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Effect of an artificial soil mix from coal fly ash and sewage sludge on soil microbial activity

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Abstract An artificial soil mix was prepared from coal fly ash and sewage sludge and an experiment was performed to evaluate their effects on soil microbial respiration. Coal fly ash at 0%, 5%, 10%, 35% and 50% w/w was mixed with dewatered sewage sludge and then each ash-sludge mixture was incubated with a sandy soil at 1:1 v/v at 28 °C for 42 days. All treatments showed the same carbon dioxide production pattern with a peak production at day 7 to day 14. Addition of ash-sludge mixtures to soil resulted in an increase in carbon dioxide production but the production rate decreased according to the ash amendment rate. The high pH of coal fly ash and the dilution effect of the sludge were the major reasons for the decrease. However, the ecological dose 50% values sharply increased from 26% at day 3 to 39% ash at day 14. This indicates the rapid acclimatization of microorganisms to the fly ash-sludge mixtures. Therefore, a brief stabilization period may be required for the establishment of soil microbial populations in soil amended with ash-sludge mixtures.

Key words Coal fly ash · Sewage sludge · Soil respiration · EcD_{50} · Artificial soil mix

Introduction

Land application is a common method for the disposal and treatment of sewage sludge because it contains an appreciable amount of N, P, and micronutrients such as Cu, Fe, and Zn which can be used as a fertilizer for agricultural soils (Chaney 1983; Matthews 1984). In addition, the enriched organic matter content in sludge can improve soil physical properties and facilitate plant growth (Paul and Clarke 1989; Pichtel and Hayes 1990). However, the enriched content of toxic metals such as As, Cd, Cr, Co, Cu, Pb, Mn, Zn and Ni in sludge may cause an excessive uptake and accumulation of these metals in plants growing on sludge which may affect human and animal health through consumption of these contaminated plants (Chaney 1983).

Liming is a common means of raising soil pH, which in turn reduces the availability of heavy metals in contaminated soils (Tiller et al. 1984). Coal fly ash has been used as a liming material for agricultural soils because of its enriched CaO and MgO contents (Mattigod et al. 1990). Therefore, using coal fly ash as a liming agent for sewage sludge will provide a possible means to reutilize the tremendous amounts of coal fly ash generated from coal-fired power plants. An earlier study (Wong 1995), showed that plant growth in soil amended with ash-sludge mixtures was significantly improved, which can be explained by the improved soil conditions, including both physical and chemical properties. However, little information is known about its effect on soil microbial activity. Therefore, the study aim was to evaluate the effect of the ash-sludge amendment on the microbial activity of a sandy soil by measuring soil respiration.

Materials and methods

Dewatered digested sewage sludge, coal fly ash and sandy soil were collected from the Tai Po Sewage Treatment Plant, the China Light and Power Co., Ltd., at the Castle Peak Station and farmland in the New Territories, respectively. The sludge was stored at 4 °C until use while fly ash and sandy soil were air dried at room temperature for 7 days. The general properties of the ash, sludge and soil samples are listed in Table 1.

The alkaline fly ash was thoroughly mixed with dewatered sludge by a mechanical blender at a rate equivalent to 0%, 5%, 10%, 35% and 50% (w/w) on a fresh weight basis. The ash-sludge mixtures were stabilized and air dried at room temperature for 1 week before grinding to pass through a 4-mm sieve to obtain a homogeneous sample. The fly ash-sludge mixtures were then mixed with a sandy soil at 1:1 (v/v). The amended soil was then moistened to its field capacity and 50 g of the moistened sample was placed in 500-ml conical flasks serving as respirometers as described by Wong and Wong (1986). The flasks were arranged in a completely randomized design inside an incubator at 28 °C for 42 days. All treatments were done in

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Table 1 Physicochemical properties of coal fly ash, sewage sludge and sandy soil. Values in parentheses are standard deviations of means of triplicates

	Fly ash		Sewage sludge		Sand soil	
pH (soil:water=1:5)	12.4	(0.2)	7.39	(0.05)	6.89	(0.04)
EC (dS m^{-1}) (soil:water=1.5)	2.02	(0.03)	4.12	(0.18)	0.02	(0.00)
Organic carbon (%)	0.15	(0.012)	27.8	(0.18)	0.16	(0.01)
Total N (%)	0.047	(0.003)	7.03	(0.02)	0.02	(0.001)
Soluble NH_4^+-N (mg kg^{-1})	4.46	(0.22)	837	(29.4)	1.53	(0.46)
Total P (%)	0.33	(0.017)	1.95	(0.09)	0.29	(0.03)
Soluble PO_4^{3-}-P (mg kg^{-1})	0.28	(0.02)	218	(11.8)	1.00	(0.12)
Moisture content (%)	0.13	(0.02)	87.3	(0.20)	1.23	(0.20)
C/N ratio	3.19		3.95		8.00	
Total element content						
Ca (%)	5.90	(0.14)	1.26	(0.27)	0.26	(0.02)
Mg (%)	0.51	(0.02)	0.35	(0.01)	0.017	(0.001)
K (%)	0.14	(0.04)	0.23	(0.01)	0.04	(0.01)
Na (%)	0.14	(0.03)	0.27	(0.09)	0.0026	(0.0001)
Fe (%)	2.50	(0.14)	0.73	(0.01)	0.78	(0.04)
B (mg kg^{-1})	1053	(18.0)	242	(11.2)	19.9	(3.01)
Cd (mg kg^{-1})	3.51	(0.04)	13.7	(1.7)	1.7	(0.05)
Cu (mg kg^{-1})	37.9	(0.06)	979	(41.6)	10.4	(1.40)
Mn (mg kg^{-1})	293	(2.6)	386	(36.3)	387	(24.7)
Zn (mg kg^{-1})	43.2	(1.5)	1268	(32)	72.5	(5.20)

Table 2 Chemical properties of soil mixed with ash-amended dewatered sludge at 1:1 (v/v) before incubation. The ash amendment rates for sewage sludge were 0%, 5%, 10%, 35% and 50% (w/w). Values are standard deviations of means of triplicates

Ash amendment rate	pH	EC (dS m^{-1})	B	Cu	Fe	Mn	Zn	NH_4^+-N	NO_3^--N	PO_4^{3-}-P
			(mg kg^{-1})							
0%	7.85 c	0.89 a	4.03 d	2.31 c	3.39 b	0.68 a	0.46 a	506 a	2.43 a	86 a
	0.06	0.08	0.40	0.11	1.79	0.032	0.031	76	0.52	7.28
5%	7.87 c	0.78 b	4.29 d	2.29 c	2.65 bc	0.64 a	0.21 c	452 a	3.03 a	36 b
	0.04	0.01	0.65	0.24	0.87	0.075	0.017	79	1.62	6.79
10%	8.00 c	0.67 c	5.43 c	2.75 b	1.79 bc	0.57 a	0.28 b	290 b	1.71 a	19.8 c
	0.05	0.03	0.41	0.28	0.06	0.045	0.011	47	0.20	2.63
35%	8.23 b	0.64 c	10.86 b	2.40 b	0.93 bc	0.18 b	0.19 cd	173 c	2.80 a	10.7 d
	0.17	0.01	0.76	0.36	0.13	0.029	0.035	47	1.12	1.09
50%	8.60 a	0.064 c	13.0 a	4.59 a	0.62 c	0.23 b	0.15 de	124 c	2.15 a	7.70 de
	0.04	0.04	0.31	0.13	0.21	0.033	0.025	26	0.68	0.56
Soil	6.89 d	0.020 d	3.76 d	0.067 d	10.3 a	0.21 b	0.13 c	1.53 d	3.43 a	1.00 e
	0.04	0.001	0.85	0.021	2.72	0.043	0.015	0.46	1.15	0.12
LSD	0.15	0.054	1.06	0.39	2.45	0.24	0.042	95	1.78	7.53

Values followed by the same letter within the same column do not differ significantly at the 5% level according to the Least Significant Difference test

triplicate. Carbon dioxide produced at various time intervals of the incubation period was trapped in NaOH solution and was determined by back titration of the excess alkali with 0.1 *N* HCl after precipitation with $BaCl_2$ (Page et al. 1982). Another set of triplicate incubators were also set up and subsamples were removed to measure the changes in pH and EC during an incubation period of 70 days (soil:water=1:5 w/v).

One hundred grams of the moistened soil mixtures was collected before incubation, air dried at room temperature for 1 week and then ground to pass through a 2-mm sieve for soil chemical analysis. Soluble B, Cu, Zn, Mn, Fe, Cd, PO_4^{3-}-P, NH_4^+-N and NO_3^--N were extracted with deionized water using a 1:5 soil:water (w/v) (Page et al. 1982). pH and EC were measured for the water extracts immediately before filtering. Ammoniacal-N, PO_4^{3-}-P and B contents were measured using the indophenol blue method, molybdenum blue method and azomethine-H method, respectively (Page et al. 1982). Copper, Zn, Mn, Fe and Cd were determined using atomic absorption spectroscopy.

All data were analysed using the SAS statistical package with an IBM PC (Little and Hills 1978). One-way ANOVA was carried out to compare the means of the different treatments; where significant *F* values were obtained, differences between individual means were tested using the Least Significant Difference Test.

Results and discussion

Chemical properties of soil amended with ash-sludge mixture before incubation

Table 2 gives the initial soil chemical properties following ash-sludge amendment. pH increased from 6.9 to 8.6 with an increase in the application rate of coal fly ash. This can be explained by the increase in CaO and MgO from the addition of alkaline coal fly ash (Wong and Wong 1986). Instead of an increase as soil pH, soil EC decreased slightly with an increase in ash amendment level, which is likely due to the precipitation of soluble cationic salts in soil caused by the increasing pH following ash amendment. Soluble B contents increased significantly with increase in ash amendment rate, which were higher than the phytotoxicity level of 5 mg kg^{-1} for treatment with ash-sludge application rates of >5% ash-sludge mixture (Chapman 1966). The addition of ≥35% ash-sludge amendment significantly reduced the soluble Zn, Mn and Fe contents of the ash-sludge-amended soil. The reduced availability of heavy metals following ash amendment can be explained by the pH-dependent characteristics of these metals (Brady 1974). Instead of a decrease, Cu increased according to the ash amendment rate, which might be due to the formation of soluble Cu-organic complexes at high pH. Ammoniacal-N and PO_4^{3-}-P decreased with increasing ash amendment level, which might be due to the volatilization of NH_4^+-N at high pH conditions and the precipitation of PO_4^{3-}-P with Ca and Mg, respectively. No significant difference in NO_3^--N content was noted for the various treatment groups, which is likely due to the low initial nitrate content in sewage sludge.

Changes of pH and EC during incubation

The pH of all treatment groups increased initially and then decreased after 10 days of incubation (Fig. 1a). Soil amended with 10% fly ash showed the most rapid decline in pH. The release of NH_4^+-N from the decomposition of the high organic N in the sludge explained the initial rise in pH (data not shown). In the later declining phase, the decrease in pH might be due to the conversion of NH_4^+-N to NO_3^--N in aerobic conditions (data not shown) and the generation of organic acids from the decomposition of organic matter. Addition of sludge and ash-sludge mixtures caused a significant increase in soil EC simply because of the high amount of soluble salts in both sewage sludge and coal fly ash (Fig. 1b). The initial EC decreased with an increase in ash amendment rate but an opposite trend was noted after 28 days of incubation.

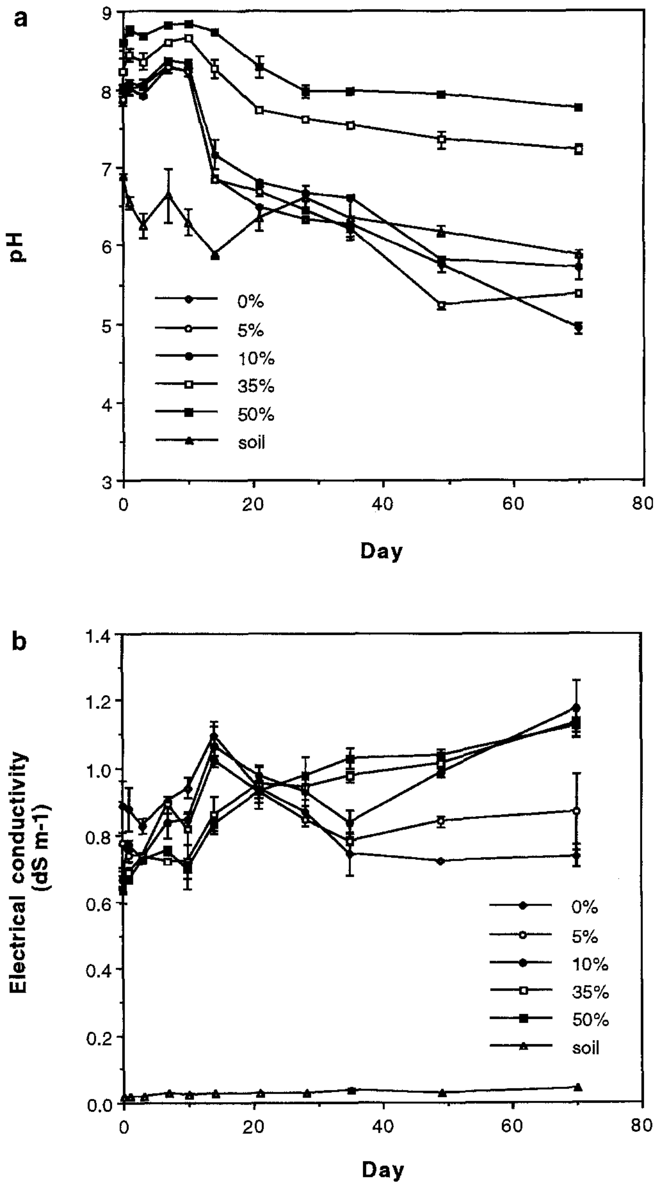

Fig. 1a,b pH (**a**) and electrical conductivity (**b**) of soil mixed with ash-amended sludge (1:1 v/v) during an incubation period of 70 days. The ash amendment rates for sludge were 0%, 5%, 10%, 35% and 50% (w/w)

Soil respiration

The microbial activity of the sandy soil control remained low throughout the incubation period, which can be explained by the low organic and nutrient contents of sandy soil (Fig. 2). The addition of both sewage sludge and ash-sludge mixtures resulted in a significant increase in CO_2 production. The increase can be explained by the high N content and easily oxidizable substrates such as sugar and carbohydrates in sludge, which favour heterotrophic microbial activity (Pichtel and Hayes 1990; Gildon and Rimmer 1993). However, respiratory activity was significantly lower, with an increase in the ash amendment level of the ash-sludge mixtures in comparison to sludge alone. The correlation coefficient between pH and microbial respiration was –0.98 (P<0.001), indicating that the high pH of the ash-sludge-amended soil might inhibit soil microbial activity. Pichtel (1990) also reported that respiration was markedly inhibited at a pH higher than 8 for soil receiving lime amendment. Boron also had a negative correlation with microbial respiration (r^2=–0.93, P<0.001). Since B is commonly used as a chemical agent for killing plant pathogens (Mathur and Bhatnagar 1990), it may also have an adverse effect on soil microbial growth. Moreover, the decrease may be due to the diluted sludge content with an increase in ash amendment level, which reduced the nutri-

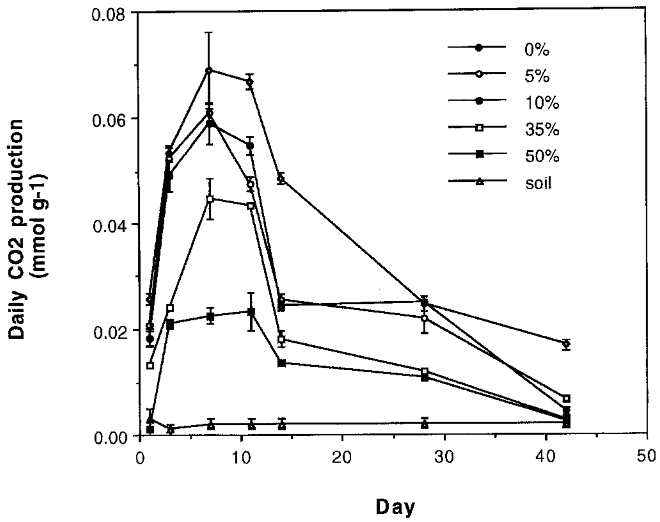

Fig. 2 Changes in daily CO_2 production in soil mixed with ash-sludge mixtures during an incubation period of 70 days. The ash amendments rates for sludge were 0%, 5%, 10%, 35% and 50% (w/w)

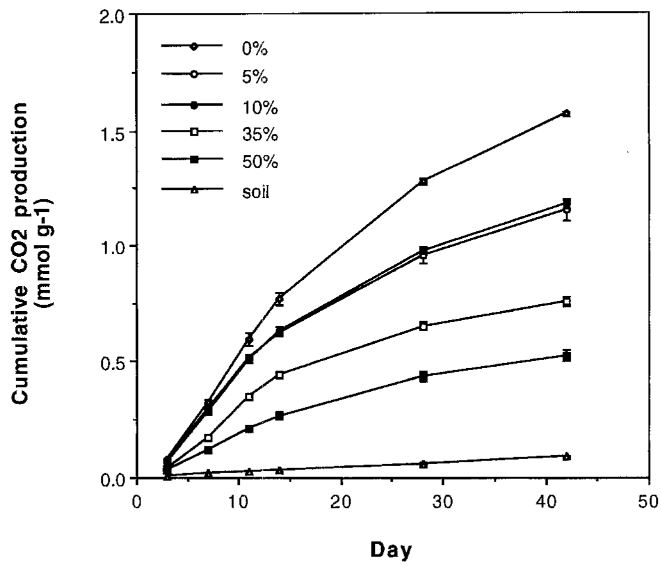

Fig. 3 Cumulative CO_2 production in soil mixed with ash-sludge mixtures during an incubation period of 70 days. The ash amendment rates for sludge were 0%, 5%, 10%, 35% and 50% (w/w)

ent contents and number of microorganisms brought out from the sludge in the ash-sludge mixtures.

The CO_2 production pattern was characterized by an initial build-up phase and a final decline phase for all treated soils. The initial microbial build-up is likely due to the moistening of soil, which activated the microbial growth (Wong and Wong 1986). The gradual increase can also be explained by adaptation of the indigenous microorganisms to the amended conditions (Wong et al. 1995). On the other hand, the decline phase following the build-up phase can be explained by the using up of one or more essential nutrients and the accumulation of toxic metabolites during incubation (Wong and Wong 1986).

The total amount of CO_2 produced decreased as ash content increased (Fig. 3). Similar results were also reported by Pichtel (1990) for fly ash-sludge-amended soils. Soil receiving 10% ash amendment had a similar amount of cumulative CO_2 production to that with 5% ash. An ecological dose 50% (EcD_{50}) of the treated soil was adopted here to quantify the inhibitory effects of coal fly ash-sludge mixtures on soil microbial respiration. It is defined as the concentration of a pollutant that inhibits a microbe-mediated ecological process by 50% at a specific time (Babich et al. 1983). The calculated EcD_{50} was 26%, 42%, 40%, 39%, 36% and 32% for 3, 7, 11, 14, 28 and 42 days, respectively. A lower EcD_{50} value indicated the higher inhibitory effect of fly ash on the amended soil (Wong and Wong 1986). The decrease in fly ash inhibition in the initial period was due to the adaptability of the microbial population and the growth of tolerant species in the ash-sludge-amended soil (Bewley and Stotzky 1983). In the later period, the decrease in EcD_{50} values was mainly due to the conditional changes in soil such as nutrient depletion and accumulation of toxic metabolites rather than inhibition coming from the toxic components of coal fly ash.

Conclusions

The results of the present study confirm the beneficial effect of the ash-sludge mixtures in improving the microbial activity of a sandy soil expressed in terms of soil CO_2 production rate. However, an increase in ash amendment percentage significantly reduced the soil microbial activities because of the high pH of coal fly ash and the dilution effect on sludge content. Other factors such as EC and trace metal contents were not associated with the inhibition. The toxicity of B on soil microbial activity requires further study to establish their relationship. Nevertheless, the soil respiration rate of the highest ash amendment level was still higher than that of the control soil. The inhibitory effect of fly ash on soil microbial activity decreased with increasing time. Therefore, a preincubation period should be allowed for the ash-sludge mixtures before plant growth, especially at a high ash amendment rate, in order to allow the ash to stabilize and to provide better growth conditions for microbial activity. However, the microbial inhibition was not associated with our plant growth results (Wong 1995). The yields in ash-sludge-amended soil were significantly higher than that of the soil with sludge alone. This raises a question as to the validity of using soil microbial activity alone to evaluate the effect of organic amendment on plant yield. Further investigation is warranted to verify this question.

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