

Synthetic Aggregates Produced by Different Wastes as a Soil Ameliorant, a Potting Media Component and a Waste Management Option.

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1. Introduction

In most developed and developing countries with increasing population, prosperity and urbanization, one of the major challenges for them is to collect, recycle, treat and dispose of increasing quantities of solid waste and wastewater. It is now well known that waste generation and management practices have increased several alarming issues on the socio-economics, human health, aesthetics and amenity of many communities, states, and nations around the world (Meyers et al., 2006; Louis, 2004). Industrialized economies extract vast quantities of natural resources from the environment to provide modern amenities and commodities. On the other hand, pollutants associated with the production and consumption of commodities, as well as post-consuming commodities, go back into the environment as residues (Moriguchi, 1999). Although varying in degree and intensity, the solid waste problem around the world is exacerbated by limited space and dense populations (Melosi, 1981). The problem of collecting, handling and disposing of wastes is dealt with using different techniques and approaches in different regions. A waste management hierarchy based on the most environmentally sound criteria favors waste prevention/minimization, waste re-use, recycling, and composting. In many countries, a large percentage of waste cannot presently be re-used, re-cycled or composted and the main disposal methods are land filling and incineration. In addition, traditionally, managing domestic, industrial and commercial waste consisted of collection followed by disposal, usually away from urban activity, which could be waterways, Open ocean or surface areas demarcated for the purpose viz. landfills. With the increased volume and variety of hazards posed by new waste products, the situation has exceeded its saturation point at many localities (McCarthy, 2007). In 2006 the USA land filled 54% of solid wastes, incinerated 14%, and recovered, recycled or composted the remaining 32% (EPA, 2008). The percentage of solid waste disposed at landfills accounted for 3% in Japan (2003), 18% in Germany (2004), 36% in France (2005), 54% in Italy (2005) and the USA (2005), and 64% in the UK (2005). As legislation becomes more stringent and land filling becomes less cheap option. For example, there has been a significant reduction in the amount of wasteland filled in the UK and Italy. In 1995, Italy land filled 93% of solid waste, and the UK 83%. Recent studies have revealed that waste disposal processes have considerable impacts on climate change due to the

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associated greenhouse gases (GHGs) emission (Elena, 2004; Sandulescu, 2004; USEPA, 2002). Land filling processes are found to be the largest anthropogenic source of CH₄ emission in the United States. In 2004, there were 140.9 Tg of CO₂ equivalent of CH₄ (approximately 25% of the United States' annual CH₄ emission) emitted from the landfills, which shared 2.65% of the national global-warming damage. In addition, 19.4 and 0.5 Tg of CO₂ equivalent of CO₂ and N₂O were, respectively, released from the combustion processes (USEPA, 2006). These evidences show that waste disposal systems are one of the most significant contributors to potential climate change, as the associated-emission cannot be effectively mitigated under current management conditions. Moreover, Incineration is also cannot be recommended as an efficient method since it is also creating toxic gases and GHGs. In addition, wide range of waste materials (sewage sludge, industrial waste) is increasingly spread on agricultural land as soil amendments. These undoubtedly produce a number of positive effects on soil quality, but also raise concern about potential short-term (e.g. pathogen survival) and long-term effects (e.g. accumulation of heavy metals). Climate change will also become a major incentive to the use of biosolids on agricultural land, especially in regions where longer periods of low rainfall and mean higher temperatures are expected. In many parts of the world (e.g. Europe, USA) agricultural soils receive large volumes of soil amendments. Approximately 5.5 million dry tones of sewage sludge are used or disposed of annually in the United States and approximately 60% of it is used for land application (NRC, 2000). The application of biosolids to soil is likely to increase as a result of the diversion of waste away from landfill sites, and due to increasing cost of artificial fertilizers (UNEP, 2002; Epstein, 2003). Simply application of waste as an amendment to agricultural lands made some environmental problems such as air pollution due to tiny particles of coal fly ash (CFA). Therefore, it is worthwhile to find out alternative methods for waste disposal. Consequently, unconventional synthetic aggregates were produced from different waste materials (sewage sludge, paper waste, oil palm waste, sugarcane trash, starch waste, CFA, wood chips, coir dust, cattle manure compost, chicken manure compost etc...) to utilize them in agriculture as a soil amendment, fertilizer support, and potting media for containerized plant cultivation (Jayasinghe & Tokashiki, 2006; Jayasinghe et al., 2005, 2008, 2009 a,b,c,d,e,f,g). These synthetic aggregates proved that they can be utilized in agriculture very effectively. Moreover, these kinds of unconventional synthetic aggregate production have not much been reported in the literature. Therefore, this chapter describes the production, characterization and different utilization methods of synthetic aggregates in agriculture.

2. What is a Synthetic Aggregate (SA)?

Aggregate structure is schematically shown in Figure 1. It is composed with rigid or composite materials, fibrous materials and a binder.

2.1 Rigid or composite materials

Sewage sludge, sugarcane trash, wood chip, CFA, compost, soil etc. can be regarded as rigid materials. The rigid materials give the rigidity and the strength of the aggregate by enmeshing into fibrous matrix. Figure 2 shows the scanning electron microscopic (SEM) image of a coal fly ash paper waste aggregate, which is showing the rigid CFA particles are enmeshed into the fibrous paper waste matrix by the binder.

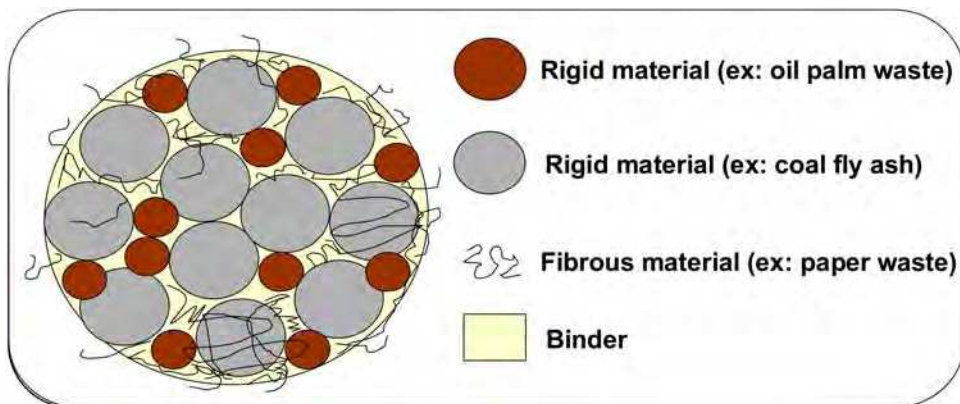


Fig. 1. Schematic diagram of the synthetic aggregate.

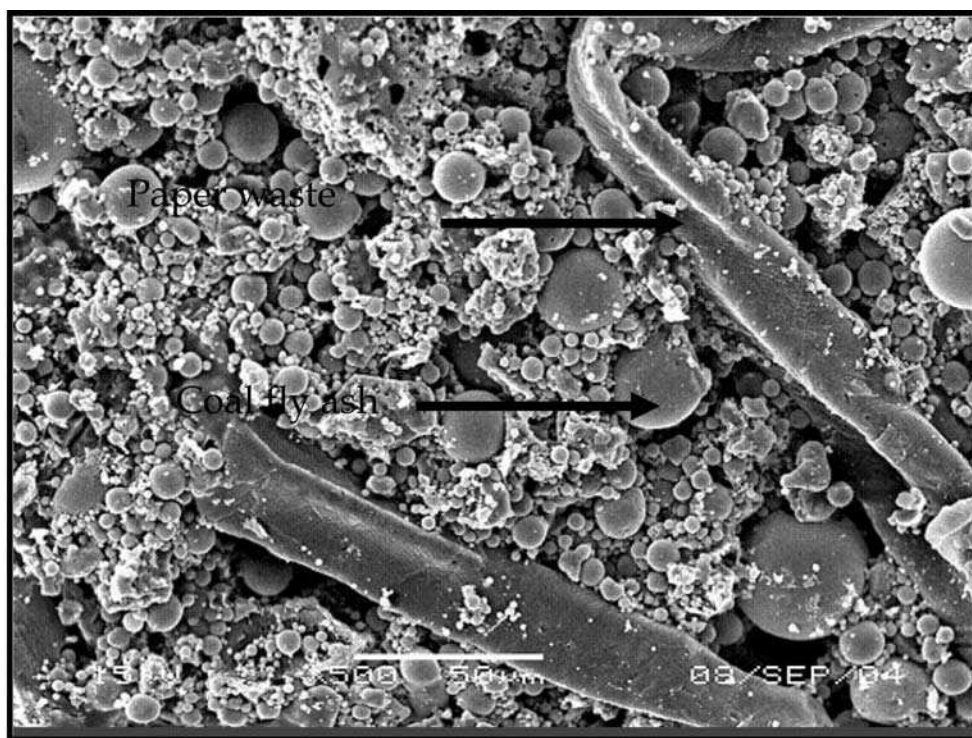


Fig. 2. Scanning electron micrograph of a coal fly ash-paper waste synthetic aggregate.

2.2 Fibrous materials

The formation of aggregate requires a matrix to adhere the rigid particles. Then this matrix can form the aggregate structure by binding the rigid particles into the matrix by the binder. Paper waste, coco fiber, wheat and rice straw and oil palm fiber can be used as the fibrous

materials. Figure 2 shows the porous paper waste matrix, which provides the binding sites to the CFA particles. Porous spaces can be observed within the aggregate, which can improve the aeration and the water holding capacity of the aggregates as a growth substrate (Jayasinghe et al., 2007). Fibrous materials in the aggregates also assist to increase the micro pores in the aggregate-soil amendment mixtures during the humification of aggregates by microbes after mixing them into the soil as an amendment.

2.3 Binder

The formation of aggregate requires both physical rearrangement of particles and the stabilization of the new arrangement. Therefore effective binder should be added in order to obtain stable aggregates. Several binding mechanisms exist between organic polymers and mineral surfaces to provide stable aggregates. Organic polymers have been used quite effectively to stabilize soil structure in recent years. Many researchers have shown that the application of polyacrylamide maintained high infiltration rate during rainfall and reduced soil surface sealing and runoff soil losses (Ben-Hur & Keren, 1997; Sojka et al., 1998; Green et al., 2000). Polysaccharides added to soil as soil conditioners improve soil's physical properties that are important for plant growth and increase soil's resistance against disruptive forces and erosion. Organic polymers have been used quite effectively to stabilize soil structure in recent years. Polysaccharides stabilize soil aggregates because of their contribution as cements and glues. (Taskin et al., 2002). There is a considerable amount of starch which is a polysaccharide coming out as waste material from Okinawa flour industry (Okinawa, Seifun Ltd). Utilization of the starch waste is currently under the potential capacity. Therefore, the starch waste was utilized as an organic binder for the synthetic aggregate production. In addition, several inorganic binders can be used to produce synthetic aggregates. Acryl resin emulsion binder EMN-coat /21 and Calcium hydroxide with calcium sulfate can also be used as the binder to produce aggregates.

2.4 Production of synthetic aggregates

Production process of aggregates is given in Figure 3. EIRICH mixer, Ploughshare mixer or Pelleger machine can be used for the production of heterogeneous aggregates. Heterogeneous aggregates means the aggregates containing different particle sizes. Pelleter machine can be utilized to produce homogenous (same size) aggregates. EIRICH mixer was used for small scale aggregate production and pelleger machine and pelleter was used in major scale aggregates production. Different proportions of raw materials were mixed in the pelleger or EIRICH mixer for 1-3 minutes. Then binder was added and mixed for another 1-2 minutes. Finally whole mixture was mixed for another 2-5 minutes in high speed rotation to form aggregates. Raw materials with binder mixture were inserted to the pelleter machine for the production of homogenous aggregates. Moreover, diameter and the length of the aggregates can be adjusted according to the requirement.

2.5 Different types of aggregates with various types of wastes.

Different types of aggregates can be developed with the available waste in the site or area. Some of the developed aggregates from different wastes are described below (Figure 4). Basically aggregates can be divided into two types.

1. Heterogeneous aggregates

These aggregates contain different sized aggregates. Following are some of the heterogeneous aggregates developed from various materials.

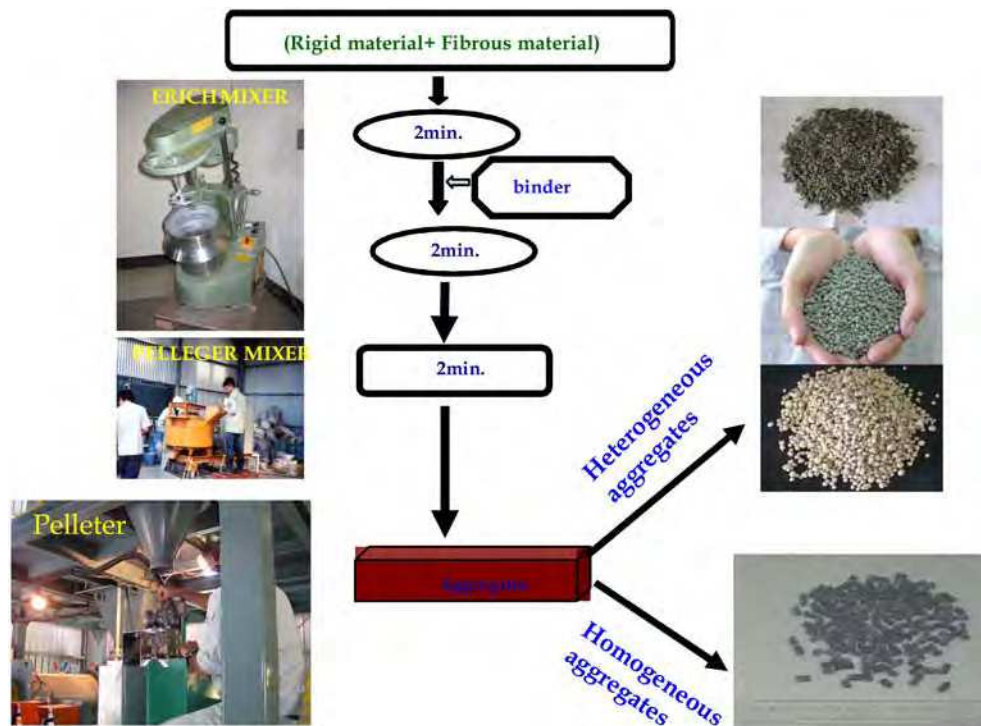


Fig. 3. Production process of different types of aggregates.

- i. Coal fly ash based aggregates
These aggregates were developed from CFA, paper waste or oil palm waste with organic or inorganic binders (Figure 4a).
 - ii. Soil aggregates
These were developed from low productive acidic red soil with paper waste, coco fiber, or oil palm waste (Figure 4b) with organic or inorganic binders.
 - iii. Acid soil-coal fly ash aggregates
These were developed by acid soil and the coal fly ash with paper waste, sewage sludge (SS), CFA with organic or inorganic binder. (Figure 4 c)
 - iv. Sewage sludge based aggregates
These aggregates were developed from sewage sludge and zeolite with an inorganic binder. (Figure 4d)
 - v. Compost based aggregates
These were produced from different types of composts and soil with organic or inorganic binders (Figure 4e)
2. Homogenous aggregates
These aggregates have same sized aggregates and pelleter machine was used for the production of these aggregates.
These aggregates are called as synthetic pellet aggregates. Coal fly ash (CFA), soil, compost, paper waste, coco fiber, oil palm waste, sewage sludge and organic or inorganic binders can be utilized as raw materials for these types of aggregates. (Figure 4f)

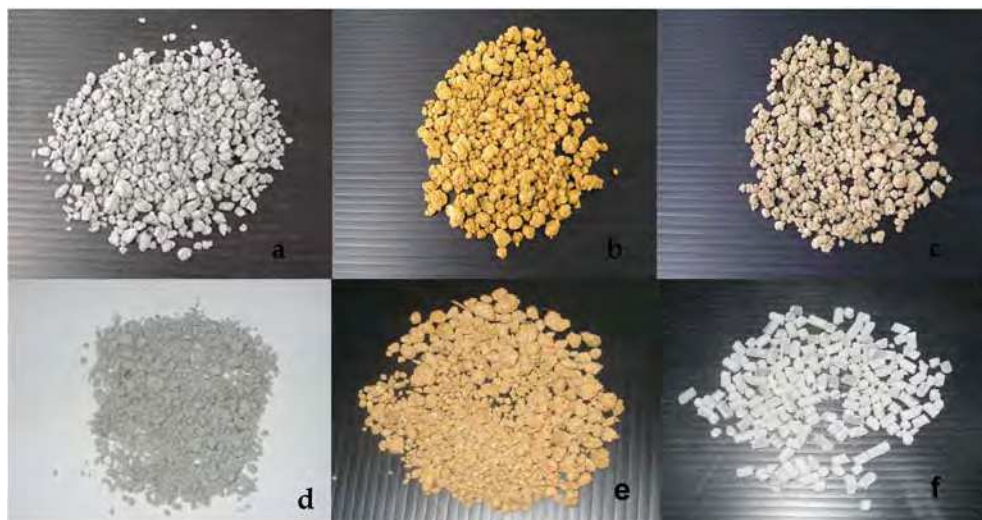


Fig. 4. Different types of aggregates produced from different materials. (a) coal fly ash paper waste aggregates, (b) soil aggregates, (c) acid soil coal fly ash aggregates, (d) sewage sludge based aggregates, (e) compost based aggregates, (f) pellet aggregates (homogeneous aggregates)

3. Physical and chemical properties of synthetic aggregates

3.1 Physical properties

Particle size distributions of synthetic aggregates developed by different materials are given in the Table 1. Particle size distribution of a substrate is important because it determines pore space, air and water holding capacities (Raviv et al., 1986). Mean distribution of the aggregate media showed that fraction between 5.60 and 2.00 mm was the most abundant fraction in all types of synthetic aggregates (Table 1). An excess of fines in a substrate clogs pores, increases non-plant-available water holding capacity and decreases air filled porosity (Spiers & Fietje, 2000). Therefore, these synthetic aggregates which are having higher percentage of larger- sized particles can be utilized to enhance the properties of problematic soils having higher finer particles to improve its porosity and hydraulic conductivity. Synthetic aggregates developed from low productive acid soil and paper waste addition to the problematic grey soil in Okinawa, Japan significantly enhanced the particles >2.00 mm and hence the hydraulic conductivity and porosity were significantly increased (Jayasinghe et al., 2009d). All of synthetic aggregates shown in the Table 1 are heterogeneous which are having different sized aggregates. Synthetic pellet aggregates can be developed with single particle sized diameter which are called as homogenous aggregates. These pellet aggregates can be produced with the required diameter as a tailor made production. In addition, aggregate diameter of heterogeneous aggregates depends upon the material type and quantity, binder type and quantity and the mixing time. Therefore, suitable particle sizes of heterogeneous synthetic aggregates can be designed according to the requirement. Synthetic aggregates particle sizes are varying with the required situation. For an example particle sizes for a potting medium are different from particle sizes required as a soil ameliorant. As

a potting medium relatively higher percentage of smaller sized-diameter particles should be utilized to improve the potting media characteristics.

Aggregate type	>5.60 mm	5.60-3.35 mm	3.35-2.00 mm	2.00-1.00 mm	1.00-0.50 mm	>0.50 mm
A	25.61	30.19	28.32	8.54	5.20	2.14
B	10.77	19.85	36.98	13.15	7.91	11.34
C	23.86	28.14	25.74	9.44	8.09	4.73
D	6.34	16.92	16.98	19.44	21.23	19.09
E	26.20	30.28	27.54	8.73	5.02	2.23
F	7.10	15.21	18.77	15.91	22.87	20.14

A: coal fly ash paper waste aggregates with starch binder (Jayasinghe et al., 2009b),

B: acid soil aggregates with starch binder (Jayasinghe et al., 2008),

C: acid soil coal fly ash aggregates with starch binder, (Jayasinghe et al., 2008),

D: acid soil compost aggregates with inorganic binder,

E: coal fly ash aggregates with inorganic binder (Jayasinghe et al., 2009a),

F: sewage sludge aggregates with inorganic binder.

Table 1. Particle size distribution of synthetic aggregates.

Bulk density, particle density, hydraulic conductivity, water holding capacity and aggregate strength of the synthetic aggregates are given in the Table 2. Bulk density of a substrate gives a good indication of porosity, which determines the rate at which air and oxygen can move through the substrate. Bulk density values of all substrate given in the table showed low values compared to red soil (1.26 g cm^{-3}) in Okinawa Japan. These low values are due to the coal fly ash, paper waste, and sewage sludge in the developed synthetic aggregates. It is also evident that there were significant differences between bulk density values of aggregates produced with different coal fly ash additions to red soil (Jayasinghe et al., 2005). The particle density of the synthetic aggregates was also low compared to the red soil. Red soil gave a particle density of 2.61 g cm^{-3} . Hydraulic conductivity of a substrate is a measure of the ability of air and water to move through it. Hydraulic conductivity is influenced by the size, shape and continuity of the pore spaces, which in turn depend on the bulk density, structure and the texture. Hydraulic conductivity of the aggregates showed higher values compared to the red soil and grey soil studied in Okinawa, Japan. The red soil and grey soils showed hydraulic conductivity values of 6.62×10^{-5} and 6.67×10^{-5} , respectively. The water holding capacity of the synthetic aggregates given in the table varied between 0.59 and 0.68 kg kg^{-1} , which are increased values compared to the red soil (0.48 kg kg^{-1}) in Okinawa Japan (Jayasinghe et al., 2009e). Aggregate strength of the produced aggregates varied between 2.58-4.01 kg cm^{-2} . Synthetic aggregates developed by using coal fly ash, paper waste, and starch waste gave an average aggregate strength in the range of 2.05-3.58 kg cm^{-2} , which can be considered as higher aggregate strengths (Jayasinghe et al., 2005, 2006, 2008). Higher aggregate strengths indicate resistance of the aggregate to the erosion. Therefore, these synthetic aggregates can withstand to erosion compared to soil particles.

3.2 Chemical properties

Chemical properties of the different types of synthetic aggregates are given in the Table 3. It is evident that pH of aggregates were varied in a wide range from 4.57 to 10.72. A, C, E and

G aggregates having higher pH values were produced by using CFA as a material in the aggregates. The original pH of the CFA used to produce synthetic aggregates was varied in the range of 11.36-11.80. Therefore, CFA aggregates gave alkaline pH values. The hydroxide and carbonate salts in CFA gave one of its principle beneficial chemical characteristics, the ability to neutralize acidity in soils (Pathan et al., 2003). Therefore, these alkaline synthetic aggregates can be used as a buffer material to neutralize the acidic problematic soils. Jayasinghe et al., (2006) reported that 25% of synthetic CFA based aggregates addition increased the acidic pH (4.62) of red soil into 6.25. Type B aggregates were developed from acidic red soil with paper wastes showed acidic pH of 4.57 due to acidic soil. Type D aggregates were produced from acidic red soil with cattle manure compost which neutralized the acidic pH of the red soil and gave a pH of 6.40. Type F aggregates gave a pH of 7.58 due to the alkaline sewage sludge (pH=7.72) in the aggregates. It is evident that the pH of the aggregates depends on the materials which were used to form the aggregates. Aggregates showed high electrical conductivity (EC) except type B due to high essential and non essential elements in the aggregates. Type B aggregates produced from red soil and paper waste, which did not contain much element concentrations, gave the lowest EC. But coal fly ash had high concentrations of different elements, which subsequently raised the EC of the CFA based aggregates. The EC and metal content of soil increases with increasing amount of CFA application (Sikka & Kansal, 1994). Aggregates developed from sewage sludge (SS) also showed high EC due to the presence of high concentrations of elements in the sewage sludge (SS). Gil et al., (2008) reported that SS was characterized by higher EC. The High EC in SS may be due to presence of high concentrations of different types of elements.

Aggregate type	Bulk density (gcm ⁻³)	Particle density (gcm ⁻³)	Hydraulic conductivity (cms ⁻¹)	Water holding capacity (kgkg ⁻¹)	Aggregate strength (kgcm ⁻²)
A	0.56	2.48	2.80x10 ⁻²	0.62	3.91
B	0.87	2.44	1.87x10 ⁻²	0.63	2.58
C	0.80	2.20	3.74x10 ⁻²	0.68	3.06
D	0.64	2.48	2.80x10 ⁻²	0.67	3.76
E	0.64	2.31	1.87x10 ⁻²	0.59	3.88
F	0.54	2.08	2.24x10 ⁻²	0.61	4.01
G	0.52	2.20	2.80x10 ⁻²	0.60	3.92

A: coal fly ash paper waste aggregates with starch binder,

B: acid soil aggregates with starch binder,

C: acid soil coal fly ash aggregates with starch binder,

D: acid soil compost aggregates with inorganic binder,

E: coal fly ash aggregates with inorganic binder,

F: sewage sludge aggregates with inorganic binder,

G: synthetic pellet aggregates (diameter is 10 mm).

Table 2. bulk density, particle density, hydraulic conductivity, water holding capacity and aggregates strength of the synthetic aggregates.

	A	B	C	D	E	F	G
pH	9.82	4.57	9.71	6.40	10.72	7.58	9.28
EC(mSm ⁻¹)	96.16	6.36	57.50	48.76	90.40	156.26	80.76
C (g kg ⁻¹)	120.82	85.40	66.21	101.12	55.22	291.80	113.61
N (g kg ⁻¹)	0.71	0.40	0.40	1.06	0.42	29.10	0.62
P (g kg ⁻¹)	0.11	0.08	0.05	0.46	0.06	14.65	0.20
Na (g kg ⁻¹)	0.87	0.24	0.44	0.71	0.78	0.54	0.88
K (g kg ⁻¹)	1.51	0.18	0.76	2.34	1.56	0.62	1.61
Mg (g kg ⁻¹)	0.72	0.38	0.47	0.87	0.73	4.12	0.91
Ca (g kg ⁻¹)	3.34	1.10	2.31	2.12	37.25	65.64	3.18
B (mg kg ⁻¹)	16.86	0.12	10.33	0.42	19.34	0.51	12.17
Mn (mg kg ⁻¹)	15.82	20.28	18.73	24.14	19.20	109.66	14.88
Cu (mg kg ⁻¹)	18.47	13.21	16.22	22.66	18.50	188.02	19.12
Zn (mg kg ⁻¹)	34.63	21.35	28.93	32.12	34.60	485.07	31.98
Cr (mg kg ⁻¹)	7.62	1.21	5.45	0.98	7.60	34.42	7.02
Cd (mg kg ⁻¹)	ND	ND	ND	ND	ND	0.40	ND
Se (mg kg ⁻¹)	ND	ND	ND	ND	ND	ND	ND
Pb (mg kg ⁻¹)	7.56	3.01	5.88	3.66	7.60	26.33	8.02
As (mg kg ⁻¹)	ND	ND	ND	ND	ND	ND	ND

A: coal fly ash paper waste aggregates with starch binder,

B: acid soil aggregates with starch binder,

C: acid soil coal fly ash aggregates with starch binder,

D: acid soil compost aggregates with inorganic binder,

E: coal fly ash aggregates with inorganic binder,

F: sewage sludge aggregates with inorganic binder,

G: synthetic pellet aggregates (diameter is 10 mm).

EC: electrical conductivity, ND: not detected.

Table 3. Chemical properties of synthetic aggregates.

Carbon (C) content of aggregates also varied in a greater range and depends on the material type in the aggregate. The N content of the aggregate types of A, B, C, E and G showed low N amount. But D and F gave high N content. Aggregate D contains cattle manure compost while F contains sewage sludge. Moreover, aggregates enriched with N, P and K can be developed by adding respective N, P and K chemical fertilizer as a material to produce aggregates. All of the aggregates gave low phosphorous (P) content except the type E since it is composed with high P containing SS. Aggregates having CFA, compost and SS (A, C, D, E and F) gave high concentrations of Na, K, Mg and Ca in the aggregates. Chemically, 90–99% of CFA is comprised of silicon (Si), aluminum (Al), Ca, Mg, Na and K (Adriano et al., 1980). Aggregates developed from coal fly ash gave high boron (B) content compared to other aggregates. This is due to high B content of the CFA. CFA contains significant levels of B (Lee et al., 2008).

Heavy metal concentrations of the different aggregates are given in Table 3. Selenium (Se) and Arsenic (As) were not detected in any aggregates, and Cadmium (Cd) was detected

only in F. The copper (Cu), chromium (Cr), manganese (Mn), zinc (Zn) and lead (Pb) concentrations were generally well below the maximum pollutant concentrations of individual metals for land application suggested by the US Environmental Protection Agency (USEPA, 1993). The maximum pollutant concentrations of individual heavy metal content for land application of sewage sludge given by the US Environmental Protection Agency are (all in mg/kg); As 41, Cr 1200, Cu 1500, Zn 2800, Pb 300, Cd 39 and Se 36, respectively (USEPA, 1993). Furthermore, average concentrations of heavy metals reported in uncontaminated soils are (all in mgkg⁻¹); 6 As, 70 Cr, 30 Cu, 90 Zn, 35 Pb and 0.35 Cd, respectively (Adriano, 2001). Though the concentrations of heavy metals were below the uncontaminated soil values and not alarming, there should be routine inspections to ensure that heavy metal concentrations remain within safe limits.

4. Aggregate utilization

4.1 Synthetic aggregates as a soil ameliorant to problematic soils

4.1.1 Synthetic aggregates as a soil ameliorant to low productive acidic red soil.

4.1.1.1 Coal fly ash paper waste starch binder aggregates

Widely spread red soil ("Kunigami Mahji") in sub-tropical Okinawa, Japan, is not suitable for crop production due to its poor physical (Tokashiki et al., 1994) and chemical properties, such as its acidic nature, low organic matter content, and poor nutrient availability (Kobayashi & Shinagawa, 1966; Hamazaki, 1979). Therefore, CFA paper waste aggregates developed with CFA, paper waste and starch binder were used as a soil ameliorant to improve the low productive acidic soil. Aggregates were produced by combining CFA and paper waste using an Eirich mixer (R-02M/C27121) with starch binder. 500 g of coal fly ash and 50 g of paper waste were mixed in the Eirich mixer by adding 250 ml of starch binder to produce aggregates. Developed aggregates were used as a soil ameliorant to low productive acidic soil with the objective of enhancing the soil physical and chemical properties to improve the growth and development of Komatsuna (*Brasica rapa*) which is a popular vegetable in Japan. The different amendment rates of the experiment are given in Table 4.

Treatments	Description
T1	Aggregates only
T2	75 % of aggregates
T3	50% of aggregates
T4	25% of aggregates
T5	10% of aggregates
T6	Acidic red soil only.

Table 4. Different treatments were used under the study.

4.1.1.1.1 Influence of aggregate addition to red soil on the growth and development of Komatsuna

Aggregate addition of 25% with acidic red soil ("Kunigami Mahji") as a soil amendment, favorably improved Komatsuna yield by giving the highest significant increase in plant height, fresh and oven dry yield over other treatments (Table 5). Treatments of 10% of aggregate addition gave the second highest average values of yield. Aggregates only (T1)

and acid soils only (T6) showed the lowest mean values of height and yield (Table 5). Therefore, aggregate addition to the soil as a soil amendment improves the crop production in comparison with acidic red soil. Aggregate addition percentages of 50% and 75% did not show any significant difference between them, but, significantly differed from the treatments of 25% of aggregate addition and acidic red soil only. Aggregate addition modified the acidic pH conditions to nearly neutral conditions at the 10% and 25% percentages. Therefore, synthetic aggregates, which were produced from coal fly ash, buffer the acidic red soils, while forming conducive crop growth environment by binding soil particles with coal fly ash aggregates, which improves the crop growth and soil physico-chemical properties.

Treatments	Dry weight (gpot ⁻¹)	Fresh weight (gpot ⁻¹)	Height (cm)
T1	0.25 ^d	1.50 ^e	5.02 ^d
T2	2.33 ^c	12.50 ^d	14.13 ^c
T3	2.92 ^c	17.00 ^c	16.16 ^c
T4	8.10 ^a	48.00 ^a	24.21 ^a
T5	7.13 ^b	45.00 ^b	21.08 ^b
T6	0.30 ^d	2.00 ^e	6.11 ^d

(Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test (P=0.05).

Table 5. Influence of aggregates as a soil ameliorant on crop growth and yield of Komatsuna.

4.1.1.1.2 Effect of aggregate addition on soil characteristics

Aggregate addition to acidic red soil significantly improves the water holding capacities (Table 6) of the soil. Addition of 25% of aggregates increased the water holding capacity by 6%. Moreover, aggregates addition significantly improved the hydraulic conductivity (Table 6) of the soil. Addition of 25% of aggregates increased the hydraulic conductivity of the aggregate soil mixture by 10 times. Moreover, aggregate addition up to 25% significantly reduced the bulk density (Table 6) of the red soil from 1.23 gcm⁻³ to 1.05 gcm⁻³, which improves the soil porosity. Addition of aggregates, improves the soil porosity, water holding capacity and soil hydraulic conductivity. Acidic red soil has originally a very low permeability and it leads to heavy erosion due to run off (Hamazaki, 1979). Addition of these stable aggregates can be suggested as an alternative method to minimize the erosion in acidic red soil. Because high Ca content in these aggregates came from CFA can enhance the aggregation of soil particles together (Jayasinghe & Tokashiki, 2006). Aggregate addition neutralized the acidic soil pH. Aggregate addition percentage of 25% level changed the original pH value of the soil from 4.62 to 6.25, which was nearly a neutral value. Furthermore, electrical conductivity (EC) of soil mixture increases with the addition of aggregates (Table 6). C/N ratios of the soil-aggregate mix also show a significant variance. Application of these aggregates helps to build up C content in the soil as well (Table 6). Aggregate addition of 25% increased organic carbon from 1.62 to 28.80 gkg⁻¹. Therefore, innovative coal fly ash aggregates addition as a soil amendment improves soil physical and chemical properties of problematic low productive acidic red soil, which automatically improves crop production in the soil.

Characteristics	T1	T2	T3	T4	T5	T6
EC (mSm^{-1})	73.67 ^a	55.24 ^b	39.64 ^c	18.57 ^d	10.06 ^e	3.27 ^f
pH	9.26 ^a	8.37 ^b	7.86 ^c	6.25 ^d	5.78 ^e	4.62 ^f
WHC	0.61 ^a	0.59 ^b	0.57 ^b	0.54 ^c	0.53 ^{cd}	0.51 ^d
SHC (cms^{-1})	2.20×10^{-2a}	6.22×10^{-3b}	2.24×10^{-3b}	2.94×10^{-4c}	2.73×10^{-4c}	6.62×10^{-5d}
C (gkg^{-1})	110.25 ^a	83.18 ^b	55.97 ^c	28.80 ^d	12.56 ^e	1.62 ^f
N (gkg^{-1})	0.60 ^a	0.52 ^a	0.54 ^a	0.46 ^a	0.48 ^a	0.47 ^a
C/N ratio	200 ^a	162 ^b	116 ^c	65 ^d	31 ^e	4 ^f
BD (gcm^{-3})	0.61 ^e	0.87 ^d	0.98 ^c	1.05 ^{bc}	1.12 ^b	1.23 ^a

EC: electrical conductivity,

WHC: water holding capacity,

SHC: saturated hydraulic conductivity,

BD: bulk density. (Means followed by the different superscript letter in the same row differed significantly according to Duncan's multiple range test ($P=0.05$)).

Table 6. Physico-chemical characteristics of soil - aggregate amendments

4.1.1.2 Coal fly ash paper waste inorganic binder aggregates (CSA)

CSA (see type E from the Table 1, 2 and 3) were produced by combining coal fly ash and paper waste using an Eirich mixer (R-02M/C27121) with calcium hydroxide and calcium sulfate. 1000 g of coal fly ash and 75 g of paper waste were mixed in the Eirich mixer with 50 g of calcium hydroxide and 50 g of calcium sulfate by adding 350 ml of water to produce CSA. Particle size distribution, physical and chemical properties of CSA were given in Table 1, 2 and 3.

4.1.1.2.1 Scanning Electron Microscopy (SEM)

SEM images of Figure 5-A and B represent detailed micro-morphology of CFA particles. SEM images of CFA particles showed crystalline and amorphous silicate glasses ("stable glasses") of various sizes (Figure 5-A-a) according to 4 typical phases of CFA described by Klose et al., (2003). CFA consists of many glass-like particles, which are mostly spherical shaped and ranged in particle size from 0.01 to 100 μm (Davison et al., 1974). Physically, CFA occurs as very finer particles having an average diameter of <10 μm and has low to medium bulk density, high surface area and light texture (Jala & Goyal, 2006). CFA particles are hollow empty spheres called as cenospheres (Figure 5-B-c) filled with smaller amorphous particles and crystals (Plerosphers). These tiny CFA particles are easily airborne (Hodgson & Holliday, 1966). Therefore, initial idea of CSA production was to bind tiny airborne CFA particles into fibrous paper waste matrix by starch waste. Figure 5-C and 5-D show the micro-morphological configuration of CSA, where paper waste matrix provides the structural surface to adhere CFA particles. Figure 5-C shows aggregation of CFA particles to paper waste matrix with the assistance of starch. Paper waste matrix increased the surface area of CSA (Figure 5-D). SEM images of SA revealed that SA is a dual composite material having greater surface area with well enmeshed CFA particles in paper waste matrix with the help of starch waste providing porous spaces within the CSA. In a previous study it was reported that CFA showed an increased surface area, capillary action, and nutrient-holding capacity when incorporated to soil (Fisher et al., 1976). Therefore, CSA can be regarded as a material having a higher surface area, which can be utilized to improve the nutrient holding capacity, when incorporated to the soil as a soil amendment.

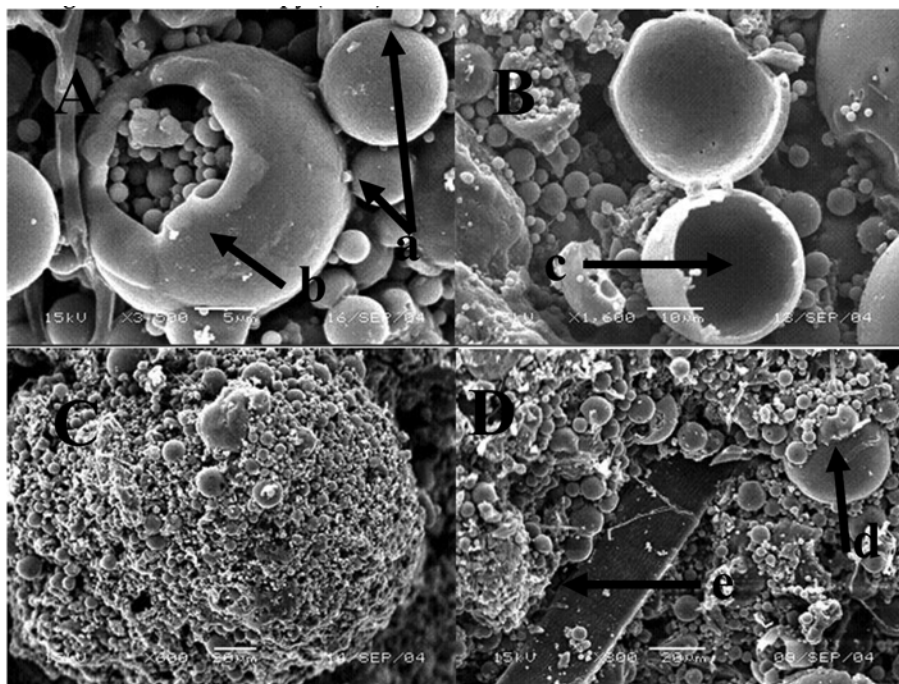


Fig. 5. (A and B) Scanning electron micrographs of CFA particles, showing the micro morphology and varies sizes of coal fly ash particles. (a) stable glasses of various sizes (b and c) cenospheres: (C and D) part of a macro-aggregate (CSA) is produced by CFA and paper waste (d: coal fly ash, e: paper waste).

4.1.1.2.2 Coal fly ash paper waste aggregates as a soil ameliorant to red soil for Komatsuna production

The different aggregate amendment ratios used in the experiment are given in Table 7. Komatsuna (*Brassica rapa* var. *Pervidis*), also known as Japanese mustard spinach, was grown in a pot experiment to study the influence of CSA amendment in acidic red soil on crop production.

Treatments	Description
T1	Red soil only
T2	CSA :Red soil (1:1) (V/V)
T3	CSA: Red soil (1:5) (V/V)
T4	CSA :Red soil (1:10) (V/V)

CSA: Coal fly ash based synthetic aggregates

Table 7. Different treatments were used under the study.

4.1.1.2.2.1 Effects of CSA amendment on soil physical and chemical properties of the soil

4.1.1.2.2.1.1 Physical properties

CSA addition significantly ($P < 0.05$) decreased the soil bulk density by about 30, 14 and 11% in T2, T3 and T4, respectively. Since, CSA reduced the soil bulk density; it can enhance the

porosity and permeability. CSA addition enhanced the hydraulic conductivity of the soil, which may have improved the red soil. Hydraulic conductivity values of treatments T2, T3 and T4 were significantly higher ($P < 0.05$) than that of original red soil (T1) which had a very low hydraulic conductivity of $6.62 \times 10^{-5} \text{ cm s}^{-1}$ (Table 8). The addition of CSA increased hydraulic conductivity of T3 and T4 by ten times and T2 by 100 times. CSA addition to red soil also reduced particle density compared with the original soil. Particle densities of the T2, T3 and T4 were reduced by 7.10, 5.28 and 2.26%, respectively in comparison with original soil (T1). Water holding capacity of the T2 (0.59 kgkg^{-1}) was increased by 23% compared to the T1 due to incorporation of CSA. This fraction in T3 and T4 were 12.5 and 10%, respectively.

Treatments	Bulk density (gcm^{-3})	Saturated hydraulic conductivity (cms^{-1})	Particle density (gcm^{-3})	Water holding capacity (kgkg^{-1})
T1	1.26 ^a	$6.62 \times 10^{-5\text{c}}$	2.65 ^a	0.48 ^c
T2	0.89 ^d	$5.52 \times 10^{-3\text{a}}$	2.46 ^d	0.59 ^a
T3	1.08 ^c	$2.81 \times 10^{-4\text{b}}$	2.51 ^c	0.54 ^b
T4	1.12 ^b	$2.72 \times 10^{-4\text{b}}$	2.59 ^b	0.53 ^b

(Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test ($P=0.05$)).

Table 8. Physical properties of different treatments used under the study.

The particle size distribution of the different growth media used in the study are shown in Table 9. It showed that red soil had a larger amount of particles $< 2 \text{ mm}$. CSA contains 84.02% of particles $> 2 \text{ mm}$, while this fraction in red soil (T1) was 44.30%. Moreover, coal fly ash particles ranging from 0.01 to $100 \mu\text{m}$ (Page et al. 1979), which can easily become air borne. Production of CSA from CFA significantly increased the particle size diameters (Table 9). CSA production reduced the finer fraction and increased the larger particles, which would reduce handling difficulties. Incorporation of CSA into red soil significantly ($P < 0.05$) increased the fraction $> 2 \text{ mm}$ by 65.34, 53.34, and 46.36%, in T2, T3 and T4, respectively. Moreover, red soil had a high percentage (29.14 %) of particles $< 0.5 \text{ mm}$, while this fraction in CSA, T2, T3 and T4 were 2.23, 10.18, 15.86 and 18.32 %, respectively. CSA as a

Treatments	$>5.60\text{mm}$ (Weight %)	5.60-3.35 mm	3.35-2.00 mm	2.00-1.00 mm	1.00-0.50 mm	$< 0.50 \text{ mm}$
CSA	26.20 ^a	30.28 ^a	27.54 ^a	8.73 ^d	5.02 ^e	2.23 ^e
T1	6.61 ^e	18.93 ^d	18.76 ^c	14.86 ^b	11.70 ^d	29.14 ^a
T2	19.18 ^b	25.87 ^b	20.29 ^b	11.88 ^c	12.60 ^c	10.18 ^d
T3	14.12 ^c	20.56 ^c	18.66 ^c	14.84 ^b	15.96 ^b	15.86 ^c
T4	9.24 ^d	18.52 ^d	18.60 ^c	17.92 ^a	17.40 ^a	18.32 ^b

CSA: coal fly ash based aggregates, (Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test ($P=0.05$)).

Table 9. Particle size analyses of the CSA, red soil, and CSA-soil amendment mixtures.

soil amendment considerably increased percentage of particles > 2 mm and decreased particles < 0.5 mm. In addition, CSA addition gave a uniform distribution of particles across each particle size class.

4.1.1.2.2.1.2 Chemical properties

The chemical properties of the different treatments are shown in Table 10. The pH values of red soil, coal fly ash and CSA were 5.12, 10.87 and 10.72, respectively. Addition of alkaline CSA to the acidic red soil significantly ($P < 0.05$) decreased the pH, such that T3 and T4 were almost neutral. CSA improved the acidic pH of the red soil to values suitable for plant growth. The EC of the CSA produced was 90.40 mS m^{-1} compared with 4.18 mS m^{-1} in the original red soil. CSA addition to the red soil increased the soil EC; the EC values in T2, T3 and T4 were 60.28, 20.13 and 14.48 mS m^{-1} , respectively. CSA addition to soil significantly increased the Na, K, Mg and Ca concentrations compared to original soil (Table 10). Therefore, CSA addition as a soil amendment not only improves soil physical and chemical properties but also it can improve the soil fertility by supplying nutrients such as Ca, Mg and K. The CEC values of T2, T3 and T4 were significantly ($P < 0.05$) higher than the original red soil, which had CEC of $4.30 \text{ Cmol}_c \text{ kg}^{-1}$ (Table 10). The CEC increments in T2, T3 and T4 were 1.86, 1.76 and $1.62 \text{ cmol}_c \text{ kg}^{-1}$, respectively compared to T1. It is evident that CSA addition to the red soil increased the CEC in comparison with the original soil. C content of all treatments with CSA additions increased compared with the original soil (Table 10), due to incorporation of paper waste with a C content of 374.8 g kg^{-1} . The N and P contents of the different treatments were low (0.30-0.50 and $0.03\text{-}0.05 \text{ g kg}^{-1}$) and not significantly different between treatments.

Treatments	pH	EC (mS m^{-1})	C (g kg^{-1})	N (g kg^{-1})	P (g kg^{-1})	CEC ($\text{Cmol}_c \text{ kg}^{-1}$)	Na (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})
T1	5.12 ^d	4.18 ^d	1.73 ^d	0.40 ^a	0.03 ^a	4.30 ^b	0.06 ^d	0.05 ^d	0.02 ^d	0.07 ^d
T2	8.59 ^a	60.28 ^a	18.55 ^a	0.50 ^a	0.04 ^a	6.16 ^a	0.43 ^a	0.72 ^a	0.39 ^a	11.36 ^a
T3	7.13 ^b	20.13 ^b	7.80 ^b	0.40 ^a	0.05 ^a	6.06 ^a	0.24 ^b	0.47 ^b	0.26 ^b	3.45 ^b
T4	6.37 ^c	14.48 ^c	4.12 ^c	0.30 ^a	0.03 ^a	5.92 ^a	0.19 ^c	0.29 ^c	0.16 ^c	1.78 ^c

(Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test ($P=0.05$). ($n=3$). (EC: electrical conductivity, CEC: cation exchange capacity).

Table 10. Chemical properties of different treatments used under the study

Heavy metal concentrations of the different amendment mixtures are given in Table 11. The Cu, Cr, Mn, Zn and Pb concentrations were higher in the amendment mixtures compared with original red soil. Se and Cd were not detected in any treatments, and As was detected only in T2. Heavy metal concentrations of the amendment mixtures were generally well below the maximum pollutant concentration of individual metals for land application suggested by the US Environmental Protection Agency (USEPA, 1993). The average concentrations of heavy metals reported in uncontaminated soils are (all in mg kg^{-1}): As 6, Cr 70, Cu 30, Zn 90, Pb 35, Mn 1000, and Cd 0.35, respectively (Adriano, 2001). The heavy metal concentrations in all amendment mixtures in this experiment were generally below the heavy metal concentrations reported in uncontaminated soils. Kim et al. (1994) reported that heavy metals did not accumulate in a paddy soil following CFA addition at 120 Mg ha^{-1} . Though the concentrations of heavy metals were below uncontaminated soil

values and not alarming, there should be routine inspections to ensure that heavy metal concentrations remain within safe limits.

Treatments	Cu (mgkg ⁻¹)	Cr (mgkg ⁻¹)	Zn (mgkg ⁻¹)	Pb (mgkg ⁻¹)	Cd (mgkg ⁻¹)	Se (mgkg ⁻¹)	As (mgkg ⁻¹)	Mn (mgkg ⁻¹)
T1	11.7 ^b	5.8 ^b	29.8 ^b	5.6 ^b	ND	ND	ND	20.7 ^a
T2	19.77 ^a	7.1 ^a	44.2 ^a	9.4 ^a	ND	ND	0.1	21.1 ^a
T3	18.54 ^a	6.7 ^a	40.6 ^a	8.3 ^a	ND	ND	ND	20.8 ^a
T4	13.65 ^b	5.9 ^b	35.1 ^b	6.7 ^b	ND	ND	ND	20.3 ^a
USEPA	1500	1200	2800	300	39	36	41	-
Y*	30	70	90	35	0.35	0.4	6	1000

(Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test ($P=0.05$). (n=3). USEPA =US Environmental Protection Agency standards (1993). Y*: uncontaminated soil (* Adriano, 2001), ND; not detected

Table 11. Heavy metal concentrations of different amendment mixtures.

4.1.1.2.2.2 Influence of CSA as a soil amendment in red soil for Komatsuna cultivation

The growth parameters and the nutrient contents in Komatsuna grown in red soil with different ratios of CSA additions are shown in Table 12. CSA as a soil amendment significantly increased growth and yield parameters of Komatsuna (*Brassica rapa*) compared with the red soil control (T₁). The CSA: soil of 1:5 (T₃) and 1:10 (T₄) increased plant height and fresh weight yield of Komatsuna about three and 12 times, respectively. The CSA: soil of 1:1 (T₂) increased plant height and fresh weight yield by approximately two times and four times, respectively. These yield increases were due to the enhanced physical and chemical properties of the soil from CSA amendment. The CSA addition also enhanced water holding capacity, hydraulic conductivity, CEC and pH compared to original soil, which created a conducive environment to attain higher crop growth and yield parameters. The CSA: soil of 1:5 (T₃) and 1:10 (T₄) increased soil pH from acidic 5.12, to 7.13 and 6.37, respectively (Table 10). The CECs of T₃ and T₄ were 40 and 37% higher than the original soil due to CSA incorporation. In a previous study it was reported that, mixed application of CFA and paper factory sludge caused appreciable change in soil physical and chemical properties, increased pH and increased rice (*Oryza sativa*) crop yield (Molliner & Street, 1982). In addition, a mixture of CFA with organic matter is expected to further enhance biological activity in soil (Jala & Goyal, 2006), reduce leaching of major nutrients and beneficial for vegetation (Tripathi et al., 2004).

The nutrient content of plants grown in different substrates is given in Table 12. The N content in shoot tissues from the CSA-amended mixtures was higher than that of the red soil (Table 12). CFA in CSA generally increases plant growth and nutrient uptake (Aitken et al., 1984), and has been shown to supply essential nutrients to crops on nutrient deficient soils and to correct deficiencies of Mg, Ca, K, molybdenum, sulfur and Zn (El-Mogazi et al., 1988). The decreased P content in shoot tissues obtained from red soil is probably due to reduced P availability at a higher soil pH and higher Ca content following CFA amendment (Wong & Wong, 1990). The CSA: soil of 1:1 gave an alkaline pH of 8.59, which did not

Treatments	Plant height (cm)	Fresh weight (gpot ⁻¹)	Dry weight (gpot ⁻¹)	N (%)	P (%)	K (%)	Mg (%)	Ca (%)	Cu (mgkg ⁻¹)	Mn (mgkg ⁻¹)	Zn (mgkg ⁻¹)	Pb (mgkg ⁻¹)
T1	7.25 ^c	3.84 ^c	0.29 ^c	1.46 ^c	0.56 ^a	2.9 ^c	0.6 ^c	0.5 ^b	3.0 ^a	92.64 ^a	30.4 ^d	0.4 ^a
T2	14.36 ^b	15.19 ^b	2.91 ^b	1.87 ^b	0.26 ^d	3.8 ^a	1.5 ^a	4.5 ^a	3.2 ^a	39.74 ^d	36.7 ^a	0.5 ^a
T3	23.44 ^a	46.95 ^a	8.87 ^a	2.21 ^a	0.32 ^c	3.6 ^{ab}	1.4 ^{ab}	4.4 ^a	3.1 ^a	50.12 ^c	35.2 ^b	0.5 ^a
T4	21.03 ^a	43.59 ^a	7.25 ^a	2.18 ^a	0.44 ^b	3.4 ^b	1.2 ^b	4.3 ^a	3.3 ^a	54.16 ^b	34.1 ^c	0.4 ^a

(Means followed by the different superscript letter in the same column differed significantly according to Duncan's multiple range test ($P=0.05$).($n=3$).

Table 12. The growth parameters and the nutrient content in the Komatsuna plants.

improve growth and yield parameters of Komatsuna, which needs a pH of 6.0–7.5 for healthy growth. It is likely that the high pH (8.59), high EC (60.28 mS m⁻¹) and its related nutrient bioavailability accounted for the reduced growth and yield parameters of Komatsuna in the T2 treatment compared with T3 and T4. High pH of substrate can sharply decrease availabilities of P, iron (Fe) and Mn (Peterson, 1982). The lowest shoot concentration of Mn was given by plants grown in T2 treatment (Table 12). Similar results were found in a previous study conducted using CFA as an amendment to container substrate for *Spathiphyllum* production by Chen & Li (2006). The growth and yield parameters of Komatsuna grown in red soil were significantly lower than the CSA-amended treatments. Red soil had acidic pH of 5.12, which can decrease plant availability of Ca and Mg but increase solubility of micronutrients. Shoot concentrations of Ca and Mg were lower but Mn was higher in plants grown red soil (T1) than those grown in CSA addition treatments (Table 12). Additionally, low pH was reported to directly affect the permeability of root cell membranes and leakage of various ions from roots (Yan et al., 1992). Moreover, the K, Mg and Ca concentrations of shoots in the CSA mixtures significantly increased because CSA was enriched with these elements. Both shoot K, Ca and Mg contents were all above the deficiency limits of 0.7-1.5 % (Chapman 1966), 0.14 % (Loneragen & Snowball, 1969) and 0.06 % (Chapman, 1966), respectively. The highest Mn concentration was reported in the shoots from the red soil. Nevertheless, the Mn concentrations were much higher than the diagnostic deficiency level of 20 mg kg⁻¹ (Chapman 1966). Zn concentrations in the CSA mixtures were higher than in red soil but well below the toxicity limit of 150 mg kg⁻¹ (Elsewi et al., 1980). Se and Cd were not detected in any tissues. Therefore heavy metal content in plant tissue was below the toxicity limits. CSA as a soil amendment can be suggested as a good practice for Komatsuna production in this low-productive acidic red soil, due to enhanced soil physical and chemical properties. The CSA: soil of 1:5 and 1:10 gave the maximum growth and yield parameters of Komatsuna.

4.1.1.3 Other types of coal fly ash based aggregates as a soil ameliorant

CFA based aggregates can be developed by including oil palm waste and coco fiber and also can be used as a soil amendment to improve low productive red soil to enhance crop production. Since CFA aggregates did not contain high N content, aggregates can be developed by adding N fertilizer source to the aggregates and those aggregates can be used as a fertilizer and a soil ameliorant for crop production. One of our experiments (Jayasinghe et al., 2009b) showed that these kind of N added aggregates improved physical and chemical properties of low productive acidic soil and improved the growth and yield parameters of Komatsuna in red soil compared to original soil. In addition, homogenous

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