Duncan's multiple range test.

For the soils used, treatment of 1 kg of soil for 150 sec was sufficient to eliminate populations of *Pythium, Fusarium*, and most nematodes. However, marginal survival of *Rhizoctonia*, cysts of *H. glycines*, and vesicular-arbuscular mycorrhizal fungi was observed in some soils at this treatment rate. Treatment of 4 kg of soil for 425 sec gave results approximately equivalent to treatment of 1 kg soil for 150 sec for those organisms assayed. Before routine use of MW oven treatment of a particular soil is undertaken, preliminary tests of the effect of treatment time on the organism(s) of interest should be conducted. Ideally, soil should be treated only enough to eliminate the organism(s) of interest; however, excessive MW treatment does not appear to drastically affect soil nutrients.

In general, the relative susceptibility of soil microorganisms to MW treatment was: *Pythium, Fusarium*, and non-cyst-forming nematodes > *Rhizoctonia*, VA mycorrhizal fungi, and *H. glycines* cysts > bacteria, actinomycetes, and thermotolerant fungi. Although this relative ranking is similar to that found for susceptibility to aerated steam treatment (4), some differences apparently exist. In particular, *Fusarium* spp. have been reported to tolerate higher aerated steam temperatures than *Rhizoctonia* spp. (4), but *Fusarium* was less tolerant than *Rhizoctonia* to MW treatment. This difference may be due to interactions of susceptibility with treatment time and temperature. *Fusarium* may tolerate long periods at moderately high temperature (ie, aerated steam treatment) better than *Rhizoctonia*, but tolerate short periods at higher temperatures (ie, MW treatment) more poorly than *Rhizoctonia*. It is also possible that the apparent differences are due to the use of different assay procedures.

Compared with autoclaving or high-rate fumigation with methyl bromide-chloropicrin, MW treatment released fewer nutrients into the soil solution, had less effect on populations of soil prokaryotes, and resulted in less recolonization by *Fusarium* and other fungi. Thus, MW treatment appears to be the most desirable method of soil treatment of those tested; however, other relatively mild methods of soil treatment, such as aerated steam, low-rate fumigation, or low-rate ionizing radiation, also may compare favorably.

Overall, MW treatment of soil appears to be a relatively easy, rapid, and inexpensive method of pasteurizing relatively small amounts of soil. Although large-scale applications are unlikely, the method may be convenient and appropriate for use in experiments where moderate amounts of pasteurized soil are needed. Soil can be placed in a plastic (preferably polypropylene) bag, treated, and stored in the same bag with a minimum alteration of soil moisture. Additionally, treatment in an MW oven might be used in the pasteurization of intact soil cores, in the diagnostic treatment of soil, and by home horticulturists for the treatment of small amounts of potting mix.

LITERATURE CITED

1. Anonymous. 1981. Microwave ovens. Consumer Reports 46(3):128-137.
2. Baker, K. F., and Fuller, W. H. 1969. Soil treatment by microwave energy to destroy plant pathogens. Phytopathology 59:193-197.
3. Barker, K. R., Gooding, G. V., Jr., Elder, A. S., and Eplee, R. E. 1972. Killing and preserving nematodes in soil samples with chemicals and microwave energy. J. Nematol. 4:75-79.
4. Bollen, G. J. 1969. The selective effect of heat treatment on the microflora of a greenhouse soil. Neth. J. Plant Pathol. 75:157-163.
5. Copson, D. A. 1975. Microwave Heating. AVI Publ. Co., Westport, CT. 615 pp.
6. Dreyfuss, M. S., and Chipley, J. R. 1980. Comparison of effects of sublethal microwave radiation and conventional heating on the metabolic activity of *Staphylococcus aureus*. Appl. Environ. Microbiol. 39:13-16.
7. Eglitis, M., and Johnson, F. 1970. Control of seedling damping-off in greenhouse soils by radiofrequency energy. Plant Dis. Rep. 54:268-271.
8. Ferriss, R. S. 1981. Soil pasteurization by microwave oven treatment. (Abstr.) Phytopathology 71:873.
9. Ferriss, R. S., and Mitchell, D. J. 1976. Evaluation of three selective media for the recovery of *Rhizoctonia solani* from soil. (Abstr.) Proc. Amer. Phytopathol. Soc. 3:335-336.
10. Flowers, R. A. 1976. A selective medium for isolation of *Rhizoctonia* from soil and plant tissue. (Abstr.) Proc. Amer. Phytopathol. Soc. 3:219.
11. Giovannetti, M., and Mosse, B. 1980. An evaluation of techniques for measuring vesicular-arbuscular mycorrhizal infection in roots. New Phytol. 84:489-500.
12. Heald, C. M., and Wayland, J. R. 1975. Factors affecting control of *Rotylenchulus reniformis* with UHF electromagnetic energy. J. Nematol. 7:171-174.
13. Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York. 413 pp.
14. Jermyn, M. A. 1975. Increasing the sensitivity of the anthrone method for carbohydrate. Anal. Biochem. 68:332-335.
15. Lowe, R. H., and Hamilton, J. L. 1967. Rapid method for determination of nitrate in plant and soil extracts. J. Agric. Food Chem. 18:359-361.
16. Martin, J. K. 1975. Comparison of agar media for counts of viable soil bacteria. Soil Biol. Biochem. 7:401-402.
17. Mircetich, S. M., and Kraft, J. M. 1973. Efficiency of various selective media in determining *Pythium* populations in soil. Mycopathol. Mycol. Appl. 50:151-161.
18. Moore, S. 1968. Amino acid analysis: Aqueous dimethyl sulfoxide as a solvent for the ninhydrin reaction. J. Biol. Chem. 243:6281-6283.
19. Mulder, D. (editor) 1979. Soil Disinfestation. Elsevier, New York. 368 pp.
20. O'Bannon, J. H., and Good, J. M. 1971. Applications of microwave energy to control nematodes in soil. J. Nematol. 3:93-94.
21. Papavizas, G. C. 1967. Evaluation of various media and antimicrobial agents for isolation of *Fusarium* from soil. Phytopathology 57:848-852.
22. Phillips, J. M., and Hayman, D. S. 1970. Improved procedures for clearing and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. Trans. Br. Mycol. Soc. 55:158-161.
23. Schuman, G. E., Stanley, M. A., and Knudson, D. 1973. Automated total nitrogen analysis of soil and plant samples. Soil Sci. Soc. Am. Proc. 37:480-481.
24. Steiner, G. W., and Watson, R. D. 1965. Use of surfactants in the soil dilution and plate count method. Phytopathology 55:728-730.
25. Vela, G. R., and Wu, J. F. 1979. Mechanism of lethal action of 2450-MHz radiation on microorganisms. Appl. Environ. Microbiol. 37:550-553.
26. Wainright, M., Killham, K., and Diprose, M. F. 1980. Effects of 2450 MHz microwave radiation on nitrification, respiration and S-oxidation in soil. Soil Biol. Biochem. 12:489-493.