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Microbial ecology of soils surrounding nuclear and thermal power plants in Taiwan

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Abstract

This paper reports a study of the effect of three nuclear and one thermal power plants on the microbial ecology of soils. Populations of bacteria, actinomycetes, fungi, cellulolytic microbes, phosphate-solubilizing microbes and nitrogen-fixing microbes in the soil in the vicinity of each plant were studied. Soils were acidic at three sites, and moisture contents of the power plant soils were lower than those of the surrounding areas. Microbial populations of the topsoils (0–20 cm deep) were higher than the subsoils (21–40 cm deep), and only 10–15% of them showed significant difference ($P < .05$). Thirty-three percent of the samples from the surrounding areas had higher microbial population than those from the power plant areas, but 19% was the reverse. Populations of cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes varied with sampling locations, season and environmental conditions. Ratios of cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes to total viable counts in some samples of the surrounding areas were significantly higher than in the power plant areas. Although the microbial populations of power plant soil and its surrounding area were somewhat different, it cannot be attributed as an effect of power plant operation, as the differences were not consistent.

Keywords: Microbial ecology; Nuclear and thermal power plant; Cellulolytic, Phosphate-solubilizing and nitrogen-fixing microbes

1. Introduction

Energy consumption increases with industrialization and human activities. In Taiwan, primary energy consumption increased by 6.68% during the period 1990–1996, which includes increased consumption of petroleum (5.59%), natural gas (11.56%), coal (0.57%), hydro (15.4%) and nuclear (20.24%). Electricity is generated from hydro (7.2%), thermal (67.8%) and nuclear (24.8%) sources in Taiwan.

Electricity generation and transmission are not completely free of risk factors. For example, hydroelectricity may affect water resources and aquatic ecology, thermal electricity leads to CO_2, SO_x and NO_x emission and deposition of fly ash, and nuclear electricity has the risks associated with nuclear radiation and waste disposal. Abnormalities in fish found on the northeastern coast of Taiwan in 1994, cooling system problems of the Iowa nuclear power plant in 1970, nuclear power plant damage of Russia in 1986, radiation emission in waste recovery and cooling water leakage of Japan nuclear power plants in 1997 and 1999, respectively, were some of the major incidents associated with the operation of nuclear power plants (Wang, 1997). Microbes are the most abundant organisms and may be very sensitive to changes in environmental conditions in soil. The present study aims to use parameters of microbial ecology as an index of the environmental impact of nuclear and thermal power plant operation in Taiwan.

2. Materials and methods

2.1. Sampling sites

Three nuclear power plants and one crude oil thermal power plant in Taiwan were chosen for the present study (Table 1). Soil samples were collected at different distances [0.1, 0.5(thermal power plant only), 1.0, 2.0, 5.0 and 10.0 km] from the power generator. Samples at distances 0.1, 0.5, 1.0 and 2.0 km were inside the power plant area, whereas samples at distances 5.0 and 10.0 km were outside the power plant (i.e. surrounding areas). Topsoil (0–20 cm deep) and subsoil (21–40 cm deep)

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Table 1
Location and soil properties of test power plants

Power plant	Location	Depth	Soil pH	Soil moisture content (%)	Operation since
Nuclear power plant No. 1	Shimen, Taipei	Topsoil[a]	4.40 ± 0.24 ~ 7.09 ± 0.43	26.90 ± 3.17 ~ 45.42 ± 7.09	1978, 1979
		Subsoil[b]	4.47 ± 0.31 ~ 7.19 ± 0.67	26.13 ± 4.35 ~ 45.31 ± 6.89	
Nuclear power plant No. 2	Wanli, Taipei	Topsoil	4.38 ± 0.21 ~ 6.35 ± 1.09	18.76 ± 3.94 ~ 46.16 ± 4.57	1981, 1982
		Subsoil	4.42 ± 0.24 ~ 6.79 ± 1.01	16.20 ± 3.45 ~ 42.59 ± 4.78	
Nuclear power plant No. 3	Henchuen, Pingtung	Topsoil	7.49 ± 0.34 ~ 7.83 ± 0.36	10.33 ± 6.37 ~ 22.88 ± 7.62	1984, 1985
		Subsoil	7.58 ± 0.28 ~ 7.98 ± 0.17	8.77 ± 4.27 ~ 19.62 ± 7.37	
Hsieh-ho thermal power plant	Keelung, Taiwan	Topsoil	4.34 ± 0.19 ~ 6.60 ± 0.57	18.97 ± 6.29 ~ 31.26 ± 6.12	1985
		Subsoil	4.38 ± 0.16 ~ 7.55 ± 0.47	14.82 ± 3.73 ~ 30.75 ± 5.70	

[a] Topsoil (0–20 cm deep).
[b] Subsoil (21–40 cm deep).

were sampled at each site during the period from August 1996 to June 1999.

2.2. Culture media and growth conditions

Bacterial counts were carried out at 25°C after 5 days of incubation on nutrient agar medium containing (g/l): beef extract, 3.0; peptone, 5.0; and agar, 15.0 at pH 6.8 ± 0.1. Actinomycetes were cultivated at 25°C for 7 days on glycerol–yeast extract medium comprised of (g/l) glycerol, 5; yeast extract, 2.0; K_2HPO_4, 1.0; and agar, 15 with pH 7.0 ± 0.1. Streptomycin and cycloheximide were amended to inhibit the growth of bacteria and fungi, respectively, at a final concentration of 10 μg/ml. Fungi were grown at 25°C for 5 days on Rose bengal medium containing (g/l): glucose, 10.0; peptone, 5.0; K_2HPO_4, 1.0; $MgSO_4 \cdot 7H_2O$, 0.5; Rose bengal, 0.033; and agar, 15.0 at pH 6.8 ± 0.1. Cellulolytic microbes were counted at 25°C after 7 days of incubation on Mandels–Reese medium with carboxymethylcellulose (CMC, Sigma) as the sole carbon source and sprayed the Congo red with clear zone around the colony (Yang et al., 1998). Phosphate-solubilizing microbes were measured at 25°C after 5 days on rock phosphate medium and had a clear zone around the colony (Yang et al., 1998). Nitrogen-fixing microbes were characterized at 25°C after 7 days of incubation on nitrogen-free L-malic acid medium (Yang et al., 1998). All the experiments were carried out in triplicates. Soil samples were collected at different seasons from August 1996 to June 1999.

2.3. Chemical analysis

Soil moisture content was determined by drying the sample at 105°C overnight to a constant mass. Soil pH was measured in five times the volume of distilled water with a pH meter (Good digital pH meter model 2002, Taiwan) (Yang and Chang, 1999). Air and soil temperatures were determined directly or 5 cm below soil surface with a thermometer. Experiments were carried out in triplicate. Data were subjected to analysis of the coefficient of variance and the Duncan's multiple range test ($P \leqq .05$) using the Statistical Analysis System (SAS Institute, 1988).

3. Results

3.1. Soil properties

Nuclear power plants No. 1 and No. 2 and Hsieh-ho thermal power plant are located in the northern part of Taiwan, and the soil pH values were between 4.88 and 7.96 (Table 1). Most of the soil belonged to the weak acidic type, except the topsoil at 0.1 km distance away from power generator of nuclear power plant No. 1 and thermal power plant. Nuclear power plant No. 3 is located in the southern part of Taiwan, and soil pH values were between 7.19 and 8.30 that belonged to the weak alkaline soil type. From the statistical analysis, it was observed that the soil pH varied significantly ($P < .05$) between the plant area and the surrounding area of nuclear power plants No. 1 and No. 2 and Hsieh-ho thermal power plant (Table 2). Soil pH values of nuclear power plant No. 3 were found to be significantly higher than the other power plants located in Taipei. The pH of the subsoil was usually higher than that of the topsoil, but the difference between them was not significant ($P > .05$). The pH of the surrounding area of the power plants in the northern part of Taiwan was very similar due to the same environmental conditions and soil type. While the pH values of the power plant areas were somewhat different due to different soil types. The seasonal variation of soil pH was not significant in all power plants studied.

Soil moisture content tended to increase away from the power plant area. Moisture content of the subsoil was 0.5–5.0% lower than that of the topsoil. Soil moisture content of nuclear power plant No. 3 was between 3.45% and 37.69% in the topsoil and the value ranged from 3.78% to 28.48% in the subsoil. Soil moisture content of the other three power plants located in the northern part of Taiwan ranged from 8.78% to 56.08% in the topsoil and the value was between 6.66% and 48.57% in the subsoil. Seasonal variation of soil moisture content was different between the power plants located in the northern part and in the southern part (Table 2). Soil moisture content of power plants located in the northern part was high in winter and low in summer due to the raining season in winter. It was the reverse in the power plant located in the southern part for the raining season in the summer. From the statistical analysis, it is found that: (1)

Table 2
Soil pH and moisture content at different sites of power plants and their statistical analysis

		Power plant			
Distance (km)	Depth	Nuclear power plant No. 1	Nuclear power plant No. 2	Nuclear power plant No. 3	Hsieh-ho thermal power plant
(a) Soil pH					
0.1	Topsoil	$7.09 \pm 0.43^{b,A}$	$5.14 \pm 0.54^{c,C}$	$7.79 \pm 0.26^{a,A}$	$5.49 \pm 0.28^{c,BC}$
	Subsoil	$7.19 \pm 0.67^{b,A}$	$5.32 \pm 0.40^{d,C}$	$7.98 \pm 0.17^{a,A}$	$5.88 \pm 0.71^{c,BC}$
1.0 (0.5)[a]	Topsoil	$5.21 \pm 0.23^{d,BC}$	$5.88 \pm 0.37^{c,B}$	$7.82 \pm 0.18^{a,A}$	$6.34 \pm 0.16^{b,B}$
	Subsoil	$5.03 \pm 0.21^{c,C}$	$6.09 \pm 0.40^{b,B}$	$7.93 \pm 0.17^{a,A}$	$6.33 \pm 0.25^{b,B}$
2.0 (1.0)[a]	Topsoil	$5.59 \pm 0.47^{c,B}$	$6.35 \pm 1.09^{b,A}$	$7.49 \pm 0.34^{a,B}$	$6.60 \pm 0.57^{b,B}$
	Subsoil	$5.35 \pm 0.29^{c,B}$	$6.79 \pm 1.01^{b,A}$	$7.58 \pm 0.28^{a,B}$	$7.55 \pm 0.47^{a,A}$
5.0 (4.1)[a]	Topsoil	$4.40 \pm 0.24^{c,D}$	$4.64 \pm 0.46^{c,D}$	$7.83 \pm 0.36^{a,A}$	$4.34 \pm 0.19^{c,C}$
	Subsoil	$4.47 \pm 0.31^{c,D}$	$4.43 \pm 0.20^{c,D}$	$7.59 \pm 0.25^{a,B}$	$4.38 \pm 0.16^{c,C}$
10.0	Topsoil	$4.64 \pm 0.43^{c,D}$	$4.38 \pm 0.21^{c,D}$	$7.82 \pm 0.13^{a,A}$	–[b]
	Subsoil	$4.76 \pm 0.25^{c,CD}$	$4.42 \pm 0.24^{c,D}$	$7.91 \pm 0.14^{a,A}$	–
(b) Soil moisture content (%)					
0.1	Topsoil	$26.90 \pm 3.17^{a,C}$	$18.76 \pm 3.94^{b,B}$	$10.33 \pm 6.37^{c,C}$	$20.90 \pm 5.27^{b,B}$
	Subsoil	$26.13 \pm 4.35^{a,C}$	$16.20 \pm 3.45^{c,BC}$	$8.77 \pm 4.27^{d,C}$	$20.83 \pm 5.08^{b,B}$
1.0 (0.5)[a]	Topsoil	$35.99 \pm 6.40^{a,BC}$	$21.26 \pm 4.76^{b,B}$	$13.06 \pm 6.85^{c,B}$	$25.13 \pm 7.64^{b,AB}$
	Subsoil	$39.27 \pm 4.03^{a,B}$	$19.64 \pm 3.49^{b,B}$	$10.55 \pm 4.35^{c,C}$	$23.28 \pm 5.50^{b,B}$
2.0 (1.0)[a]	Topsoil	$45.42 \pm 7.09^{a,A}$	$21.68 \pm 6.65^{b,B}$	$13.06 \pm 6.49^{c,B}$	$18.97 \pm 6.29^{bc,B}$
	Subsoil	$45.31 \pm 6.89^{a,A}$	$16.75 \pm 4.75^{b,BC}$	$12.35 \pm 4.78^{b,B}$	$14.82 \pm 3.73^{b,C}$
5.0 (4.1)[a]	Topsoil	$45.39 \pm 4.25^{a,A}$	$44.51 \pm 7.33^{a,A}$	$20.25 \pm 9.77^{c,A}$	$31.26 \pm 6.12^{b,A}$
	Subsoil	$42.09 \pm 3.85^{a,AB}$	$42.16 \pm 5.33^{a,A}$	$19.62 \pm 7.37^{c,A}$	$30.75 \pm 5.70^{b,A}$
10.0	Topsoil	$41.35 \pm 7.38^{a,AB}$	$46.16 \pm 4.57^{a,A}$	$22.88 \pm 7.62^{b,A}$	–[b]
	Subsoil	$35.97 \pm 3.37^{b,BC}$	$42.59 \pm 4.78^{a,A}$	$18.20 \pm 6.26^{c,A}$	–

Means ± S.D. Means ($n = 7-10$) in the same row that did not share the same small alphabetic superscripts were significantly different at 5% level according to Duncan's multiple range test. Means in the same column that did not share the same capital alphabetic superscript were significantly different at 5% level according to Duncan's multiple range test.
Sampling dates of nuclear power plant No. 1 were August 7, 1996; November 13, 1996; January 21, 1997; February 27, 1997; May 15, 1997; August 12, 1997; November 19, 1997; February 17, 1998; and May 28, 1998. Sampling dates of nuclear power plant No. 2 were September 5, 1996; November 27, 1996; January 15, 1997; February 26, 1997; May 14, 1997; August 12, 1997; November 19, 1997; February 16, 1998; and May 28, 1998. Sampling dates of nuclear power plant No. 3 were September 15, 1997; December 27, 1997; April 11, 1998; October 11, 1998; December 20, 1998; March 2, 1999; and June 23, 1999. Sampling dates of Hsieh-ho thermal power plant were September 18, 1996; November 13, 1996; January 21, 1997; February 27, 1997; May 15, 1997; August 12, 1997; November 18, 1997; February 16, 1998; May 25, 1998; and August 25, 1998.
[a] Distances from the power generator at Hsieh-ho thermal power plant.
[b] Not available.

Moisture content had a significant difference ($P < .05$) between the power plant area and the surrounding area, and between power plants in the northern part and in the southern part of Taiwan. (2) Nuclear power plant No. 1 had a significantly higher moisture content, whereas nuclear power plant No. 3 had a significantly lower value.

3.2. Bacterial population

Bacterial populations in the test power plant area ranged from 10^5 to 10^7 CFU/g dry soil (Table 3). The bacterial population showed no significant difference between the plant area and the surrounding area. The population was high in summer and low in winter (data not shown), which might be due to temperature difference. Although nuclear power plants No. 1 and No. 2 and Hsieh-ho thermal power plants had different sampling periods, they are located in the northern part of Taiwan, and the environmental conditions and soil type were very similar. Therefore, the fluctuation of soil bacterial populations showed a similar tendency. The difference in bacterial population among the power plants in the northern Taiwan is not significant. Bacterial populations of the topsoil were higher than that of the subsoil because of higher nutrient content and oxygen concentration, and 63.2% of them had significant difference between the topsoil and the subsoil. The nuclear power plant No. 3 had the highest bacterial population because of the neutral soil pH and high temperature.

3.3. Actinomycete population

Actinomycetes are known to have a diverse set of enzymes to degrade complex compounds for energy and biomass production. Actinomycete populations of the topsoil were between 10^3 and 10^6 CFU/g dry soil, and the values of the subsoil ranged from 10^2 to 10^6 CFU/g dry soil. The actinomycete population was also higher in summer in the topsoil and lower in winter (data not shown) in the subsoil. The actinomycete population did not vary much in the plant area and the surrounding area (only 10.5%), but it showed a considerable difference between the topsoil and subsoil in all the studied areas (around 36.8%). This may

Table 3
Microbial populations at different sites of power plants and their statistical analysis

Distance (km)	Depth	Power plant: Nuclear power plant No. 1	Nuclear power plant No. 2	Nuclear power plant No. 3	Hsieh-ho thermal power plant
(a) Bacterial populations (CFU/g dry soil)					
0.1	Topsoil	$(1.11\pm0.62)\times10^{7}$ ^{a,A}	$(2.38\pm1.41)\times10^{6}$ ^{bc,AB}	$(1.47\pm0.77)\times10^{7}$ ^{a,A}	$(5.32\pm1.63)\times10^{6}$ ^{b,A}
	Subsoil	$(7.95\pm1.21)\times10^{6}$ ^{a,A}	$(1.32\pm0.40)\times10^{6}$ ^{b,AB}	$(4.18\pm1.38)\times10^{6}$ ^{ab,B}	$(2.99\pm0.95)\times10^{6}$ ^{b,AB}
1.0 (0.5)[a]	Topsoil	$(8.09\pm1.29)\times10^{6}$ ^{a,A}	$(4.74\pm1.32)\times10^{6ab,AB}$	$(7.37\pm1.43)\times10^{6}$ ^{a,A}	$(5.92\pm1.59)\times10^{6}$ ^{a,A}
	Subsoil	$(4.01\pm1.36)\times10^{6}$ ^{a,AB}	$(2.53\pm0.58)\times10^{6}$ ^{a,AB}	$(4.19\pm1.22)\times10^{6}$ ^{a,B}	$(3.20\pm1.30)\times10^{6}$ ^{a,AB}
2.0 (1.0)[a]	Topsoil	$(3.56\pm1.92)\times10^{6}$ ^{a,AB}	$(4.18\pm2.34)\times10^{6}$ ^{a,AB}	$(1.63\pm0.86)\times10^{7}$ ^{a,A}	$(9.52\pm1.28)\times10^{6}$ ^{a,A}
	Subsoil	$(1.47\pm0.67)\times10^{6}$ ^{a,B}	$(1.93\pm0.71)\times10^{6}$ ^{a,AB}	$(3.13\pm0.72)\times10^{6}$ ^{a,B}	$(1.85\pm0.82)\times10^{6}$ ^{a,AB}
5.0 (4.1)[a]	Topsoil	$(4.95\pm1.69)\times10^{6}$ ^{b,AB}	$(4.38\pm1.41)\times10^{6}$ ^{b,AB}	$(1.60\pm0.36)\times10^{7}$ ^{a,A}	$(3.61\pm1.86)\times10^{6}$ ^{b,AB}
	Subsoil	$(2.66\pm0.72)\times10^{6}$ ^{b,B}	$(3.89\pm1.82)\times10^{6}$ ^{ab,AB}	$(6.63\pm1.29)\times10^{6}$ ^{a,A}	$(2.07\pm0.81)\times10^{6}$ ^{b,AB}
10.0	Topsoil	$(1.94\pm0.87)\times10^{7}$ ^{a,A}	$(7.31\pm1.73)\times10^{6}$ ^{a,A}	$(1.38\pm0.66)\times10^{7}$ ^{a,A}	–[b]
	Subsoil	$(6.37\pm1.08)\times10^{6}$ ^{a,A}	$(3.56\pm0.77)\times10^{6}$ ^{a,AB}	$(6.96\pm1.83)\times10^{6}$ ^{a,A}	–
(b) Actinomycetes populations (CFU/g dry soil)					
0.1	Topsoil	$(2.66\pm1.37)\times10^{5}$ ^{a,A}	$(8.67\pm1.28)\times10^{4}$ ^{b,B}	$(8.35\pm1.85)\times10^{5}$ ^{a,A}	$(1.48\pm0.67)\times10^{5}$ ^{a,A}
	Subsoil	$(2.41\pm1.49)\times10^{5}$ ^{a,A}	$(8.44\pm1.35)\times10^{4}$ ^{b,B}	$(5.74\pm1.36)\times10^{5}$ ^{a,A}	$(6.83\pm1.06)\times10^{4}$ ^{b,AB}
1.0 (0.5)[a]	Topsoil	$(1.41\pm0.42)\times10^{5}$ ^{a,AB}	$(1.23\pm0.50)\times10^{5}$ ^{a,A}	$(5.56\pm1.22)\times10^{5}$ ^{a,A}	$(2.60\pm1.24)\times10^{5}$ ^{a,A}
	Subsoil	$(9.00\pm1.68)\times10^{4}$ ^{b,B}	$(7.83\pm1.67)\times10^{4}$ ^{b,B}	$(6.16\pm1.40)\times10^{5}$ ^{a,A}	$(1.21\pm0.77)\times10^{5}$ ^{a,A}
2.0 (1.0)[a]	Topsoil	$(9.80\pm1.20)\times10^{4}$ ^{b,B}	$(1.62\pm0.65)\times10^{5}$ ^{a,A}	$(2.33\pm1.46)\times10^{5}$ ^{a,A}	$(1.44\pm0.91)\times10^{5}$ ^{a,A}
	Subsoil	$(3.41\pm1.38)\times10^{4}$ ^{a,B}	$(7.28\pm1.36)\times10^{4}$ ^{a,B}	$(5.03\pm1.54)\times10^{4}$ ^{a,B}	$(3.67\pm1.00)\times10^{4}$ ^{a,B}
5.0 (4.1)[a]	Topsoil	$(7.14\pm2.04)\times10^{4}$ ^{b,B}	$(1.05\pm0.34)\times10^{5}$ ^{a,A}	$(7.45\pm1.63)\times10^{5}$ ^{a,A}	$(1.07\pm0.48)\times10^{5}$ ^{a,A}
	Subsoil	$(7.17\pm1.26)\times10^{4}$ ^{b,B}	$(1.08\pm0.54)\times10^{5}$ ^{a,A}	$(5.71\pm1.36)\times10^{5}$ ^{a,A}	$(4.18\pm1.10)\times10^{4}$ ^{b,B}
10.0	Topsoil	$(1.43\pm0.48)\times10^{5}$ ^{a,AB}	$(2.76\pm1.33)\times10^{5}$ ^{a,A}	$(6.27\pm1.54)\times10^{5}$ ^{a,A}	–[b]
	Subsoil	$(1.52\pm0.21)\times10^{5}$ ^{a,AB}	$(1.50\pm0.66)\times10^{5}$ ^{a,A}	$(1.65\pm0.82)\times10^{5}$ ^{a,A}	–
(c) Fungal populations (CFU/g dry soil)					
0.1	Topsoil	$(5.65\pm1.19)\times10^{5}$ ^{a,AB}	$(3.58\pm1.71)\times10^{5}$ ^{a,A}	$(3.46\pm0.72)\times10^{5}$ ^{a,A}	$(4.24\pm1.31)\times10^{5}$ ^{a,A}
	Subsoil	$(3.08\pm0.91)\times10^{5}$ ^{a,AB}	$(5.52\pm1.03)\times10^{4}$ ^{b,B}	$(8.80\pm1.02)\times10^{4}$ ^{b,B}	$(1.49\pm0.38)\times10^{5}$ ^{ab,A}
1.0 (0.5)[a]	Topsoil	$(7.36\pm0.42)\times10^{5}$ ^{a,AB}	$(4.89\pm1.03)\times10^{5}$ ^{a,A}	$(5.62\pm1.73)\times10^{5}$ ^{a,A}	$(3.43\pm0.96)\times10^{5}$ ^{a,A}
	Subsoil	$(5.36\pm1.10)\times10^{5}$ ^{a,AB}	$(2.67\pm0.82)\times10^{5}$ ^{a,A}	$(5.68\pm1.27)\times10^{5}$ ^{a,A}	$(2.12\pm0.54)\times10^{5}$ ^{a,A}
2.0 (1.0)[a]	Topsoil	$(3.52\pm0.62)\times10^{5}$ ^{a,AB}	$(6.34\pm1.16)\times10^{5}$ ^{a,A}	$(7.91\pm1.01)\times10^{5}$ ^{a,A}	$(5.09\pm1.09)\times10^{5}$ ^{a,A}
	Subsoil	$(2.44\pm0.72)\times10^{5}$ ^{a,AB}	$(1.02\pm0.27)\times10^{5}$ ^{a,A}	$(4.75\pm1.77)\times10^{5}$ ^{a,A}	$(3.08\pm1.53)\times10^{5}$ ^{a,A}
5.0 (4.1)[a]	Topsoil	$(5.41\pm1.54)\times10^{5}$ ^{a,AB}	$(6.80\pm1.61)\times10^{5}$ ^{a,A}	$(4.82\pm1.02)\times10^{5}$ ^{a,A}	$(4.22\pm1.05)\times10^{5}$ ^{a,A}
	Subsoil	$(3.85\pm1.41)\times10^{5}$ ^{a,AB}	$(5.22\pm1.17)\times10^{5}$ ^{a,A}	$(3.32\pm1.15)\times10^{5}$ ^{a,A}	$(2.25\pm0.79)\times10^{5}$ ^{a,A}
10.0	Topsoil	$(1.53\pm0.56)\times10^{6}$ ^{a,A}	$(1.01\pm0.38)\times10^{6}$ ^{a,A}	$(1.52\pm0.81)\times10^{6}$ ^{a,A}	–[b]
	Subsoil	$(9.40\pm1.40)\times10^{5}$ ^{a,A}	$(4.03\pm1.25)\times10^{5}$ ^{a,A}	$(3.75\pm0.74)\times10^{5}$ ^{a,A}	–

Means ± S.D. Means ($n=7-10$) in the same row that did not share the same small aphabetic superscripts were significantly different at 5% level according to Duncan's multiple range test. Means in the same column that did not share the same capital alphabetic superscript were significantly different at 5% level according to Duncan's multiple range test.
Sampling dates were described in Table 2.

[a] Distances from the power generator at Hsieh-ho thermal power plant.

[b] Not available.

due to higher nutritional content of the topsoil (Table 3). Nuclear power plant No. 3 had the highest actinomycete population among all the studied power plants and this can be attributed to the neutral soil pH and high temperature.

3.4. Fungal population

The fungal population was found to be higher in summer as a result of higher temperature that favors fungal growth. Fungal population (14.3%) in the surrounding area was found to be higher than that of the power plant area, while 12.5% of them was the reverse. Although fungal populations of the topsoil were higher than those of the subsoil in all studied power plants, only 10.5% of them had significant differences.

According to Table 3, it was found that: (1) Topsoil of the plant area at nuclear power plant No. 1 had a significantly less population than that in the surrounding area of the other three power plants except at 10 km away from the power generator. (2) Subsoil neighboring power generator (0.1 km) at nuclear power plants No. 2 and No. 3 had significantly lower populations than other sampling sites or other two power plants.

3.5. Cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes

Cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes are very important in elemental cycle and plant nutrition. The population varies with the sampling season, soil depth and location, and the ratio of these populations to the total viable count can be used as an index of the effect of power generators on microbial ecology.

The cellulolytic microbial populations were found to be in the range of 1.95×10^5 to 5.71×10^7 CFU/g dry soil in the plant area and 7.03×10^4 to 2.60×10^7 CFU/g dry soil in the surrounding area (Table 4). The percentages of cellulolytic microbe in total viable count of the plant area were 17.21–60.20%, and the values were 11.96–85.91% of the surrounding area (Table 5). From the statistical analysis of cellulolytic microbes, the results can be summarized as follows: (1) There was a significant difference among the four power plants in cellulolytic microbes. Nuclear power plant No. 1 had the highest populations, followed by No. 3 and thermal power plant, while nuclear power plant No. 2 had the least. (2) The population in the plant area was higher than that of the surrounding area due to the forest vegetation of the power plant area, but the difference was not significant in nuclear power plants (only thermal power plant had a significant difference). (3) The population in most of the topsoil was found to be higher than that in the subsoil, and 26.3% of them had a significant difference. (4) The percentage of cellulolytic microbes in total viable count of the surrounding area at nuclear power plants No. 1 and No. 2 was found to be significantly higher than that of the plant area. It was the reverse at the thermal power plant. (5) 15.7% of the topsoil had a significantly higher percentage than the subsoil, and 26.3% of the subsoil was the reverse.

Table 4
Cellolytic, phosphate-solubilizing and nitrogen-fixing microbes at different sites of power plants and their statistical analysis

Distance (km)	Depth	Power plant: Nuclear power plant No. 1	Nuclear power plant No. 2	Nuclear power plant No. 3	Hsieh-ho thermal power plant
(a) Cellulolytic microbes (CFU/g dry soil)					
0.1	Topsoil	$(5.71 \pm 1.46) \times 10^7$ a,A	$(3.42 \pm 0.17) \times 10^5$ c,A	$(6.87 \pm 1.47) \times 10^6$ b,A	$(4.53 \pm 1.51) \times 10^6$ b,A
	Subsoil	$(4.48 \pm 0.38) \times 10^6$ a,B	$(2.76 \pm 0.20) \times 10^5$ b,A	$(5.45 \pm 1.36) \times 10^6$ a,A	$(1.11 \pm 0.13) \times 10^6$ a,B
1.0 (0.5)[a]	Topsoil	$(6.66 \pm 0.14) \times 10^6$ a,B	$(2.48 \pm 0.06) \times 10^5$ b,A	$(5.06 \pm 1.89) \times 10^6$ a,A	$(2.06 \pm 0.02) \times 10^6$ a,B
	Subsoil	$(5.21 \pm 0.22) \times 10^6$ a,B	$(2.41 \pm 0.34) \times 10^5$ b,A	$(2.61 \pm 1.02) \times 10^6$ ab,A	$(1.95 \pm 0.09) \times 10^6$ ab,B
2.0 (1.0)[a]	Topsoil	$(7.59 \pm 0.98) \times 10^6$ a,B	$(1.95 \pm 0.10) \times 10^5$ b,A	$(8.68 \pm 1.21) \times 10^6$ a,A	$(6.64 \pm 0.86) \times 10^5$ b,C
	Subsoil	$(4.78 \pm 0.25) \times 10^6$ a,B	$(2.27 \pm 0.11) \times 10^5$ b,A	$(3.98 \pm 1.03) \times 10^6$ a,A	$(5.24 \pm 0.46) \times 10^5$ b,C
5.0 (4.1)[a]	Topsoil	$(6.69 \pm 1.19) \times 10^6$ a,B	$(3.09 \pm 0.18) \times 10^5$ b,A	$(5.39 \pm 1.62) \times 10^6$ a,A	$(1.14 \pm 0.13) \times 10^5$ b,C
	Subsoil	$(5.15 \pm 0.50) \times 10^6$ a,B	$(2.05 \pm 0.08) \times 10^5$ b,A	$(3.37 \pm 1.55) \times 10^6$ a,A	$(7.03 \pm 1.84) \times 10^4$ c,D
10.0	Topsoil	$(4.72 \pm 1.01) \times 10^6$ a,B	$(2.37 \pm 0.24) \times 10^5$ b,A	$(5.25 \pm 1.17) \times 10^6$ a,A	–[b]
	Subsoil	$(2.60 \pm 1.75) \times 10^7$ a,A	$(1.53 \pm 0.13) \times 10^5$ c,B	$(3.21 \pm 1.69) \times 10^6$ b,A	–
(b) Phosphate-solubilizing microbes (CFU/g dry soil)					
0.1	Topsoil	$(8.45 \pm 1.32) \times 10^6$ a,A	$(3.59 \pm 0.22) \times 10^5$ c,A	$(3.83 \pm 0.91) \times 10^6$ b,A	$(1.91 \pm 0.29) \times 10^6$ bc,A
	Subsoil	$(3.93 \pm 0.69) \times 10^6$ a,B	$(3.52 \pm 0.41) \times 10^5$ c,A	$(1.24 \pm 0.61) \times 10^6$ b,A	$(1.40 \pm 0.10) \times 10^6$ b,B
1.0 (0.5)[a]	Topsoil	$(1.06 \pm 0.05) \times 10^6$ ab,B	$(2.55 \pm 0.05) \times 10^5$ b,B	$(3.11 \pm 1.11) \times 10^6$ a,A	$(1.74 \pm 0.12) \times 10^6$ a,A
	Subsoil	$(6.82 \pm 1.56) \times 10^5$ b,B	$(1.65 \pm 0.28) \times 10^5$ b,C	$(2.07 \pm 1.22) \times 10^6$ a,A	$(1.59 \pm 0.07) \times 10^6$ a,A
2.0(1.0)[a]	Topsoil	$(7.71 \pm 0.80) \times 10^5$ b,B	$(2.26 \pm 0.07) \times 10^5$ b,B	$(2.81 \pm 1.12) \times 10^6$ a,A	$(4.76 \pm 0.81) \times 10^5$ b,B
	Subsoil	$(4.24 \pm 0.49) \times 10^5$ ab,C	$(1.79 \pm 0.03) \times 10^5$ b,BC	$(6.14 \pm 1.73) \times 10^5$ a,B	$(1.15 \pm 0.13) \times 10^5$ b,C
5.0 (4.1)[a]	Topsoil	$(8.98 \pm 1.02) \times 10^5$ b,B	$(2.18 \pm 0.03) \times 10^5$ b,B	$(3.84 \pm 0.81) \times 10^6$ a,A	$(9.16 \pm 0.65) \times 10^4$ c,C
	Subsoil	$(6.68 \pm 0.65) \times 10^5$ ab,B	$(2.04 \pm 0.04) \times 10^5$ b,B	$(1.76 \pm 0.65) \times 10^6$ a,A	$(9.21 \pm 0.54) \times 10^4$ b,C
10.0	Topsoil	$(8.82 \pm 1.48) \times 10^5$ a,B	$(1.72 \pm 0.12) \times 10^5$ b,BC	$(1.84 \pm 0.87) \times 10^6$ a,A	–[b]
	Subsoil	$(6.12 \pm 1.34) \times 10^5$ a,B	$(1.79 \pm 0.15) \times 10^5$ b,BC	$(8.06 \pm 1.07) \times 10^5$ a,B	–
(c) Nitrogen-fixing microbes (CFU/g dry soil)					
0.1	Topsoil	$(2.67 \pm 0.16) \times 10^6$ a,A	$(1.59 \pm 0.03) \times 10^5$ b,A	$(2.08 \pm 0.76) \times 10^6$ a,A	$(2.81 \pm 0.17) \times 10^6$ a,A
	Subsoil	$(1.84 \pm 0.20) \times 10^6$ a,A	$(2.33 \pm 0.07) \times 10^5$ b,A	$(1.39 \pm 0.51) \times 10^6$ a,A	$(1.99 \pm 0.03) \times 10^6$ a,B
1.0 (0.5)[a]	Topsoil	$(7.94 \pm 1.09) \times 10^5$ b,B	$(1.49 \pm 0.07) \times 10^5$ c,A	$(2.04 \pm 0.60) \times 10^6$ ab,A	$(2.68 \pm 0.21) \times 10^6$ a,A
	Subsoil	$(5.59 \pm 0.14) \times 10^5$ ab,B	$(1.82 \pm 0.28) \times 10^5$ b,A	$(1.75 \pm 0.57) \times 10^6$ a,A	$(3.48 \pm 0.55) \times 10^6$ a,A
2.0 (1.0)[a]	Topsoil	$(4.40 \pm 0.43) \times 10^5$ b,B	$(8.51 \pm 1.42) \times 10^4$ c,B	$(3.81 \pm 1.85) \times 10^6$ a,A	$(7.24 \pm 0.87) \times 10^5$ b,B
	Subsoil	$(2.26 \pm 0.47) \times 10^5$ b,C	$(2.02 \pm 0.06) \times 10^5$ b,A	$(2.43 \pm 0.74) \times 10^6$ a,A	$(5.69 \pm 1.42) \times 10^5$ b,C
5.0 (4.1)[a]	Topsoil	$(1.69 \pm 0.10) \times 10^5$ b,C	$(5.03 \pm 0.16) \times 10^4$ c,C	$(3.87 \pm 1.76) \times 10^6$ a,A	$(2.59 \pm 0.12) \times 10^5$ b,C
	Subsoil	$(1.29 \pm 0.12) \times 10^5$ b,C	$(4.91 \pm 0.06) \times 10^4$ c,C	$(1.99 \pm 0.71) \times 10^6$ a,A	$(1.88 \pm 0.11) \times 10^5$ b,C
10.0	Topsoil	$(9.80 \pm 0.52) \times 10^5$ b,B	$(4.74 \pm 0.10) \times 10^4$ c,C	$(3.83 \pm 1.16) \times 10^6$ a,A	–[b]
	Subsoil	$(2.39 \pm 0.20) \times 10^5$ b,C	$(4.96 \pm 0.03) \times 10^4$ c,C	$(1.65 \pm 0.51) \times 10^6$ a,A	–

Means ± S.D. Means ($n = 7-10$) in the same row that did not share the same small alphabetic superscripts were significantly different at 5% level according to Duncan's multiple range test. Means in the same column that did not share the same capital alphabetic superscript were significantly different at 5% level according to Duncan's multiple range test.

Sampling dates were described in Table 2.

[a] Distances from the power generator at Hsieh-ho thermal power plant.

[b] Not available.

Table 5
Ratios of cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes to total viable count at different sites of power plants and their statistical analysis[a]

Distance (km)	Depth	Power Plant: Nuclear power plant No. 1	Nuclear power plant No. 2	Nuclear power plant No. 3	Hsieh-ho thermal power plant
(a) Cellulolytic microbes/total viable count					
0.1	Topsoil	23.78 ± 1.56^{b,C}	34.09 ± 2.53^{ab,C}	36.58 ± 7.99^{ab,A}	60.20 ± 7.34^{a,A}
	Subsoil	17.68 ± 0.68^{b,C}	24.97 ± 0.70^{ab,D}	37.36 ± 7.24^{a,A}	35.16 ± 3.03^{a,AB}
1.0 (0.5)[a]	Topsoil	17.21 ± 2.17^{b,C}	31.08 ± 1.20^{ab,C}	44.97 ± 6.66^{a,A}	26.49 ± 4.72^{ab,B}
	Subsoil	40.60 ± 3.69^{a,B}	32.06 ± 1.91^{a,C}	30.89 ± 7.11^{a,A}	27.68 ± 1.56^{ab,B}
2.0 (1.0)[a]	Topsoil	20.68 ± 0.94^{b,C}	24.57 ± 2.39^{b,D}	31.16 ± 3.96^{b,A}	55.74 ± 4.20^{a,A}
	Subsoil	58.55 ± 1.29^{a,AB}	34.96 ± 3.55^{b,C}	24.92 ± 7.27^{b,A}	41.94 ± 2.90^{ab,A}
5.0 (4.1)[a]	Topsoil	50.05 ± 2.64^{b,B}	72.60 ± 3.62^{a,B}	21.72 ± 4.92^{c,A}	11.96 ± 3.44^{c,C}
	Subsoil	78.81 ± 5.17^{a,A}	71.40 ± 0.23^{a,B}	21.13 ± 6.18^{b,A}	14.02 ± 2.82^{b,C}
10.0	Topsoil	83.83 ± 4.67^{a,A}	85.91 ± 0.67^{a,A}	29.46 ± 10.23^{b,A}	–[b]
	Subsoil	75.39 ± 3.86^{a,A}	46.84 ± 0.65^{b,BC}	29.32 ± 7.12^{b,A}	–
(b) Phosphate-solubilizing microbes/total viable count					
0.1	Topsoil	25.81 ± 2.79^{a,A}	35.69 ± 1.71^{a,C}	33.78 ± 7.28^{a,A}	26.27 ± 3.87^{a,B}
	Subsoil	15.38 ± 0.85^{c,B}	32.09 ± 2.89^{ab,C}	21.92 ± 5.06^{bc,B}	40.74 ± 3.71^{a,A}
1.0 (0.5)[a]	Topsoil	2.73 ± 0.36^{c,D}	32.20 ± 0.48^{a,C}	30.48 ± 9.43^{a,A}	22.32 ± 3.20^{b,B}
	Subsoil	5.74 ± 0.65^{c,D}	21.61 ± 2.14^{a,E}	22.12 ± 9.45^{a,B}	22.57 ± 3.31^{a,B}
2.0 (1.0)[a]	Topsoil	2.11 ± 0.16^{c,D}	28.34 ± 2.47^{a,D}	25.06 ± 5.01^{a,B}	24.22 ± 0.88^{a,B}
	Subsoil	5.27 ± 0.57^{c,D}	27.39 ± 2.60^{a,D}	21.28 ± 6.14^{a,B}	9.30 ± 1.61^{b,C}
5.0 (4.1)[a]	Topsoil	6.84 ± 0.59^{c,C}	52.26 ± 4.98^{a,B}	19.34 ± 3.14^{b,B}	9.28 ± 1.33^{c,C}
	Subsoil	10.59 ± 1.49^{b,C}	71.47 ± 1.84^{a,A}	23.76 ± 6.34^{b,B}	17.62 ± 3.13^{b,B}
10.0	Topsoil	16.79 ± 0.96^{b,B}	64.59 ± 0.62^{a,A}	12.47 ± 4.09^{b,B}	–[b]
	Subsoil	17.50 ± 1.06^{b,B}	55.03 ± 2.10^{a,B}	17.05 ± 4.15^{b,B}	–
(c) Nitrogen-fixing microbes/total viable count					
0.1	Topsoil	8.21 ± 0.14^{b,B}	15.82 ± 1.39^{b,B}	17.74 ± 3.50^{b,B}	38.23 ± 4.16^{a,B}
	Subsoil	7.22 ± 0.27^{b,B}	21.22 ± 1.26^{b,B}	28.44 ± 6.43^{b,A}	56.64 ± 1.29^{a,A}
1.0 (0.5)[a]	Topsoil	2.02 ± 0.02^{b,C}	18.79 ± 0.52^{ab,B}	22.81 ± 4.71^{ab,A}	35.24 ± 4.48^{a,B}
	Subsoil	4.80 ± 0.42^{c,B}	23.74 ± 1.21^{b,B}	20.42 ± 2.22^{b,A}	47.73 ± 4.59^{a,A}
2.0 (1.0)[a]	Topsoil	1.20 ± 0.06^{c,C}	10.56 ± 0.03^{b,C}	20.19 ± 4.15^{b,A}	60.73 ± 4.49^{a,A}
	Subsoil	2.75 ± 0.51^{c,C}	31.08 ± 3.35^{b,A}	26.78 ± 7.26^{b,A}	50.17 ± 3.33^{a,A}
5.0 (4.1)[a]	Topsoil	1.28 ± 0.13^{b,C}	11.88 ± 0.62^{ab,C}	15.81 ± 3.55^{ab,B}	22.98 ± 4.95^{a,C}
	Subsoil	2.04 ± 0.34^{c,C}	17.22 ± 0.41^{b,B}	18.05 ± 3.64^{b,B}	36.17 ± 3.17^{a,B}
10.0	Topsoil	18.89 ± 2.36^{a,A}	17.81 ± 0.83^{a,B}	22.57 ± 3.41^{a,A}	–[b]
	Subsoil	6.95 ± 0.17^{b,B}	15.37 ± 0.98^{ab,B}	26.34 ± 3.15^{a,A}	–

Means ± S.D. Means ($n = 7-10$) in the same row that did not share the same small alphabetic superscripts were significantly different at 5% level according to Duncan's multiple range test. Means in the same column that did not share the same capital alphabetic superscript were significantly different at 5% level according to Duncan's multiple range test. Sampling dates were described in Table 2.

[a] Distances from the power generator at Hsieh-ho thermal power plant.

[b] Not available.

For phosphate-solubilizing microbes: (1) The population was high at nuclear power plant No. 3, while the value was significantly low at nuclear power plant No. 2 (Table 4). (2) 55.6% of the population at the plant area was significantly higher than that at the surrounding area. (3) 57.9% of the population at the topsoil was significantly higher than that at the subsoil. (4) The percentage of phosphate-solubilizing microbe in total viable count of the plant area was between 2.11% and 40.74%, and the value ranged from 6.84% to 71.47% in the surrounding area (Table 5). The percentage was significantly lower at nuclear power plant No. 1, while the value was significantly higher at nuclear power plant No. 2. (5) 41.7% of the percentage of phosphate-solubilizing microbes at the plant area was significantly higher than that at the surrounding area, and 41.7% of them was the reverse.

For nitrogen-fixing microbes: (1) The population was significantly lower at nuclear power plant No. 2, and the value was significantly higher at nuclear power plant No. 3 (Table 4). (2) 66.7% of the population at the plant area was significantly higher than that at the surrounding area. (3) The population in the topsoil was higher than that in the subsoil, but 15.8% of them were significantly different. (4) The percentage of nitrogen-fixing microbe in the total viable count at the plant area was between 1.20% and 60.73%, and it ranged from 1.28% to 36.17% at the surrounding area (Table 5). The percentage was significantly higher at thermal power plant, while the value was significantly lower at nuclear power plant No. 1. (5) The percentages at the plant area and at the surrounding area were not significantly different. (6) The percentage was higher in the subsoil than in the topsoil, and 36.84% of them showed significant differences.

4. Discussion

Soil pH values of the surrounding area were lower than those of the power plant area. This may be due to the fact that chemical fertilizers were applied for crop production in the surrounding area. A total of 58% of agricultural land in Taiwan is reported as acidic. Soil pH also depends on soil type, crop vegetation and environmental conditions. Soil pH was neutral to weakly alkaline (pH 7.05–8.14) at nuclear power plant No. 3 located in the southern part of Taiwan with the ultisol, while soil pH was acidic (pH 4.09–6.52) in the other three power plants located in the northern part of Taiwan because of the inceptisol. High organic matter content in the surface layer and organic acid accumulation as a result of incomplete degradation of organic matter were found in Tatachia forest soil in central Taiwan (Chen and Yang, 2000). The forest soil pH was between 3.38 and 4.90 (Yang et al., 1998). The same tendency was also observed in Wekerom forest soil of Netherlands where the soil pH was 3.8 (Berg et al., 1998).

Bacterial and actinomycete populations were low in the surrounding area at Hsieh-ho thermal power plant due to the low soil pH (4.00–5.32 vs. 5.01–7.82); while bacterial and actinomycete populations at nuclear power plant No. 2 were low because of the low soil moisture content (6.66–27.29% vs. 27.14–47.78%). The microbial population was lower in the subsoil of the power plants than in the topsoil due to low organic carbon content, low oxygen concentration and the stickiness of the soil. Microbial population in the subsoil (21–40 cm deep) of the grassland in Tatachia mountain showed only 15–40% of bacteria, 2.1–17.4% of actinomycetes and 0.6–2.1% of fungi as in the topsoil (0–20 cm deep), respectively (Yang et al., 1998). Microbial activity, biomass, ATP content and respiration decreased with increasing depth in beech forest soil (Stockfish et al., 1995), and the bacterial population and mycelial content decreased with the depth of the pine forest (Berg et al., 1998). Nitrifying bacterial content also decreased with increasing soil depth in acidic forest soil of Douglas (de Boer et al., 1992). The microbial population was usually high in summer and low on January 21, 1997 due to the cold weather.

Cellulolytic, phosphate-solubilizing and nitrogen-fixing microbes are very important in grassland and forest soil for elemental cycle and nutritional supplement. Although these populations varied with season and location, the percentages of these microbes in the total viable count could be used to assay the change of microbial ecology. Most of the nuclear power plants are located in grassland and forest areas. Therefore, cellulolytic microbes are very important in elemental cycle and plant nutrition. The percentages of cellulolytic microbes in total viable count were found to be low at both nuclear power plants No. 1 and No. 2 due to the low soil moisture content, while it was also low at surrounding area of thermal power plant as a result of low pH. The percentage of cellulolytic microbe in total viable count in the forest of Tatachia mountain was higher than those in the power plant area due to the heavy coverage of organic layer on the surface. The percentages were between 70.69% and 91.11% in the forest soil, while the values ranged from 11.53% to 25.15% in the grassland soil of Tatachia Mountain (Yang et al., 1998), from 17.21% to 60.20% in the power plant area and from 11.96% to 85.91% in the surrounding area of power plant. Tietema and Wessel (1994) also reported that oak leaf decomposition microbes were very active in forest soil for elemental cycle.

The percentage of phosphate-solubilizing microbes in total viable count was found to be high at nuclear power plant No. 2, while it was low at nuclear power plant No. 1. The percentages were between 7.24% and 16.80% in the forest soil, while the values ranged from 1.88% to 5.67% in the grassland soil of Tatachia Mountain (Yang et al., 1998). The surrounding area had a higher percentage of phosphate-solubilizing microbes because of the application of insoluble phosphate fertilizer for crop production.

The percentage of nitrogen-fixing microbes in total viable count were found to be high at thermal power plant, while it was the reverse at nuclear power plant No. 1. The percentages were between 10.56% and 27.30% in the forest soil, while the values ranged from 2.83% to 7.26% in the grassland soil of Tatachia Mountain (Yang et al., 1998). The surrounding area had a low percentage of nitrogen-fixing microbes due to the application of nitrogen fertilizer and the inhibition of propagation of nitrogen-fixing microbes.

Microbial ecology depends on soil type, season, location and environmental conditions. Based on the present results, it can be concluded that the effect of the presence of the power generator (both thermal and nuclear) on soil microbial ecology was insignificant.

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