Evaluation of Pulverized Fuel Ash Mixed with Organic Matter to Act as a Manufactured Growth Medium

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Abstract
Combinations of PFA (Pulverized fuel ash) mixed with composted municipal organic waste were compared to a local soil and a commercial potting soil "Promix" in an attempt to asses the potential performance of the manufactured growth medium. Results from growth trials were related to the physico-chemical characteristics of the mixtures and fruits were analyzed to determine potential metal uptake

Dried fruit weights from tomatoes grown in mixtures of compost with 5, 10 and 20% PFA were significantly higher than the soil and soil with the recommended dose fertilizer. Fruit production for the 5% PFA mixture was 2.5x that from the soil and 25% higher than the soil + NPK. Fruit production in the 10 and 20% additions were >2x that in the soil. In all cases fruit production in the mixture was 30% higher than the trials with Promix. Analyses of variance indicates that the mixtures of PFA and compost are all significantly different from the control soil and rank the performance of treatments as follows PFA10:CP90> PFA5:CO95> PFA20:CP80.

In all cases element concentrations reported in tomato fruit analyzed did not exceed the maximum reported concentration range normal for plants. Furthermore, with the exception of B and Fe, element concentration means for mixtures were not significantly different from the soil or PROMIX.

Results from the trials indicate that a suitable potting medium can be created from PFA mixed with composted organic material. The physical and chemical composition of mixture promotes healthy and long-term growth without the need for fertilizers.

Introduction

The volume of coal combustion by-products generated worldwide is on the increase due to our reliance on coal as a major source of energy. There is a vast body of information on utilization of these “by-products” in building/construction, production of aggregates and, more recently, agriculture. Most of the work to date has been the result of a need to find economical ways of using the materials rather than having to dispose of them; the cause and effect relationship is obvious.

What is mainly desired by the producers of coal burning by-products is, any scheme which can demonstrate a value added to the material, making it cost effective to produce a “resource” from the “by-products”. While traditional methods of utilization (building/construction/aggregates) are appropriate, there is a large avenue of “disposal” that has not been thoroughly investigated; as a carrier/substrate for micro and macro nutrients.

Application of pulverized fuel ash (PFA) mixed with composted organic material to soil as an alternate to chemical fertilizers or mixed together alone as a growth media may be a viable alternative to the traditional methods of utilization (Byrom and Bradshaw 1991) [1]. While fertilizer application boosts the short-term crop productivity, it does not provide many of the bio-essential nutrients and organic material required for the healthy biotic function of the soil.

The potential benefits of ash addition to soil include improved structure for fine- and coarse-textured soil, improved water-holding capacity (Martens 1971 [2]; Erickson and others 1987 [3] ; Ghodrati and others 1994 [4]), increased pH (Warren 1992 [5]; Cline and others 2000 [6]), along with the potential for increases in the concentration of most macro- and micronutrients (Adriano and others 1980 [7]; Sims and others 1995 [8]). Composted organic material is rich in nitrogen, phosphorus, organic matter and many trace nutrients required for plant growth (Hue and others 1988 [9]; Walter and others 1990 [10]; Wong and others 1995 [11]). Physical properties of soil such as: porosity, structural stability and water-holding capacity are also enhanced by the addition of composted organic material (Pinamonti and others 1997 [12]). In concert these materials can act as a soil conditioner or as a stand alone growth media.

Both materials however, may contain elevated levels of potentially toxic trace metals which, when added to soil, may exceed the natural soil concentrations and/or recommended concentration guidelines. The effects of organic material and PFA addition to the soil nutrient and heavy-metal balance, N mineralisation, and land reclamation have been investigated by a number of authors (Adriano and others 1982 [13]; Pichtel and Haynes 1990 [14]; Bealu 1991 [15]; Garau and others 1991 [16]; Schwab and others 1991 [17]; Menon and others 1992 [18]; Sims and others 1993 [19]; Vincini and others 1994 [20]; Sajwan and others 1995 [21]; Wong 1995 [11]; Schumann and Sumner 1999 [22], Veresh et. al. 2002 [24], Choudry et al.2002 [25]). It should be pointed out that in most of these studies the organic material is sewage sludge, which can contain significant amounts of potentially problematic trace elements. In this study composted organic city waste from the wet/dry facility in Guelph, Ontario, Canada was used rather than composted sewage sludge and because of the nature of this material trace element concentrations are generally low.

This work testes the hypothesis that pulverized fuel ash (PFA) in conjunction with other organic materials can increase the biotic function of soil when used to enhance soil texture and provide nutrients to increase soil productivity. Growth experiments using combinations of PFA mixed with compost alone or with soil were compared to fertilized and unfertilized soil along with PROMIX, a commercially available potting mix. Transport and accumulation of selected metals in the plant parts along with changes in the physicochemical properties of the soil have been studied.

Materials and Methods.

Growth experiments with tomatoes were undertaken in order to determine the effects of adding PFA directly to soils and to mixtures of soils with organic composts. The details of the experiment conducted are given in the following section.

Trials

Growth media were prepared by combining soil from plot B5 at Environmental Sciences Western field station with pulverized fuel ash (PFA) obtained from the Lambton Power Generating Station (Silo 3 and 4 hopper pond) and composted organic material from the wet/dry facility in Guelph. The materials were homogenized using a cement mixer; details of the mixes are given in Table 1. Each treatment was replicated four times. All treatments were analyzed prior to planting and after harvest.

Tomato seedlings were planted in the treatments on June 29, 2002. On July 2, recommended doses of fertilizer were applied to the 100% soil and 100% PROMIX treatments alone. All treatments received equal watering during the growth period. On August 29 all plants were harvested, the number of fruit per plant was counted and the fresh whole plant, fruit, root, and shoot weights were recorded. After drying a fruit sub-sample of the three replicates from each treatment was analyzed.

Sample collection and analytical procedures.

The following is a brief description of the procedures implemented to determine the characteristics of the initial soil, amendment raw materials and vegetative matter collected before, during and after the project implementation.

Table 1. Trial treatments. The numbers represent percentages of each component in the mix. All percentages are given on a dry weight basis.

COMPOST	SOIL	ASH	PROMIX
5	90	5	0
5	85	10	0
5	75	20	0
5	65	30	0
10	85	5	0
10	80	10	0
10	70	20	0
10	60	30	0
20	75	5	0
20	70	10	0
20	60	20	0
20	50	30	0
95	0	5	0
90	0	10	0
80	0	20	0
0	95	5	0
0	90	10	0
0	80	20	0
0	0	0	100
0	0	0	100+NPK
0	100	0	0
0	100+NPK	0	0

Prior to the experiment, samples of pulverized fuel ash (PFA), Guelph wet/dry facility compost (compost) and soil from Environmental Sciences Western plot B5 (ESW-B5) were collected and analyzed for metal content to determine if they fall within the Canadian Environmental Quality (CEQG) guidelines, European Economic Community (EEC) guidelines, U.S. Environmental Protection Agency (USEPA) for application to agricultural soils. Soil monitoring samples were taken before and after crop harvest, and at the end of each harvest vegetative samples were collected and processed.

Fresh soil, compost and PFA samples were air dried, ground to pass through a 2mm sieve, homogenized and split into two fractions. The soil, compost and PFA samples were analyzed for total N and C by the LECO method, pH ammonia and nitrate by 0.1 M $CaCl_2$ extraction. Total element concentrations were determined for the soil, compost and PFA by aqua regia digests of samples ground to <150 um. Plant available-element content was determined by a Mehlich III extraction on the <2.0 mm fraction. The samples were analyzed for 26 elements using a Perkin Elmer PE-3300DV, ICP-OES.

The determination of element content in plant matrices is at best difficult. Errors associated with sampling, preparation, decomposition and analyses are significant and the information can be often misleading. The procedures followed here are extracted from those outlined in a collection of papers edited by Quevauviller and Herzig, 1995 [25], and were strictly adhered to in an attempt to limit sources of error generated during the processing of samples for analyses. The harvested vegetation was separated into various fractions (fruit, shoot and root) and washed repeatedly to remove adhering soil particles. The samples were then dried at 40-50^{o} C and ground and homogenized to pass though a 1-mm sieve. The dried vegetation samples were digested in 1+1 HNO_3 and HCl. The samples were analyzed for 26 elements using a Perkin Elmer PE-3300DV, ICP-OES.

Table 2.The pH and concentration of selected elements in compost, soil, pulverized fuel ash (PFA), PROMIX and recommended guidelines for agricultural and commercial applications. These materials were used to evaluate the suitability of the PFA to as an amendment for soil re-mineralization. All data except pH in mg kg^{-1}.

	Compost	**Soil**	**PFA**	**PROMIX**	**Agric.**	**Resid.**
PH	6.33	6.7	8.32	6.91	6 - 8	6 - 8
Ag	mdl	mdl	mdl	mdl	20	20
Al	4787	16911	20826	17119		
As	1.14	mdl	80.30	mdl	12	12
B	mdl	mdl	256	mdl	2	
Ba	139	67.07	224	68.46	750	500
Ca	77124	15188	21570	17762		
Cd	mdl	mdl	mdl	Mdl	1.4	10
Co	2.94	7.09	11.43	7.09	40	50
Cr	18.06	26.12	57.98	26.48	64	64
Cu	49.26	13.24	26.60	13.58	63	63
Fe	7251	16882	22749	17480		
K	10641	1528	2254	1553		
Mg	11577	4092	1579	4273		
Mn	314	385	61.56	390		
Mo	mdl	mdl	4.63	mdl	5	10
Na	4119	mdl	485	mdl		
Ni	11.88	34.93	33.82	16.98	50	50
P	7587	968	1259	944		
Pb	32.13	8.46	13.46	6.15	70	140
S	3979	mdl	2741	mdl	500	
Si	1824	3038	5401	3258		
Ti	72.72	151	702	147		
V	6.14	28.06	112	28.88	130	130
Zn	303	74.65	63.49	69.21	200	200
Zr	4.69	4.78	20.87	4.90		

Notes:
Agric.: recommended soil quality guidelines for agricultural use.
Resid.: recommended soil quality guidelines for residential use.
Information from Canadian environmental quality guidelines- Summary of existing soil quality guidelines: CCME web site 2003[29].
Compost- from the wet/dry facility Guelph; Soil- from Environmental Science Western field station; Pulverized fuel ash (PFA)- from Lampton generating station
PROMIX- commercially available potting mix, mdl=method detection limits

Raw Material and Mixture Chemistry

Raw Materials:

Chemical analyses of all raw materials was performed prior to the experiment in order to determine their suitability as potential soil amendments. The "total" element concentration (aqua regia extractable) of the compost, soil and pulverized fuel ash (PFA) along with Canadian recommended soil quality guidelines for residential and agricultural use are given in Table 2. While it is recognized that none of these materials will be used on its own as a growth medium, the guidelines are included to give maximum upper limit element concentrations in any amendment and provide some relative information as to their merit as a soil conditioner.

Comparison of the raw materials with the guidelines indicates that, on a stand alone basis, As, B, and S concentrations exceed limits in the PFA while S and Zn exceed limits in the compost. Element concentrations in the soils analyzed fell below guideline limits. The elements which occur above concentration limits were monitored closely through out the experiment, particularly in the analyses

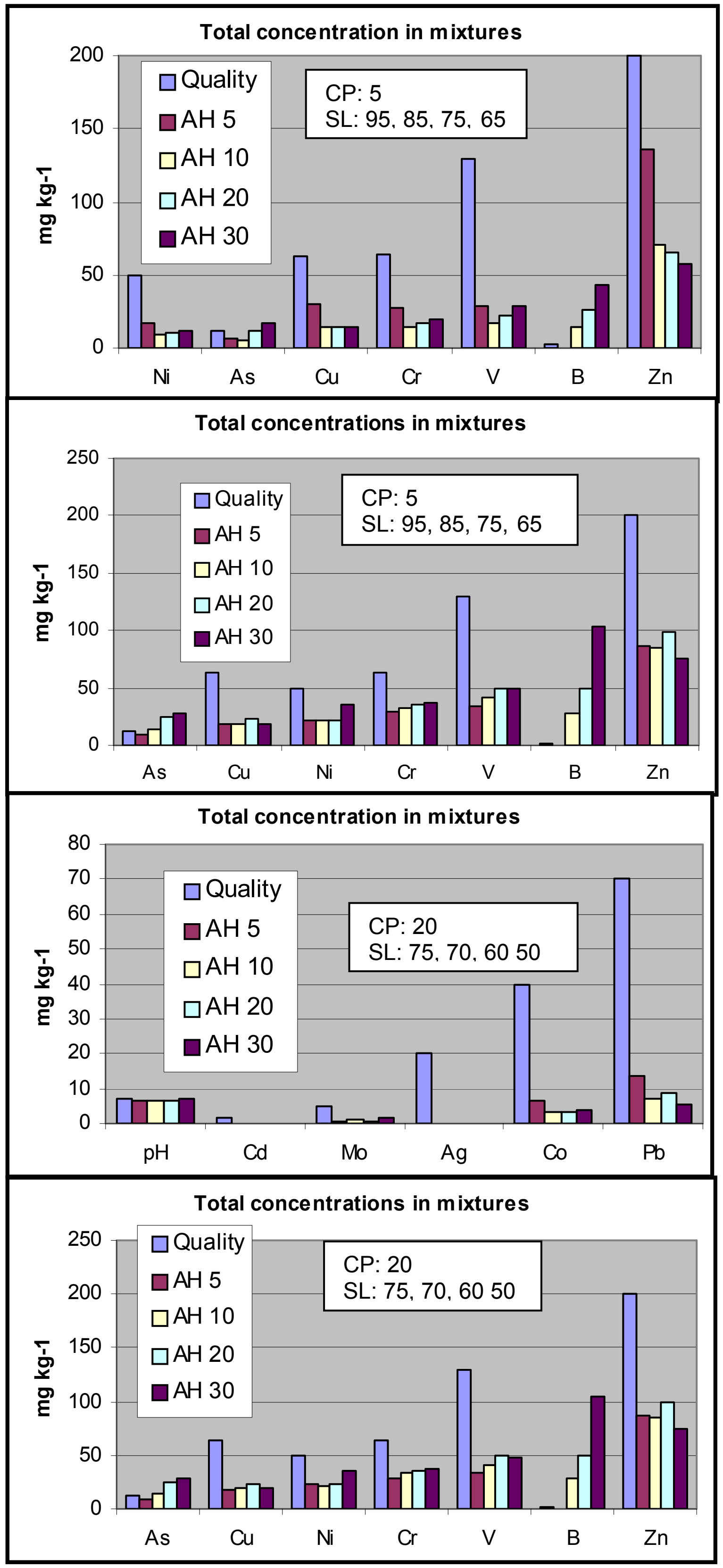

Figure 1. Before planting: the "total" (aqua regia extractable) element content in various mixtures of compost (CP), soil (SL) and pulverized fuel ash (AH). Values behind the abbreviations (AH, CP, SL) are in percent. The quality bar represents the recommended soil quality guidelines for agricultural use; CCME web site 2003 [29].

of the vegetative matter.

For “total “ element concentrations in Trial 1 PFA only As, B and S exceed soil quality guidelines Table 2. Concentrations for the remainder of the elements were below guidelines and it is thus highly unlikely that their plant available component would be in excess. Plant available micronutrient levels for Cu, Fe, Mn, Mo and Zn in the PFA are within the high to very high fertility class (Pais and Benton Jones, 1997) [26] similarly the P content appears to be relatively high (300 mg kg^{-1}, Table 3). In both cases the concerns are minimized since the maximum proportion of PFA in the mixtures is 30% thereby reducing the abundance of these elements in the mixture. In the case of P, concentrations of >50 mg kg^{-1}, and above, promote healthy crop responses and higher concentrations do not appear to be detrimental to the crop (Sims, 2000) [27].

Increasing levels of As, B and S in the mixtures is directly related to their concentration in the PFA. At a 30% PFA application As concentration is greater than 20 mg kg^{-1}, 2x higher than the recommended

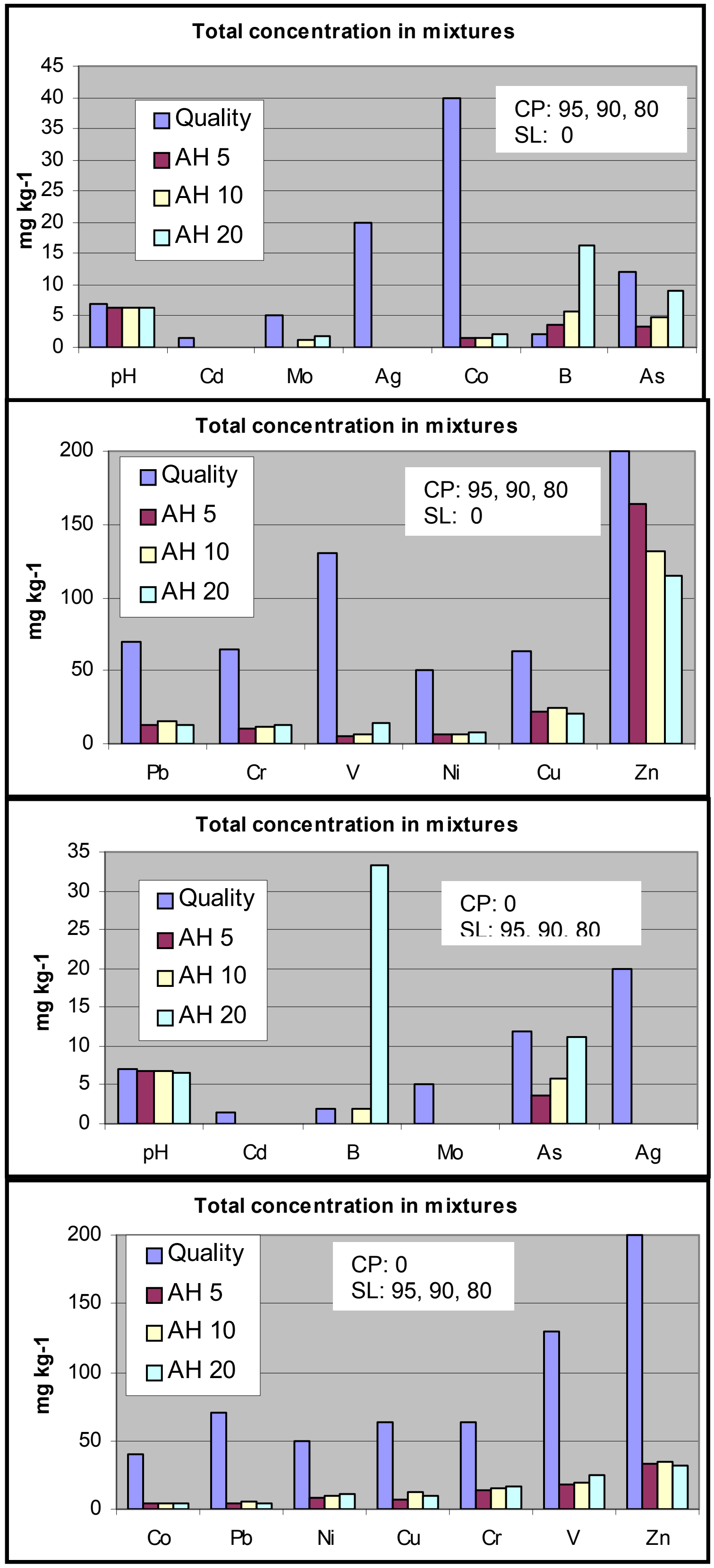

Figure 1 continued. Before planting: the “total“ (aqua regia extractable) element content in various mixtures of compost (CP), soil (SL) and pulverized fuel ash (AH). Values behind the abbreviations (AH, CP, SL) are in percent. The quality bar represents the recommended soil quality guidelines for agricultural use; CCME Web site 2003 [29].

"total" content in agricultural or residential soils, and S can reach up to 1300 mg kg^{-1}, 2.5x the recommended

limit. Boron, an essential micronutrient, has a relatively narrow range of soil concentrations where the crop response is positive; soil deficiencies occur at soluble B levels < 2 mg kg^{-1}, toxicity occurs at concentrations > 2.5 mg kg^{-1} (Pias and Benton Jones, 1997) [26]. Available B content in the 30% PFA mixtures can reach 100 mg kg^{-1}, 40x the recommended upper limit for B content in soils which may pose a problem particularly for crops which are sensitive to B.

Mixtures

In all mixtures only As, B and S exceeded soil quality guidelines (Figure 1). As expected the As and B concentration were highest in those samples with the greatest amount of PFA whereas high S content correlated with high compost additions. The other potentially problematic elements were below guideline the concentration in all mixtures.

Table 3. The pH and plant available (Mehlich III extraction) concentration of selected elements in compost, soil, pulverized fuel ash (PFA) and PROMIX a commercial potting soil. These materials were used to evaluate the suitability of the PFA to as an amendment for soil re-mineralization. All data except pH in mg kg^{-1}.

	PROMIX	Compost	Soil	PFA		PROMIX	Compost	Soil	PFA
NH_4		3.80	0.53	1.35	Mg	1654	1110	224	366
NO_3		230.	6.80	0.77	Mn	76.81	58.19	135	15.15
pH		6.33	6.91	8.32	Mo	0.34	0.19	0.19	1.19
Ag	0.05	0.040	0.03	0.02	Na	747	4065	2.75	262
Al	56.88	46.62	895	1437	Ni	5.64	1.39	2.42	6.16
As	0.81	2.21	0.83	45.20	P	422	1900	45.35	304
B	3.73	13.07	4.03	248	Pb	5.22	16.13	6.32	3.44
Ba	3.16	8.15	32.17	22.96	S	522	751	27	2603
Ca	8745	8477	4495	7923	Sb	mdl	0.05	mdl	1.46
Cd	mdl	0	0.05	0.45	Se	mdl	mdl	mdl	3.30
Co	0.08	0.09	1.05	0.99	Si	93.47	178	405	1795
Cr	mdl	0.08	0.13	6.69	Ti	0.14	0.79	0.69	0.66
Cu	9.80	2.38	4.53	11.55	V	0.31	0.20	1.04	37.55
Fe	158	279	155	477	Zn	42.71	103	4.27	13.49
K	1195	7047	129	258	Zr	0.15	0.86	5.07	3.33

Notes: mdl methods detection limits

Carbon and Nitrogen in raw materials and mixtures

The total N and C concentrations (and their various fractions) are given in Table 4. The total N content of the compost is 10x that in the soil and 20x that in the PFA. The total carbon content in the compost is only 25% more than in the PFA. Most of the C in both is organic suggesting there is a fair portion of unburned coal in the PFA.

As important as the actual content of N and C in the samples is the C/N ratio. This influences the soil microbial activity and ultimately the availability of soil N for plant uptake. The C/N ratio for the soil and compost are very similar whereas for the PFA the ratio is very high reflecting high C and very low N. C/N ratios in the Ap horizon for normal arable soils are in the 12:1 range; ratios >20:1 can be problematic resulting in limited availability of soil N (Baldock and Nelson, 2002)[28].

The concentration in the mixtures directly reflects the proportions of the components. Higher proportions of compost increase available N while increasing PFA in the mix causes the C content to rise increasing in the C/N ratio. Treatments with high PFA contents and low compost (<20%) have C/N ratios >20:1 (Table 4).

Table 4.The nitrogen (total N, NH_4, NO_3) and carbon (total C, inorganic C, organic C) contents in pulverized fuel ash (PFA), Environmental Science Western Soil and Guelph wet/dry facility compost and the various mixtures used in the trial.

Treatment			mg/L	mg/L	Total	Inorg.	Total	Organic	
Compost	Soil	PFA	NH_4	NO_3	N%	C%	C%	C%	C/N
100	0	0	3.80	230	2.21	1.05	18.60	17.55	8.38
0	100	0	0.62	14.30	0.22	0.13	2.34	2.20	10.49
0	0	100	1.35	0.77	0.12	0.89	12.40	11.50	97.64
5	90	5	1.08	25.60	0.31	0.21	3.65	3.44	11.50
5	85	10	0.47	23.50	0.31	0.25	4.15	3.90	13.28
5	75	20	0.70	22.60	0.30	0.32	5.16	4.83	17.01
5	65	30	0.98	21.10	0.29	0.40	6.17	5.76	20.99
10	85	5	1.05	22.20	0.41	0.26	4.46	4.20	10.70
10	80	10	0.71	37.30	0.38	0.30	5.38	5.07	13.97
10	70	20	0.88	45.00	0.38	0.46	6.73	6.26	17.30
10	60	30	1.25	38.30	0.32	0.65	7.08	6.42	21.72
20	75	5	1.11	39.10	0.64	0.53	6.50	5.96	10.09
20	70	10	1.25	71.30	0.61	0.39	6.59	6.20	10.77
20	60	20	1.65	59.10	0.60	0.46	7.60	7.13	12.61
20	50	30	0.76	67.30	0.59	0.54	8.61	8.06	14.51
0	95	5	0.90	56.00	0.21	0.16	2.84	2.67	13.03
0	90	10	1.08	3.76	0.21	0.20	3.34	3.13	15.68
0	80	20	0.84	2.88	0.19	0.67	5.10	4.42	25.89
95	0	5	2.77	214	2.11	1.04	18.29	17.24	8.65
90	0	10	3.86	204	2.01	1.03	17.98	16.94	8.95
80	0	20	1.52	169	1.76	0.82	18.20	17.37	10.31

Treatment values are in percent.
Inorg. = inorganic carbon; C/N = carbon:nitrogen ratio

Results from Growth Experiments

Growth Response Tomatoes

Immediately apparent from the standard deviations given in the summary growth data Table 5 and the growth response to treatments is the high degree of variability for parameters measured. Amongst treatments, additions of 10% PFA showed the greatest degree of variability and the most variation in weights was seen in the dried roots. While much of the variability can be attributed to the nature of plant growth, that shown in root measurements is also related to variable amounts of growth medium adhering to the root ball.

For the tomatoes, regardless of the parameter measured, there is a negative correlation between the amount of PFA in the mix and the response of the parameter. For example, increasing ash concentration results in the dried shoot weight decreasing in an almost linear fashion. This trend is strikingly consistent for all fractions of the plants measured.

Table 5 Growth data from tomato plants grown in various mixtures of soil, pulverized fuel ash (PFA) and compost. The values in the treatments represent percentages of each in the mixture. The data shown are means and standard deviations (SD.) for 4 replicates.

Treatment				Fresh Whole Weight	Fresh Shoot	Dry shoot	Fresh Root	Dry Root	Fresh Fruit	Dry Fruit	Fruit per plant
Compost	Soil	PFA		(g)[1]	(g)	(g)	(g)	(g)	(g)	(g)	
0	100	0	Means	202	52	11	24	11	124	10	44
			S.D.	36	7	2	12	5	23	2	15
0	100 + NPK	0	Means	352	107	20	145	20	204	20	77
			S.D.	41	15	1	212	3	21	3	6
0	Pmix	0	Means	442	90	16	115	27	234	17	65
			S.D.	58	9	2	28	7	48	2	13
0	Pmix+NPK	0	Means	646	147	26	116	38	377	30	80
			S.D.	124	22	4	15	8	90	7	22
5	90	5	Means	421	98	17	67	26	257	20	83
			S.D.	77	13	1	21	4	54	3	11
10	85	5	Means	463	106	18	53	16	305	28	108
			S.D.	100	12	2	28	7	66	6	26
20	75	5	Means	578	131	20	37	15	413	32	128
			S.D.	48	15	2	9	4	36	3	12
5	85	10	Means	383	83	16	50	24	246	23	86
			S.D.	79	13	2	25	17	74	13	27
10	80	10	Means	443	101	18	52	24	287	23	86
			S.D.	39	7	2	10	7	29	4	17
20	70	10	Means	410	109	19	33	14	267	27	96
			S.D.	81	21	5	14	8	61	4	24
5	75	20	Means	330	61	13	41	18	219	16	65
			S.D.	24	16	1	16	8	9	1	14
10	70	20	Means	340	74	14	52	17	213	18	75
			S.D.	47	8	1	14	6	28	1	15
20	60	20	Means	457	91	16	66	13	306	24	96
			S.D.	99	13	3	29	7	65	5	25
5	65	30	Means	ND	ND	ND	ND	ND	ND	ND	ND
			S.D.								
10	60	30	Means	248	51	11	39	13	156	12	64
			S.D.	47	16	4	15	8	23	3	3
20	50	30	Means	404	80	14	64	17	255	20	73
			S.D.	38	11	2	18	4	37	4	16
95	0	5	Means	558	120	17	51	18	383	27	91
			S.D.	123	14	1	12	4	103	3	13
90	0	10	Means	444	107	17	62	25	272	29	69
			S.D.	53	12	3	16	8	41	6	12
80	0	20	Means	407	95	16	33	16	274	25	92
			S.D.	86	20	3	6	7	51	3	10
0	95	5	Means	281	72	13	31	13	178	13	48
			S.D.	48	9	1	6	4	42	3	8
0	90	10	Means	221	59	12	31	13	131	10	44
			S.D.	44	15	3	4	2	45	3	8
0	80	20	Means	102	30	7	19	5	53	4	24
			S.D.	16	5	1	4	0	14	1	4

1. (g) = grams; 2. Pmix = PROMIX potting soil; NPK = required dose fertilized

On the other hand, if we compare the tomato growth response in the mixtures relative to those grown in soil and soil plus added NPK (controls), the results reveal that growth responses in many of the treatments out perform the controls (Figure 2). Dried fruit weight in the treatments relative to the controls, shows that the 5%, 10% and 20% PFA treatments, all did better than the control without added NPK. Growth responses only in those treatments with no compost were less than the controls with added NPK. Analyses of variance indicate that the dried fruit weight of samples from 5, 10 and 20% PFA treatments, which contain >5% compost, are statistically different from the controls (100% soil). The greatest difference of means relative to the control group was seen in the 5 and 10% PFA treatments and, in all cases, the greatest difference was noted in those samples that had the highest proportion of compost.

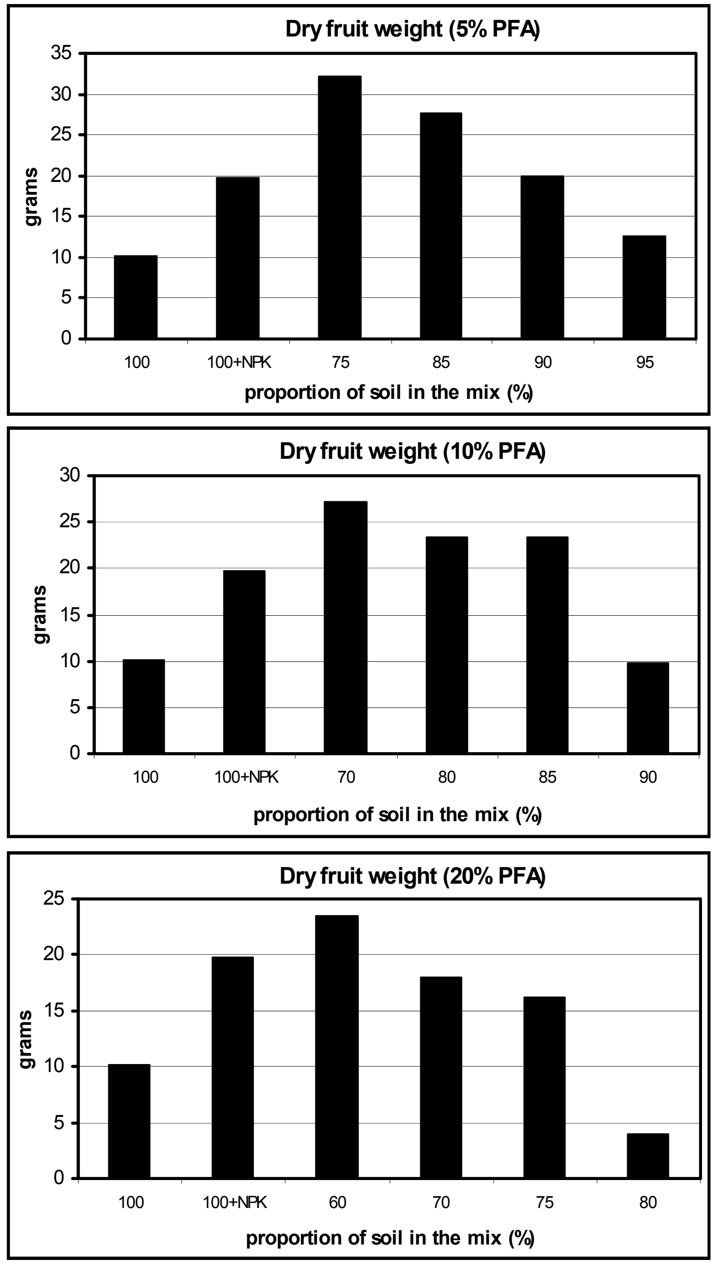

Figure 2. Dried tomato fruit weight in mixtures of soil, compost and 3 proportions of pulverized fuel ash (PFA). The soil and compost vary in the mix however in each graph the PFA remains constant. Shown are the average values from 4 replicates grown in the various mixtures

Similar to the dried fruit, there is decrease in dried shoot production in direct response to the amount of PFA in the mixture. In all cases the amount of material produced was greater in the mixes relative to the soil control. However, the control soil + NPK growth performance was better than all PFA/compost treatments. The proportion of dried root also decreased in accordance to PFA addition in the mix. Statistical analyses however, indicates that there is no relationship between PFA addition and the development of roots. This reflects the extreme variability in root weights and problems associated with the adherence of the growth media.

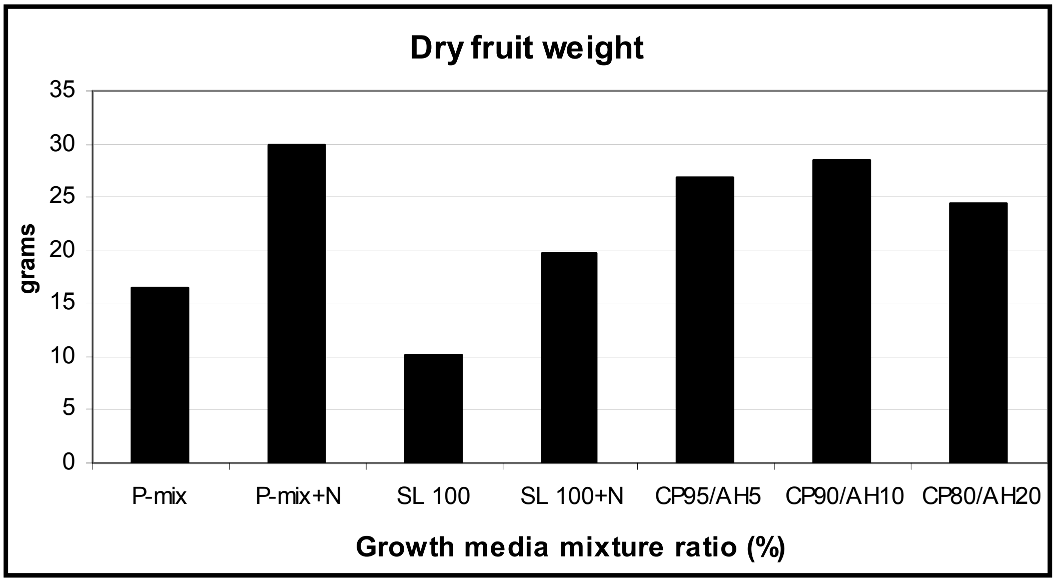

Figure 3. Dried tomato fruit weight in mixtures of pulverized fuel ash (AH) and compost at various ratios. For comparison the commercial growth media PROMIX (P-mix) and soil (SL) and the same with recommended dose fertilized are included (+N).

Experiments were conducted to assess the potential of PFA mixed with compost to act as stand alone growth media i.e. mixtures where no soil was incorporated. As indicated above, there is a slight response decrease in direct proportion to the amount of PFA added. The best response in dried fruit production was in the PROMIX with added NPK. Dried fruit weights from tomatoes grown in mixtures with 5, 10 and 20% PFA were significantly higher than the controls (soil and soil + NPK; Figure 3). Fruit production for the 5% PFA mixture was 2.5x that from the soil and 25% higher than the soil + NPK. Fruit production in the 10 and 20% additions were >2x that in the soil. Analyses of variance indicates that the mixtures of PFA and compost are all significantly different from the control soil and rank the performance of treatments as follows PFA10:CP90> PFA5:CO95> PFA20:CP80.

Chemical Analyses of Tomatoes

The concentration of potentially toxic trace elements in tomato fruit grown in compost/soil/PFA and compost/PFA mixtures are given in Table 6. Also included in these is the concentration range normally found in plants and the normal trace element content for a reference plant.

For the elements showing increasing concentration with the addition of PFA and/or compost to the soil mixture, only As, B, Ni and Fe exceeded the minimum concentration range reported for normal plants. In all cases concentrations reported in fruit analyzed from the trials did not exceed the maximum reported concentration range normal for plants. Furthermore, with the exception of B and Fe, element concentration means for mixtures were not significantly different from the soil or PROMIX controls and in all cases concentrations in the tomato fruit fell well within the range reported for reference plants.

Table 6. The concentration of trace elements in tomato fruit grown in mixtures of compost soil and pulverized fuel ash. The treatment proportions are in percent all other data listed here is in mg kg^{-1}.

Treatment			Concentration in mg kg^{-1}					
Compost	Soil	PFA	As	B	Cd	Co	Cr	Cu
5	90	5	mdl	8.6212	0.0833	mdl	mdl	3.368
5	85	10	mdl	7.6853	mdl	mdl	mdl	3.370
5	75	20	0.859	18.22	mdl	mdl	mdl	3.300
5	65	30	ND	ND	ND	ND	ND	ND
10	85	5	mdl	7.035	mdl	mdl	mdl	2.849
10	80	10	0.422	11.46	mdl	mdl	0.158	4.598
10	70	20	0.528	14.35	mdl	0.181	0.133	4.325
10	60	30	0.544	12.52	mdl	mdl	mdl	1.874
20	75	5	mdl	10.98	mdl	mdl	mdl	3.674
20	70	10	mdl	10.09	mdl	mdl	0.140	3.419
20	60	20	mdl	10.42	mdl	mdl	mdl	3.137
20	50	30	mdl	15.96	mdl	mdl	mdl	3.689
95		5	0.605	9.712	mdl	0.045	mdl	3.604
90		10	mdl	7.658	mdl	mdl	mdl	3.974
80		20	mdl	11.99	mdl	mdl	mdl	4.532
	Pmix+NPK		0.310	6.880	0.052	mdl	mdl	2.327
	Pmix		0.335	4.855	mdl	mdl	mdl	2.027
	100+npk		mdl	8.800	0.271	mdl	mdl	9.491
	100		0.866	8.957	0.252	mdl	mdl	9.056
	95	5	0.270	13.60	0.228	mdl	mdl	7.589
	90	10	mdl	27.61	0.077	mdl	mdl	8.134
	80	20	mdl	28.17	mdl	mdl	mdl	8.043
Min.			0.1	30	0.2	0.05	0.2	4
Max.			5	75	0.8	0.5	1	15
Reference			0.1	40	0.05	0.2	1.5	10

Treatment			Concentration in mg kg^{-1}					
Compost	Soil	PFA	Fe	Mn	Mo	Ni	V	Zn
5	90	5	66.94	9.194	md	0.129	mdl	11.89
5	85	10	36.59	7.905	md	0.176	mdl	9.692
5	75	20	48.59	10.79	md	0.316	mdl	14.57
5	65	30	ND	ND	ND	ND	ND	ND
10	85	5	28.53	6.672	md	0.080	mdl	9.348
10	80	10	52.47	9.149	md	0.324	mdl	13.49
10	70	20	109	12.11	md	0.281	mdl	14.45
10	60	30	25.67	6.829	md	0.108	mdl	9.222
20	75	5	48.12	8.492	md	0.212	mdl	13.78
20	70	10	40.03	9.842	md	0.168	mdl	14.77
20	60	20	35.93	7.672	md	0.330	mdl	11.75
20	50	30	39.75	8.657	md	0.129	mdl	12.86
95		5	29.17	7.011	md	0.222	mdl	13.73
90		10	108	8.529	md	0.143	mdl	13.13
80		20	48.45	9.614	md	0.107	mdl	16.27
	Pmix+NPK		21.65	12.93	md	mdl	mdl	11.55
	Pmix		26.23	12.00	md	0.190	mdl	9.773
	100+NPK		32.72	12.19	md	mdl	1.160	11.13
	100		86.37	11.52	md	mdl	1.191	13.05
	95	5	65.96	12.86	md	mdl	1.238	12.71
	90	10	47.92	12.80	md	mdl	1.196	17.41
	80	20	34.81	9.736	md	0.103	1.076	12.40
Min			20	15	0.1	0.1	0.1	15
Max			300	100	1	1	1	150
Reference				200	0.5	1.5	0.5	50

Min. and Max. refers to the minimum and maximum concentration in normal plants, reference refers to the concentration in a reference plant. From Pais and Benton Jones Jr. 2000 [26]

ND = no data, mdl = method detection limits, Pmix = PROMIX commercial potting soil, npk = recommended dose fertilizer.

concentrations in the tomato fruit fell well within the range reported for reference plants.

Conclusions

The field trials indicate that dry fruit production for tomatoes grown in mixtures of PFA + compost, mixed with soil, was greater than those in soil alone and, where the PFA is <20%, the growth response is better than the soil with recommended dose fertilizer. Furthermore the growth response in PFA and compost mixtures (alone with no added soil) as a stand-alone medium was better than local soil or the commercially available growth medium, PROMIX. A complete explanation for the growth responses could not be determined from this limited study, however a number of potential benefits derived from the addition of these materials are outlined below:

1. Water retention capacity. The addition of both PFA and compost to the soil results in textural changes that promote the retention and availability of H_2O. The introduction of organic material and limited amounts of PFA improves the soils wetting characteristics, potentially reducing water and nutrient loss.

2. Carbon nitrogen ratios (C/N). In arable soils optimum C/N ratios are approximately 12. In the mixtures with PFA contents $\leq$ 20%, the C/N ratios remain close to the optimum range for soils, $\cong$15. In this situation soil N is not lost by microorganism scavenging and is available for plant uptake.

3. Macronutrients. Of the mineral nutrients, nitrogen is required by plants in the greatest amount. PFA contains very little available N, however in combination with the compost, the plant nutrient requirements are met and the proper C/N ratios are maintained (see above 2). Along with nitrogen, phosphorous (P) and potassium (K) are common components of fertilizers. Phosphorous is an integral component in compounds within the cell nucleus and it plays an essential role in the transfer of energy within the cells. Potassium is important in the synthesis of proteins, chlorophyll and carbohydrates and aids in the absorption of N and P by the roots. Relative to the soils used in trials, P and K content in the PFA and compost are higher and their addition to the soil have improve their availability to the crop. Trial results suggest that mixture nutrient capacity and availability is greater than the soils or the unfertilized commercial potting soil.

4. Micronutrients. These elements participate primarily in a number of enzyme systems, some which bring about oxidation-reduction reactions in plants others acting as cofactors and bridging mechanisms connecting enzymes with substrates upon which they will act. Although they are required in relatively small amounts, they are essential for growth and their supply is often difficult to maintain. The beneficial effects of any individual micronutrient cannot be assessed in this study. What is indicated from the trials and

analyses is that the micronutrient content in both PFA and compost exceed that in the normal soil and, for a number of the elements, that in the commercial potting soil. Correlation of PFA/ compost addition to the soil and the available micronutrient content is positive; the amendments provide a micronutrient source. More importantly, for those elements that were elevated relative to global soil standards, in no case did the element content in the vegetation exceed the toxicity threshold.

The trials also indicate that there is limit to the amount of PFA which can be added to the mix. With this particular PFA, mixtures with proportions >20% PFA did not perform well. Identifying the specific parameters that resulted in the poor growth is beyond the scope of this study. A number of factors that may have contributed to and/or acted in concert to produce the observed results are outlined below.

1. Self cementing properties of the PFA. Observations from field trials suggest that high PFA content resulted in poor drainage. The implication here is that over time, the reaction of PFA with water produced a number of secondary mineral phases that may have partially cemented the mixture. The result is a reduction in permeability thereby limiting the availability of H_2O and oxygen to the rooting zone.

2. Fine particle size of the PFA. In conjunction with the above, the fine size of the PFA may have resulted in the clogging of the soil pores, reducing permeability and limiting H_2O and oxygen availability to plant roots.

3. Carbon nitrogen ratios (C/N). In arable soils optimum C/N ratios are approximately 12. In the mixtures with high PFA, the C/N ratios approach 20 or greater. The consequence is a net loss of soil N as microorganisms scavenge the available N to aid in the breakdown of carbonaceous material thus reducing the availability for plant nutrition. Field observations have shown that the crops grown in mixtures with high proportions of PFA were often chlorotic with woody stems, indications of nitrogen deficiency.

4. Micronutrient or trace element toxicity. The only elements that exceeded the soil quality limits are As and B; their concentration in the mixtures is directly related to the PFA content. While it is not possible to link their concentration directly to the poor growth, it is possible that in conjunction with the other factors some distress resulted. However in all treatments, element content in the vegetative material fell well within the normal range reported for normal plants.

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