

**STUDY ON SUSTAINABLE BANANA WASTE MANAGEMENT THROUGH
COMPOST AND BIOCHAR PRODUCTION FOR SOIL AMELIORATION AND
ENVIRONMENT PRESERVATION**

(土壤改良と環境保全のための堆肥化，炭化处理によるバナナ廃棄物の持続的管理に
関する研究)

Frank KALEMELAWA

JUNE 2013

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A DOCTORAL THESIS

BY

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GOD BLESS

CHAPTER 1

GENERAL INTRODUCTION

1.1 Overview

This thesis covers principles and aspects of two concepts (i.e. compost and biochar production) with potential for sustainable and profitable management of banana wastes. **Figure 1** shows a summarized schematic diagram on background and overall goal of this work.

1.2 Soil fertility situation in Sub-Saharan Africa

Sub-Saharan Africa faces severe soil-fertility depletion problems causing rapid decline in per capita food production and increase in poverty, especially among smallholder farms. Nutrient depletion is most intense in East Africa due to high nutrient-mining in harvested products, erosion and the relatively low inherent fertility of the soils (Stoorvogel et al. 1993). Losses of 130 kgN, 5 kgP and 25 kgK ha⁻¹ per year have been reported in the East African highlands (Smaling et al. 1997). Use of inorganic fertilizers for soil nutrient replenishment by smallholder farmers in Africa is still very low due to socio-economic constraints; it is estimated to be less than 10 kg ha⁻¹year⁻¹, and even less in Uganda (Heisey and Mwangi, 1996; Mwangi, 1997). The ever increasing mineral fertilizer cost is likely to further reduce the already low mineral fertilizer usage in Sub-Saharan African countries, thus deepen food crisis in the region. It is therefore important to seek alternative cost effective and environmentally sustainable agricultural technologies that use less mineral fertilizers. The goal therefore, should be to provide as much of the nutrients as possible through organic

materials, making up the shortfall of the limiting nutrients through inorganic fertilizers. This would enhance both soil fertility and better environment preservation.

1.3 State of banana and banana waste production

Bananas and plantains constitute the fourth most important global food commodity (after rice, wheat and maize) grown in more than 100 countries over a harvested area of approximately 10 million hectares, and with an annual production of 88 million tonnes (Frison and Sharrock, 1999). The all year round fruiting habit of bananas puts the crop in a superior position in bridging the 'hunger gap' between crop harvests. It therefore contributes significantly to food and income security of people engaged in its production and trade, particularly in developing countries. In Africa they provide more than 25% of the carbohydrate requirements for over 70 million people (IITA, 1998). Eastern and Southern Africa produces over 20 million tonnes of bananas which accounts for 25.58% of total world output (Karamura et.al. 1999). The Great Lakes region covering parts of Uganda, Rwanda, Burundi, Tanzania, Kenya and DRC is the largest producer and consumer of bananas in Africa (Smale, 2006) where *per capita* consumption has been estimated at more than 250 kg; the highest in the world (FAO, 1985). Uganda ranks among the top twenty World-leading producers of banana, with an annual output of 610,000 Metric tonnes (FAOSTAT, 2000) (**Figure 2**). Over ninety percent is consumed domestically thereby generating large volumes of wastes; Peelings are estimated at 390,550 Mt annually (Sentongo and Munyagwa, 2004). Cultivation is mainly done in the Countryside and the harvested fruits transported, along with inedible parts to towns and cities where upon or during processing, marketing and consumption generate massive amounts of wastes.

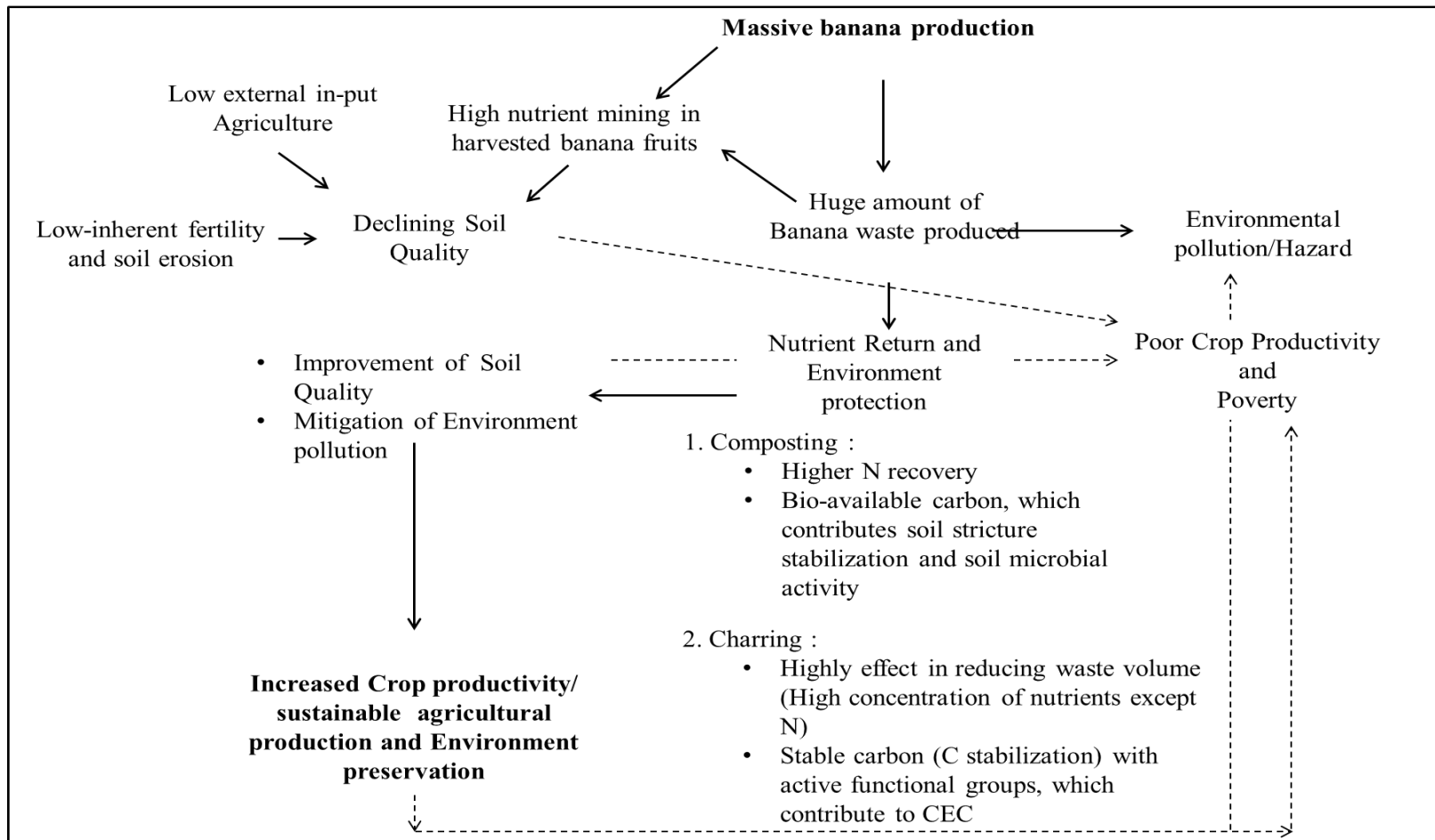


Figure 1. Schematic of study background

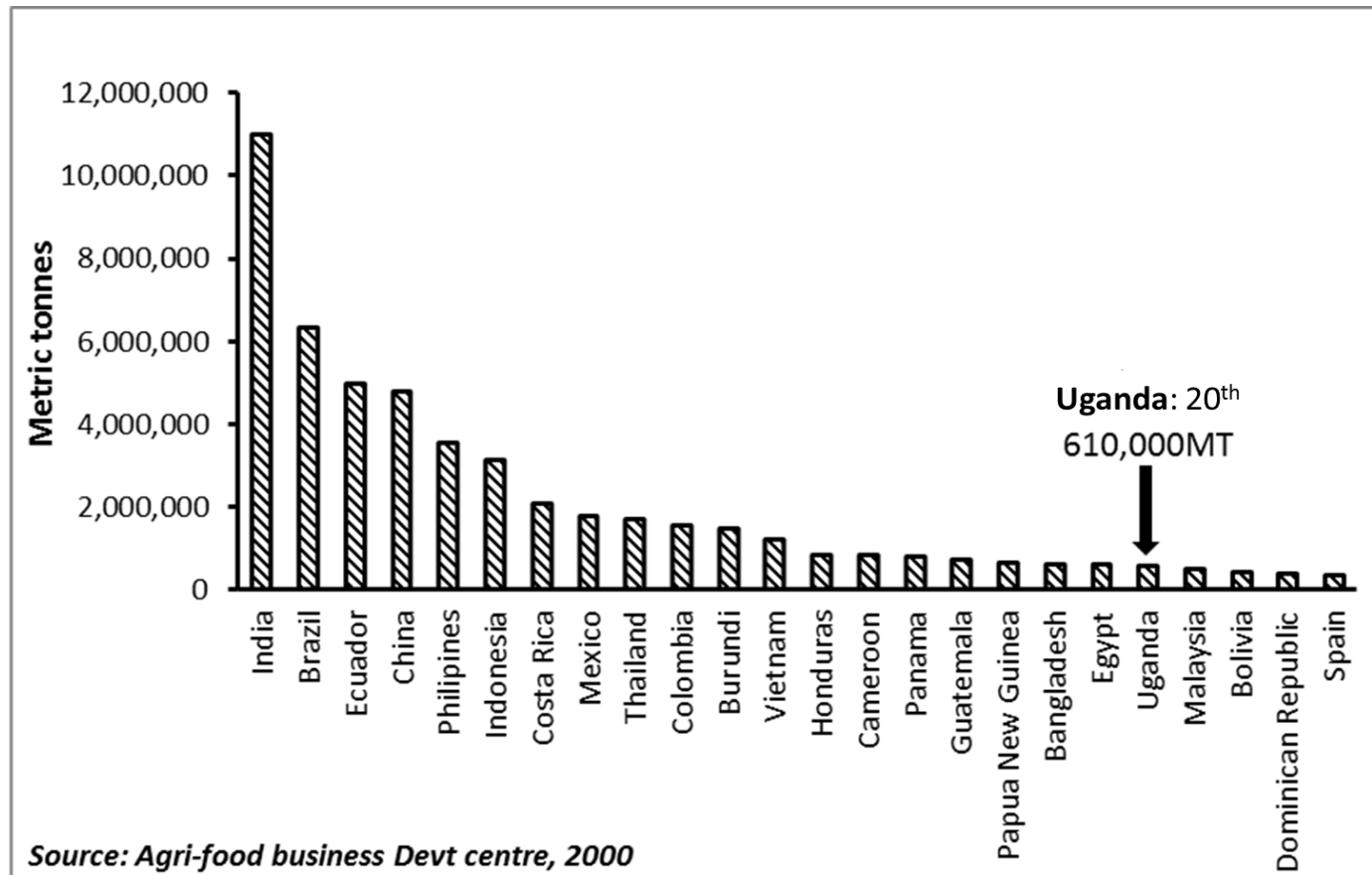


Figure 2. World-leading banana producers

1.4 Current waste management practices and related problems

In most developing countries such as Uganda, solid waste is traditionally disposed of through landfills and dumping in unregulated grounds and water bodies (lakes, Rivers). This yields several environmental drawbacks such as odor, poor hygiene, and damage to vegetation and ground/surface-waters as well as risk to nearby citizens who come in contact with landfill gases. In extreme cases it is known that houses have exploded because of seepage of landfill gas ignited by a spark (Christensen, 1998). Also, Methane (CH₄), a potent greenhouse gas (GHG), can be formed as a by-product of microbial respiration reactions that occur when organic materials decompose under anaerobic conditions. Organic waste deposited in landfills produce significant quantities of methane gas and biogenic carbon dioxide (CO₂), as well as other trace gases. The resulting CH₄ component of the landfill gas will eventually be released to the atmosphere.

1.5 Potentially viable waste management strategies

In recent years sustainable management of organic waste has focused on exploitation of the fertilizer value and energy content of the wastes materials, rather than just garbage for disposal. Compost and biochar production are such technologies that have gained interest as viable pathways for sustainable management of organic wastes due to their environment friendliness, effective pollution control potential, and ability to yield valuable by-products such as fertilizer, biofuels and biochemicals.

1.5.1 Composting

Composting is the bio-oxidative decomposition organic matter to produce a stabilized product which can be used to improve and maintain soil quality and fertility. During composting, microorganisms decompose the substrate by breaking it down from complex to simpler compounds (Sayara et al. 2010). Composting can significantly reduce waste volume in various composting systems (Peigne and Girardin, 2004). From the viewpoint of green-recycling in the ecosystem, composting is an environmentally and economically sound practice. It uses naturally occurring microorganisms to convert biodegradable organic matter into a humus-like product (Liao et al. 1993; Sims, 1994; Georgacakis et al. 1996). The process destroys pathogens, converts N from unstable ammonia to stable organic forms, reduces the volume and improves the nature of the waste (Liao et al. 1994a, b; Sims, 1994; Kashmanian and Rynk, 1995; Georgacakis et al. 1996; Sequi, 1996). The produced product with humus-like properties can be applied as a fertilizer, organic amendment or growing medium, improving soil physical properties and increasing both water retention and the supply of essential nutrients (McConnell et al. 1993; Jakobsen, 1995; Hargreaves et al. 2008; Martinez-Blanco et al. 2009). The effect of particular plant residue composts on soil properties however, depends on its dominant nutrient components (Chaves et al. 2004). **Tables 1 and 2** show physiochemical characteristics of composts from selected crop-waste biomass sources. Rice and pearl mill straw, and sorghum residues contain high K (1.5–2.5%), while rice bran, peanut hull and coconut shell composts could be useful as a N fertilizers. Information on banana waste-based compost however remains scanty; therefore composting of banana wastes to produce a stable fertilizer resource needs to be investigated as an alternative waste management pathway to landfilling, for potential benefit to the resource- poor farmers of East Africa.

Table 1. Physiochemical properties of compost prepared from different crop residues

	C:N ratio	OM	C	N	P ₂ O ₅	K ₂ O	CaO	MgO	SiO ₂
%									
Rice straw	78-88		54-56	0.64-0.69	0.05-0.11	2.0-2.1	0.42-1.2	0.3-0.52	4.9
Rice hull	70-106		39-52	0.48-0.70	0.11-0.46	0.28-1.30	0.21-0.34	0.09-0.4	12.7
Rice bran	18-22	67-78	50-55	2.0-2.4	3.60-4.47	1.43-2.45	0.13-0.35	1.11-1.78	
Corn stalks	68		55	0.81	0.37	1.61	0.35	0.48	4.1
Sorghum stalks	73		53	0.73	0.25	1.94	0.60	0.62	3.9
Soybean stems	40		51	1.28	0.14	1.63	0.18	0.15	2.9
Peanut stems	30		42	1.30	0.37	1.31	1.97	0.15	2.5
Peanut hull	28		49	1.73	0.37	1.27	1.96	0.77	1.8
Coconut shell	37	96	53	1.43	0.18	0.50	0.36	0.20	

Source: Fertilizer guideline 2001

Table 2. Nutrient content of compost prepared from different crop residues

	N	P	K
	%		
Pearl millet straw	0.65	0.75	2.50
Cotton wastes	0.44	0.10	0.66
Sorghum	0.40	0.23	2.17
Maize straw	0.42	1.57	1.65
Paddy straw	0.36	0.08	0.71
Tobacco	1.12	0.84	0.80
Pigeon pea stalk	1.10	0.58	1.28
Sugarcane trash	0.53	0.10	1.10
Wheat straw	0.53	0.10	0.10

Source: manhmairaja et al 2008

Table 3. Characteristics of biochar from different biomass

S.No	characters	Paddy straw	Maize stover	Coconut shell	Groundnut shell	Coir waste	Prosopis wood
1	pH (1:5 solid:water suspension)	9.7	9.4	9.3	9.3	9.40	7.57
2	EC (dSm ⁻¹) (1:5 solid:water suspension)	2.4	4.2	0.7	0.4	3.25	1.30
3	Cation Exchange Capacity (cmol(+))kg ⁻¹)	8.2	6.5	12.5	5.4	3.20	16.00
4	Exchangeable acidity (mmol kg ⁻¹)	22.0	27.0	32.0	14.0	9.50	49.00
5	Total organic carbon (g kg ⁻¹)	540.0	830.0	910.0	770.0	760.00	940.00
6	Total Nitrogen (g kg ⁻¹)	10.5	9.2	9.4	11.0	8.50	1.12
7	C:N ratio	51.4	90.2	96.8	70.0	89.40	83.90
8	Total Phosphorus (g kg ⁻¹)	1.2	2.9	3.2	0.6	1.50	1.06
9	Total Potassium (g kg ⁻¹)	2.4	6.7	10.4	6.2	5.30	29.00
10	Sodium (g kg ⁻¹)	14.0	21.5	16.8	5.2	9.60	38.00
11	Calcium (g kg ⁻¹)	4.5	5.6	8.5	3.2	1.80	11.00
12	Magnesium (g kg ⁻¹)	6.2	4.3	5.8	2.1	1.40	0.36

Values are mean of triplicate sample

Source: International Journal of Plant, Animal and Environment Science (www.ijpaes.com)

1.5.2 Biochar production

“Biochar” is a term used to describe the application of charred organic material to soil in a deliberate manner to either improve soil properties or to store carbon. It is a product of incomplete combustion of biomass in the absence of oxygen. It can serve as base product for production of nitrogen fertilizer (Marris, 2006), be treated with steam to generate activated carbon (McHenry, 2008) and has been suggested as a farm fertilizer (Lehmann, 2007) and as a way to improve forest productivity (Dumroese et al. 2009). As a soil amendment, biochar can increase water-holding capacity, reduce bulk density, provide additional cation exchange sites, and serve as a source of reduced carbon compounds that may benefit microbial populations (Lehmann et al. 2006; DeLuca and Aplet, 2008; Warnock et al. 2007), all of which promote plant growth. The chemical structure of charcoal is characterized with poly-condensed aromatic groups, providing prolonged biological and chemical stability that sustains the fight against microbial degradation; it also provides, after partial oxidation, the highest nutrients retention. Biochar adds some macro- (P, K, N, Ca, Mg) and micronutrients (Cu, Zn, Fe, Mn) to the soil, which are needed for sustainable agriculture (Glaser et al., 2002; Mankasingh et al., 2009). Nutrient supply potential of biochar from selected biomass sources is shown in **Table 3**. Biochar has also demonstrated potential as a tool for carbon sequestration (Lehmann et al. 2006) The aromatic nature of the charcoal formed by burning natural organic biomass is recalcitrant and has the potential for long-term C sequestration in soil (Atkinson et al. 2010) and therefore biochar offers the chance to turn bioenergy into a C-negative industry (Lehmann, 2007). The long-term stability of the biochar was demonstrated to be greater compared to non-pyrolyzed organic matter that was incorporated into soils with the same environmental conditions (Baldock and Smernik, 2002; Six et al. 2002; Liang et al. 2008); this phenomenon is illustrated in **Figure 3**. Biochar has an approximate mean residence time in the soil of more than 1000 years (Cheng et al. 2008); this long-term stability

is an essential factor in its potential utilization as a carbon sequestration agent. Meanwhile, the greatest positive effects of biochar application have been in highly degraded, acidic or nutrient-depleted soils such as the highly weathered tropical African soils (Lehmann et al. 2006). Soils in tropical regions retain less C than temperate soils, yet they support much of the world's agriculture and approximately 40% of the world's population; Tropical soils also lose soil organic matter more quickly than temperate soils due to faster mineralisation under tropical conditions (Glaser et al. 2002). Thus, biochar research is of particular relevance in the Sub-Saharan context, as many soils there exhibit very low nutrient and carbon levels. Biochars however, are not created equal; the efficiency and effectiveness of the process of their creation (as influenced by factors such as pyrolysis temperature, holding-time and MC), and the specific biomass sources used and this can affect the proportion and composition of nutrients, and thus the characterization and usability of the biochars (DeLuca and Aplet, 2008).

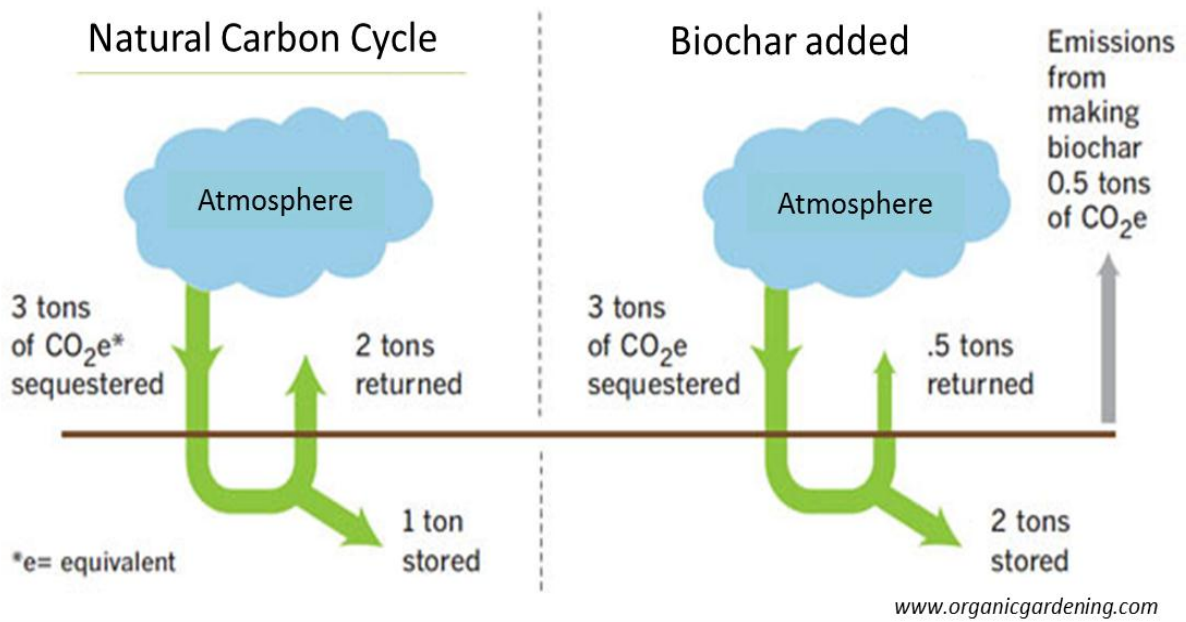


Figure 3. Biochar stability as compared to unpyrolysed/natural organic material

1.6 Overall scope and study objectives

Scope

This study covers and provides baseline data on the physiochemical characteristics of banana waste-based compost and biochar pertinent to potential utilization in soil quality improvement and environment preservation (Schematic diagram of study is presented in **Figure 4**).

Objectives

- Evaluate and recommend optimum composting and biochar production conditions for soil improvement and environment preservation
- Characterize banana residue based compost and biochar as agents for soil amendment and environment preservation

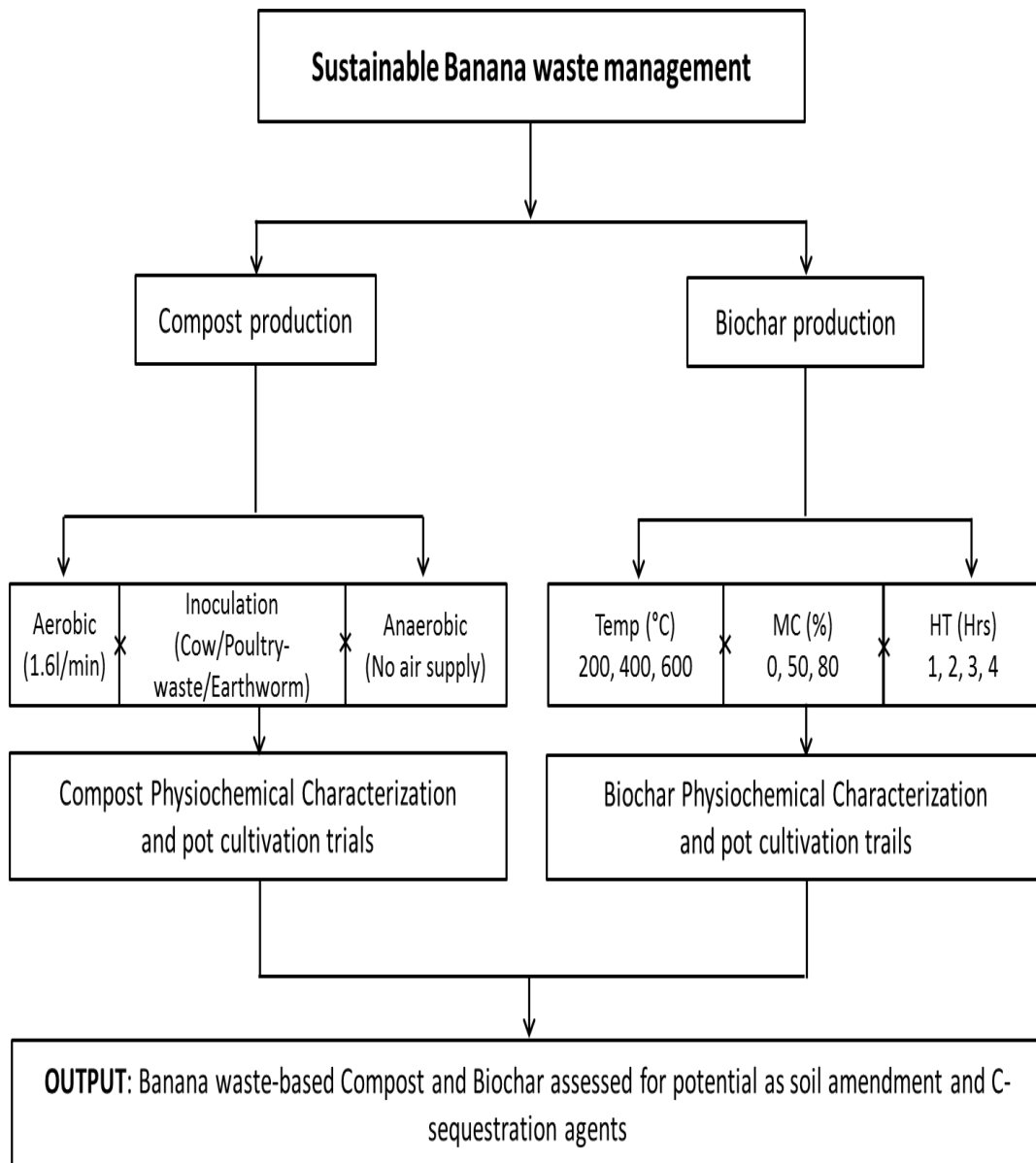


Figure 4. Summarized plan of study

CHAPTER 2

An evaluation of aerobic and anaerobic composting of banana peels treated with different inoculums for soil nutrient replenishment

2.1. Introduction

Application of crop residue compost to soil is considered a good management practice because it stimulates soil microbial growth and activity with subsequent mineralization of plant nutrients (Eriksen, 2005). The effect of particular crop residue composts on soil properties widely varies depending on dominant nutrient component present (Chaves et al. 2004). This study sought to determine the dominant mineral nutrient component of banana residue-based compost. Additionally, smallholder farmers in Uganda use simple local composting techniques such as pit or aboveground piling methods to compost animal and household wastes. Pit composting largely creates anaerobic conditions within the pit that may result into slow stabilization rate (Hudgins and March, 1998). On the contrary, aboveground piling method, usually done under shade, presents aerobic composting conditions since air currents constantly blow through the pile. The effect of pit (anaerobic) and heap (aerobic) composting on the quality characteristics of banana residue-based compost is however, still largely unknown.

Previous composting studies reported addition of various substrates as starters to enhance decomposition; the actions of earthworms have been extensively studied and include: substrate aeration, mixing, grinding, fragmentation, enzymatic digestion and microbial decomposition of substrate in intestine of earthworms (Sharma et al. 2005). Addition of urea for reducing the C/N ratio of crop waste has been practiced in the past

(Gaind and Gaur, 2000), but the recent inclination towards organic farming requires the use of nitrogen rich organic wastes that can substitute the chemical source of nitrogen. Poultry litter and cow dung are such wastes that may fit in the category of organic nitrogen supplements (low C/N ratio <12); moreover, these are widely available on most Ugandan farms. This study also assessed the effect of inoculation on the quality of banana residue-based compost.

Summarily, this work aimed to evaluate the efficacy of aerobic and anaerobic composting methods for banana peels and the effect of poultry litter, cow dung and earthworm as starter inoculums on composting, as well as to determine the dominant mineral nutrient components of banana residue-based compost.

2.2. Materials and Methods

2.2.1. Composting materials

Fresh banana peels were collected from Yamazaki Baking Co.Ltd, Okayama, Japan, and used as the major constituents of the compost mass. Partially composted cow dung and poultry litter were procured from the Field Science Centre, Faculty of Agriculture-Tottori University, and a local poultry farm in Tottori prefecture, Japan respectively, while the earthworms *Lumbricus terrestris*, a commercial product (MARUNICHI 21 Ltd., Japan) were purchased from a local market. The cow dung and poultry litter were air-dried and ground prior to use in this experiment. A summary of selected physico-chemical characteristics of the original materials prior to composting is presented in **Table 4**.

Table 4. Selected physiochemical properties of original materials prior to composting

Parameter	pH	EC (dSm ⁻¹)	Total mineral nutrients (g kg ⁻¹) air-dried					
	Compost:Water mixture 1:10,w/v		C	N	P	K	Ca	Mg
Banana peel	9.2±0.20	0.5±0.08	315±1.10	10.5±0.29	0.22±0.02	66.4±3.12	2.11±0.50	1.02±0.03
Cow dung	6.6±0.12	11.1±0.05	310±1.18	23.1±0.23	2.41±0.07	38.6±2.12	22.63±0.38	6.91±0.15
Poultry litter	7.7±0.10	10.0±0.03	321±0.98	42.5±0.18	14.80±0.73	17.6±1.13	51.91±0.81	8.63±0.09

Values are means ±SD of three replicates

2.2.2. *Experimental apparatus*

Mini- ten-liter (14 cm × 30 cm × 24 cm) styrene foam boxes were used to simulate aerobic and anaerobic composting conditions under laboratory conditions. For the aerobic setup, boxes were fitted with a 10 mm-diameter vent pipe at the top and a 3 mm air-supply tube connected to a 1.5 L. min⁻¹ air pump (Chikara α 1500, Nisso-int. Co, Japan) at the bottom. Air supply rate in the compost mass was maintained at 0.3 L min⁻¹ kg⁻¹ organic matter as recommended by Li et al. (2008), while the boxes under anaerobic composting were completely sealed. Both setups were fitted with portable automatic thermal recorders (TR-71U, T & D Co., Japan) mid-way into the compost mass.

2.2.3. *Composting procedures*

Fresh banana peels were withered to 60% moisture content under natural atmospheric conditions for about 4 weeks, chopped into small pieces of 2–5 cm in length and 5 kg aliquots placed in the two different sets of compost boxes. These were then inoculated and thoroughly mixed with 0.5 kg of either cow dung (C), poultry litter (P) or earthworm (E) at 1.6 kg m⁻³ density to obtain the following formulations: (i) plain banana peels (B) serving as control, (ii) banana peel + cow dung (BC), (iii) banana peel + poultry litter (BP) and (iv) banana peel + earthworm (BE). The two composting conditions, three formulations along with the control were then replicated three times, to give twenty-four sampling units. These were arranged in a randomized complete block design (RCBD) in a temperature-controlled room set at 40°C for a period of 12 weeks. In the aerobic setup, materials were turned weekly to allow uniform airflow throughout the composting period. Moisture content was periodically replenished at 60% using the weighing method.

2.2.4. Chemical analysis

Prior to composting, the original materials were analyzed for physicochemical characteristics: pH, electrical conductivity (EC), total nitrogen (TN), total carbon (TC) and total mineral nutrients: (Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg)). The banana peels were air dried and separately milled along with the cow dung and poultry litter. The pH and EC of samples were measured in 1:10 compost-water extracts using pH and EC meters (Models HM-30S and CM-30R-DKK, TOA electronics Ltd, Japan), respectively. Total C and N were determined by dry combustion method using an automated C-N coder (Model MT 700 Yonaco, Japan). Total mineral nutrients: P, K, Ca and Mg were determined after digestion with a H_2O_2 – H_2SO_4 mixture. Total P in the digest was determined colorimetrically on a spectrophotometer (Model U-2001, Hitachi Co., Japan) using phosphomolybdate blue method (Murphy and Riley, 1962); while total K, Ca and Mg were measured using an atomic absorption spectrophotometer (Model Z-2300, Hitachi Co., Japan).

To monitor the composting progress, the following qualitative parameters were measured: compost temperature, C/N ratio, pH, EC, available mineral nutrients (ammonium nitrogen (NH_4^+ -N), nitrate nitrogen (NO_3^- -N), P, K, Ca, and Mg). Temperature in the compost masses was recorded using automatic thermal recorders (TR-71U, T&D corp., Japan). To analyze other parameters, composite subsamples were collected from five symmetrical locations of each box at day 0 and then bi-weekly until the end of the twelve-week composting period. Collected samples were divided into two parts: one was oven dried, milled and analyzed for TC and TN by the method described earlier, while the second part was stored at 4°C and used for analysis of pH, EC, available mineral nutrients: NH_4^+ -N, NO_3^- -N, P, K, Ca, and Mg. The pH and EC were determined using the same procedure already described above; while NH_4^+ -N and NO_3^- -N were determined colorimetrically after extraction with KCl solution (1:10 w:v) using spectrophotometer (Spec model U-2001,

Hitachi Co., Japan) at 635 nm and 410 nm, respectively. Available P was determined colorimetrically in NaHCO_3 at 710 nm according to Olsen and Sommers (1982), while available K, Ca and Mg were quantified on atomic absorption spectrophotometer (Model Z-2300 Hitachi Co., Japan) after leaching with neutral $\text{CH}_3\text{COONH}_4$ (Albuquerque et al. 2004).

2.2.5 Compost maturity

Ultraviolet-visible (UV-vis) spectra of alkali compost extracts (1:50 - 0.5M NaOH) at Abs 350, A400 and A600 nm (A350, A400 and A600) were recorded on a UV-2200 (Shimadzu, Japan) spectrophotometer after shaking for 1 hour at room temperature. Spectrophotometric parameters; Humification index (HI) and decomposition index (DI) of the samples were calculated using the formulae; $\text{HI} = \text{A400}/\text{A600}$; $\text{DI} = \text{A350}/\text{A400}$ (Yamamoto et al. 2000).

2.2.6. Pot cultivation

A pot experiment was conducted on a sandy soil (nutrient-poor) under controlled laboratory conditions to evaluate the potential of banana peel-based compost as a source of K and N fertilizer. Sorghum, which requires $150 \text{ kgNPK ha}^{-1}$ was cultivated on a sandy soil in 100 cm^2 Wagner pots in a growth chamber (Koitoiron HNH-S20, Japan) set at 22°C , 80% RH. There were two main sets of treatments, where the required nutrients: 150 kgK ha^{-1} - potassium base (K-base) and 150 kgN ha^{-1} - nitrogen base (N-base) were supplied entirely using compost. In both cases, aerobically composted materials were used as they had showed better qualities as compared to those from anaerobic composting. The deficient mineral nutrients were then topped using inorganic sources. Each pot was seeded with 10 sorghum

seeds, watered and soil moisture routinely maintained at 60% by the weighting method; thinning was done at 14 days, leaving only 4 seedlings per pot. A summary of pot treatment permutations is shown in **Table 5**, while detailed fertilizer and compost mix ratios are shown in **Table 6 (a, b)**. Crop emergence was taken at 5, 6 and 7 days after planting as a percentage of seeds that sprouted. During growth, variation in leaf area index (LAI) was monitored at a 4 day interval for 3 weeks after germination. Leaf area was taken as a product of maximum leaf length and width, and then divided by area covered by the seedlings (area of Wagner pots) in order to obtain LAI. Soil characteristics after cultivation were assessed following standard procedures already described in preceding sections.

2.3 Statistical analysis

Experimental data presented are the means of three replicates; Statistical analyses were executed using Stat View software. One-way analysis of variance (ANOVA) was used to test for treatment significance and mean differences were compared using Fisher's protected least significant difference (LSD) at 5%. In addition, principal component analysis (PCA) was performed to elucidate total data variability with respect to correlation-ships between formulations, different physicochemical characteristics and composting conditions with composting time using XLSTAT 2011. Each formulation was treated as categorical data, converted to dummy variables and PCA performed along with other variables. Due to very low cumulative contribution ratio, some dummy variables were omitted.

Table 5. Summarized Pot fertilizer and compost treatment permutations

Treatment		K-from compost (kgK/ha)	Compost (t/ha Fresh wt)	Chemical (kg/ha)	N-from compost kgN/ha	Compost (t/ha Fresh wt)	Chemical (kg/ha)
	CTRL	0	0	0	0	0	0
Base	CHEM	0	0	150NPK	—	—	—
K-base	Ba	150	5.2	150NP	52	—	—
	BCa	150	5.3	150NP	53	—	—
	BPa	150	5.2	150NP	52	—	—
N-base	Ba	433	—	—	150	15.0	150P
	BCa	424	—	—	150	15.0	150P
	BPa	392	—	—	150	13.6	150P

Table 6. Detailed Pot fertilizer treatment permutations

(a)

K-Base											
Soil treatment	K content in compost (g/kg)	K required in pot (g)	Compost needed (g)	N contained in compost (g)	N required in pot	N needed from (NH ₄) ₂ SO ₄	(NH ₄) ₂ SO ₄ added (g)	P content in compost	P required in pot (g)	P needed from (NH ₄) ₂ HPO ₄ (g)	(NH ₄) ₂ HPO ₄ added (g)
Ba K-base	139.4	0.15	1.08	0.02	0.15	0.13	0.61	0.0022	0.15	0.15	0.63
BCa K-base	121.0	0.15	1.24	0.03	0.15	0.12	0.59	0.0025	0.15	0.15	0.63
BPa K-base	123.9	0.15	1.21	0.03	0.15	0.12	0.58	0.0024	0.15	0.15	0.63
Chemical	–	0.15	0.00	–	0.15	0.15	0.71	–	0.15	0.15	0.64
Control	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.0000	0.00	0.00	0.00

(b)

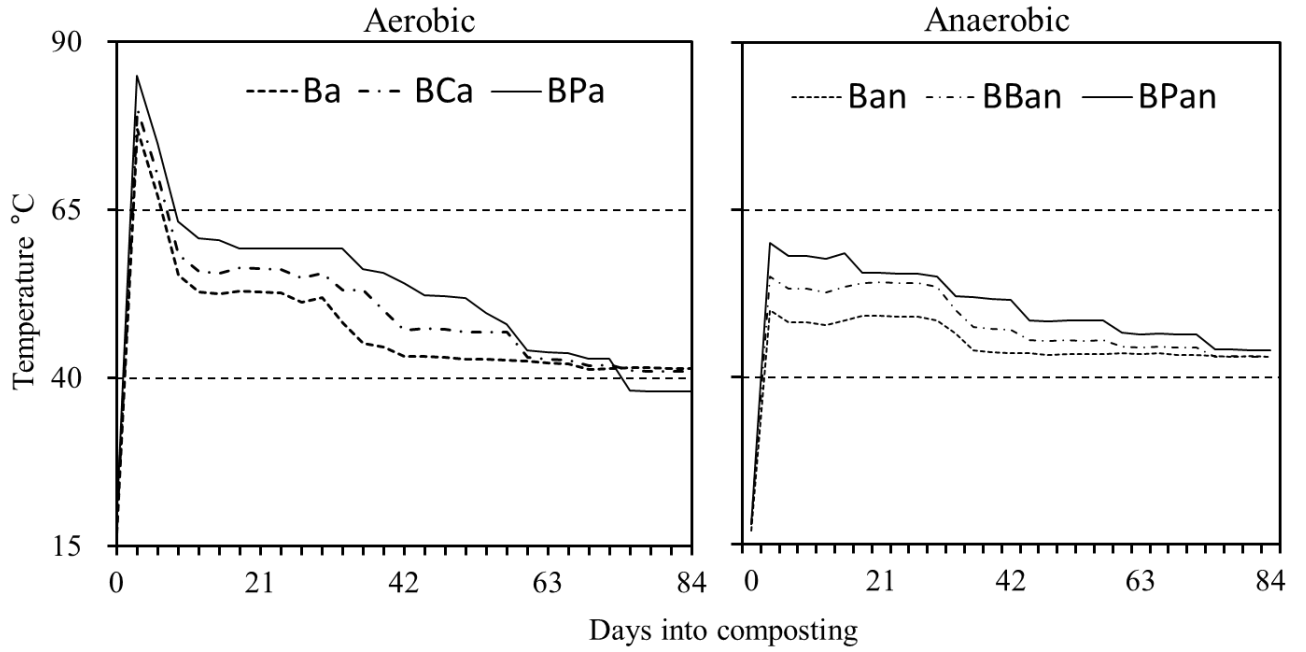
N-Base											
Soil treatment	N content in compost (g/kg)	N required in pot (g)	Compost needed (g)	K ₂ O contained in compost (g)	K required in pot	K needed from (K ₂ SO ₄)	K ₂ SO ₄ added (g)	P content in compost	P required in pot	P needed from (NH ₄) ₂ HPO ₄ (g)	(NH ₄) ₂ HPO ₄ added (g)
Ba N-base	20.0	0.15	7.50	0.44	0.15	-0.29	–	0.015	0.15	0.14	0.58
BCa N-base	21.0	0.15	7.14	0.41	0.15	-0.26	–	0.017	0.15	0.13	0.57
BPa N-base	22.0	0.15	6.82	0.39	0.15	-0.24	–	0.027	0.15	0.12	0.53
Chemical	–	0.15	–	–	0.15	0.15	0.33	–	0.15	0.15	0.64
Control	–	0.15	–	–	0.15	–	–	–	0.15	–	–

“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

2.4 Results and discussion

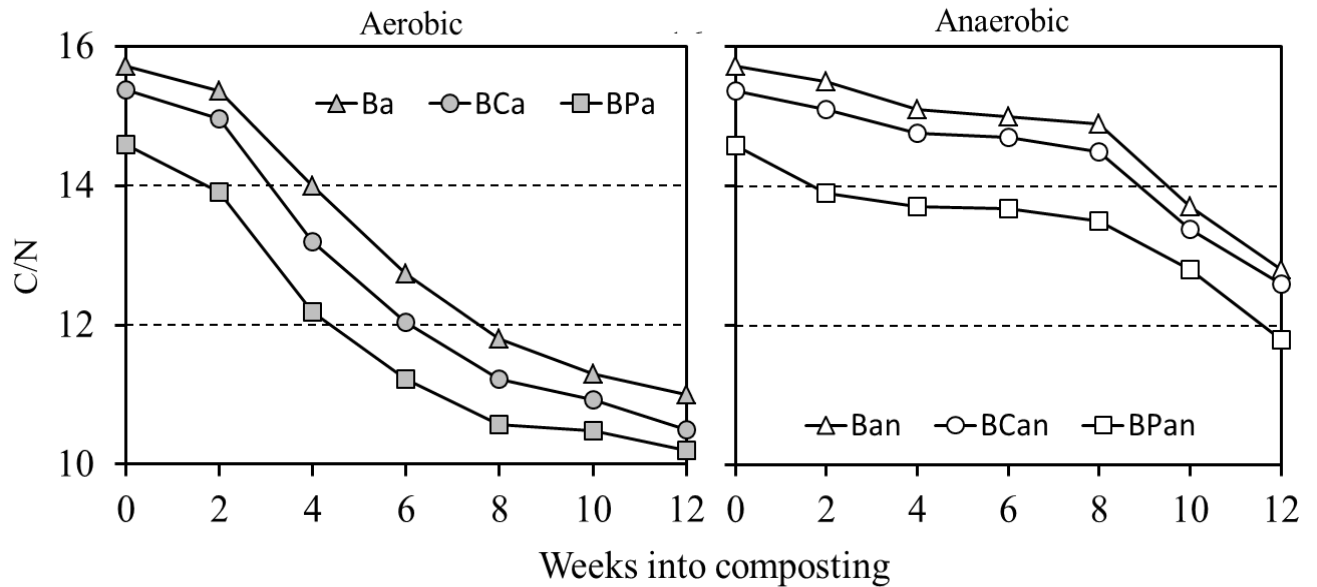
2.4.1. Temperature of composting piles

Temperature profiles for the different composting treatments are illustrated in **Figure 5**. Initial composting temperature was about 18°C, and rapidly increased to a maximum of 84.9°C and 60.0°C under aerobic and anaerobic conditions (in BP), respectively, during the first 2 weeks, dropping to 41.0°C in the last 2 weeks in the aerobic setup. Under anaerobic conditions, temperature dropped to between 44–45°C during the last 2 weeks. This trend conforms to an earlier three-stage composting cycle reported by Inbar et al. (1993) in which temperature increases to about 45°C during the first 3 days (mesophilic stage), reaches a maximum of 72°C within 4 weeks (thermophilic stage) and then the ambient temperature phase, which lasts for 8 weeks. The faster and higher temperature surge under aerobic as compared to anaerobic was likely due to increased bio-oxidative activity. Bernal et al. (2008) had found that during the different stages of biodegradation, organic compounds are degraded to CO₂ and NH₃, with consumption of copious amount of oxygen. Among the inoculum treatments, temperature build-up was in the order BP > BC > B, suggesting that inoculation promoted temperature build-up as compared to plain banana peels. This could be attributed to increased microbial activity, as a diverse population of organic matter degrading microorganisms, including *Pseudomonas* had been reported in animal wastes (Nodar et al. 1990). Additionally, mineral nutrients N and P in the inoculum formulations (BP and BC) might have promoted prolific growth and activity of the microbes. These are believed to be essential in the biodegradation of organic compounds (Gupta and Rao, 1998).



“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

Figure 5. Temperature variation of composting piles



“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

Figure 6. C/N ratio gradation during composting

Earthworm inoculation was unsuccessful, as total mortality in all vermi-beds occurred just two days into composting; likely due to the unfavourable environmental conditions such as the high temperatures of $> 40^{\circ}\text{C}$, $\text{pH} > 7$ and moisture content of $> 45\%$ (Nagavallemma et al. 2004). Other lethal substances might have been produced at the start of composting, owing to the strong smell observed, likely from volatile ester compounds; however, this needs further study to obtain conclusive evidence

2.4.2. C/N ratio

The initial C/N ratio of banana peels (30) reduced to just under 16 following a 4-week pre-composting treatment (withering) to adjust moisture content to about 60%. During composting, C/N ratio usually has a decreasing tendency and is an important parameter to index composting progress and maturity (Charest and Beauchamp, 2002). **Figure 7** shows C/N ratio variations of the different formulations under both aerobic and anaerobic composting conditions. At the start of composting, C/N ratio of the formulations averaged 15.7, 15.3 and 14.6 for B, BC and BP formulations, respectively, and by the end of composting, it had dropped to 11.0, 10.5 and 10.2 under aerobic and 12.8, 12.6 and 12.0 under anaerobic composting for B, BC and BP formulations respectively. This decline was likely due to mineralization of substrates present in the initial composting materials, or an increase in total N resulting from a concentration effect as C is biodegraded (Sanchez-Monedero et al. 2001). Aeration significantly facilitated C/N ratio decline ($p < 0.05$) as compared to anaerobic composting; for instance, BP-formulation under aerobic conditions attained a C/N ratio of 12 in week 4–5 while it took 12 weeks to attain the same C/N under anaerobic conditions. Regardless of the aeration condition, inoculated treatments generally

showed faster rate of C/N ratio decline than plain banana peels. Overall inoculum effect was in the order BP > BC > B, under both aerobic and anaerobic composting conditions. Faster C/N decline under aerobic and among the different inoculum treatments could be largely attributed to higher bio-oxidative activity, as earlier described. The final compost C/N ratio of 10–12 in all treatments was within the range of 10–15, which is ideal for final stabilized composts (Boldrin et al. 2010).

Total Carbon (TC) degradation of the four formulations under both aerobic and anaerobic composting conditions showed only a slight difference, owing to earlier (~36%) carbon losses during the withering treatment prior to composting. Initial TC concentrations ranged 33.0–38.5%, decreasing across all treatments as composting progressed to between 22.0–22.5% under aerobic and 23.2–26.8% under anaerobic conditions, at the end of composting (Table 8). This decline could have resulted from degradation of labile C as composting progressed. Higher Carbon loss under aerobic conditions is reflective of the higher bio-oxidative activity as compared to anaerobic conditions. Final compost TC content is similar to that from other crop biomass sources, such as wheat: 21.9% (Gaind and Gaur, 2000).

2.4.3. pH and EC

Generally, pH varied within a narrow range of 9.2–9.3 at the start to 9.3–9.7 at the end of the composting period (**Table 7**). A precipitous rate of increase occurred in the first 2 weeks, then a gentle increase with composting progress. Initial increase in pH was likely due to ammonia production following protein degradation as was explained by Albuquerque et al. (2006). Decline in the rate of pH increase later on was likely due to ammonia volatilization and increase in concentration of water-soluble base cations arising from organic

matter decomposition. All 24 samples showed high alkalinity ($\text{pH} > 9$), likely due to the inherently high K content (6.64%) in the banana peels. Available K^+ in water-soluble form could have combined with bi-carbonic acids (HCO_3^-) produced during the organic matter mineralisation to form potassium hydroxide (KOH), a strong base. Similarly, biodegradation of the organic acids and mineralization of organic compounds also favour pH rise (Paredes et al. 2000). Aerobic composting showed slightly higher pH than anaerobic process, likely due to higher K release that resulted from the higher bio-oxidative activity. Among the inoculum treatments, B formulation showed higher pH as compared to BC and BP inoculum treatments, and this might have been due to the higher K content in B. The final compost pH of > 9 is slightly higher than the recommended range of 6–8, but typical in the composting of organic wastes, (Barreira et al. 2008). The strongly alkaline banana peel-based compost could be potentially beneficial as an acidity control agent for the increasingly acidic soils of Uganda. Electrical conductivity increased from 0.53 to 0.77 dS m^{-1} in Ba, 0.58 to 0.79 dS m^{-1} in BCa and 0.56 to 0.83 dS m^{-1} in BPa (**Table 7**) during composting which was probably due to chemical transformation into more soluble inorganic salt forms during organic matter decomposition, and the concentration effect due to the net loss of dry mass (Silva et al. 2009). The effect of poultry litter inoculation was highly significant ($p < 0.05$) as compared to cow dung and plain peels under both aerobic and anaerobic conditions. Though the trend under anaerobic composting was not consistent, mean EC values were significantly lower ($p < 0.05$) than those obtained under aerobic composting. Final EC values were well below the upper limit of 4.0 dS m^{-1} which is considered tolerable by plants of medium salinity sensitivity (Lasaridi et al. 2006).

Table 7. EC – pH gradation during composting

Week	0		2		4		6		8		10		12	
	EC (dS/m)	pH	EC (dS/m)	pH	EC (dS/m)	pH	EC (dS/m)	pH	EC (dS/m)	pH	EC (dS/m)	pH	EC (dS/m)	pH
Ba	0.53	9.30	0.58	9.46	0.60	9.28	0.63	9.32	0.66	9.94	0.75	9.52	0.77	9.68
BCa	0.58	9.32	0.59	9.47	0.66	9.31	0.60	9.30	0.64	9.86	0.78	9.45	0.79	9.54
BPa	0.56	9.22	0.67	9.50	0.70	9.30	0.70	9.32	0.75	9.89	0.81	9.56	0.74	9.61
Ban	0.53	9.17	0.49	9.35	0.55	9.20	0.56	9.26	0.56	9.73	0.59	9.45	0.59	9.44
BCan	0.58	9.18	0.50	9.33	0.59	9.20	0.59	9.21	0.58	9.66	0.58	9.44	0.57	9.48
BPan	0.57	9.17	0.53	9.01	0.64	8.97	0.63	9.11	0.64	9.48	0.64	9.21	0.65	9.29

Values are means of three triplicate samples measured in 1:10 H₂O

“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

2.4.4. Available nutrient contents

Knowledge of the mineral nutrient content of compost is of prime importance as it varies widely, and is an important determinant of the end use for the compost (Zethner et al. 2000). Variation in the concentration of available primary (N - (NH_4^+ -N and NO_3^- -N), P, K) and secondary (Ca and Mg) mineral nutrients during the composting process is shown in **Figure 6**.

2.4.5. Nitrogen

Most of the mineral N in the composts was in ammonium nitrogen (NH_4^+ -N) form, with very low detectable nitrate nitrogen (NO_3^- -N). NH_4^+ -N rapidly increased and attained its peak (2.28–3.90 g kg⁻¹ under aerobic and 2.47–6.52 g kg⁻¹ under anaerobic conditions) in the first 2–4 weeks and gradually decreased to between 0.77–1.27 g kg⁻¹ (aerobic) and 1.65–4.37 g kg⁻¹ (anaerobic) toward the end of composting period (**Figure 6a**). The initial rapid rise was due to thermophilic decomposition of organic forms of nitrogen such as proteins and amino acids into ammonia (Paredes et al. 2000), however, the decline in the latter part was not proportional to the increase in NO_3^- -N concentration, which suggested that some of the NH_4^+ -N might have been lost through NH_3 volatilization and/or microbial denitrification. Tiquia et al. (2002) had reported high NH_3 volatilisation losses and immobilisation by microorganisms under strong alkaline conditions (pH >9). Throughout the composting period and in all inoculum treatments, NH_4^+ -N concentration was significantly higher ($p < 0.05$) under anaerobic conditions as compared to the aerobic process, probably as a result of volatilization losses due to pressurised air circulation (Solano et al. 2001) and the higher rate of nitrification under aerobic composting that might have resulted from relatively more favourable conditions especially oxygen for survival of the nitrifying bacteria (**Figure 6b**).

Nitrification is a bio-oxidative process, requiring oxygen for normal functioning of the nitrifying bacteria (Tiquia and Tam, 2002). Inoculated treatments also showed higher NH_4^+ -N concentration than plain peels, with BP showing the highest effect for most of the composting period, but at the end, concentration was not significantly different from BC and B. Higher NH_4^+ -N under inoculated conditions was likely due to additive effect and higher bioactivity, especially in BP, while the subsequent rapid decline (in BP) was due to higher ammonia volatilization arising from easily mineralizable compounds such as uric acid in the poultry litter.

NO_3^- -N exhibited a clear trend only under aerobic composting conditions. Generally, a meagre increase occurred during week- 2, and remained stable until week- 6. A rapid increase was then observed after week- 10, with the peak occurring in week- 12 (**Figure 6b**). The low NO_3^- -N accumulation in the early part was probably caused by the high amount of ammonia and temperature during that period, which could have inhibited nitrification through microbial inactivation and/or de-naturation (Stentiford and de Bertoldi, 2010). Among the different inoculums in the aerobic setup, NO_3^- -N concentration was significantly higher ($p < 0.05$) in BPa during the first 2-8 weeks as compared to BCa and Ba, but rate of increase reduced towards the end of the composting period. In the anaerobic condition, NO_3^- -N concentration was also highest in BPan treatments but the differences with BCan and Ban were statistically insignificant. Summarily and in all treatments however, NO_3^- -N concentration remained very low ($< 0.02\text{g kg}^{-1}$) throughout the composting period, probably due to the high pH conditions (9.2-9.9). The nitrifying bacteria responsible for nitrate formation are largely inactivated by the pH value of >7.5 and temperature $>40^\circ\text{C}$ (Tiquia et al. 2002).

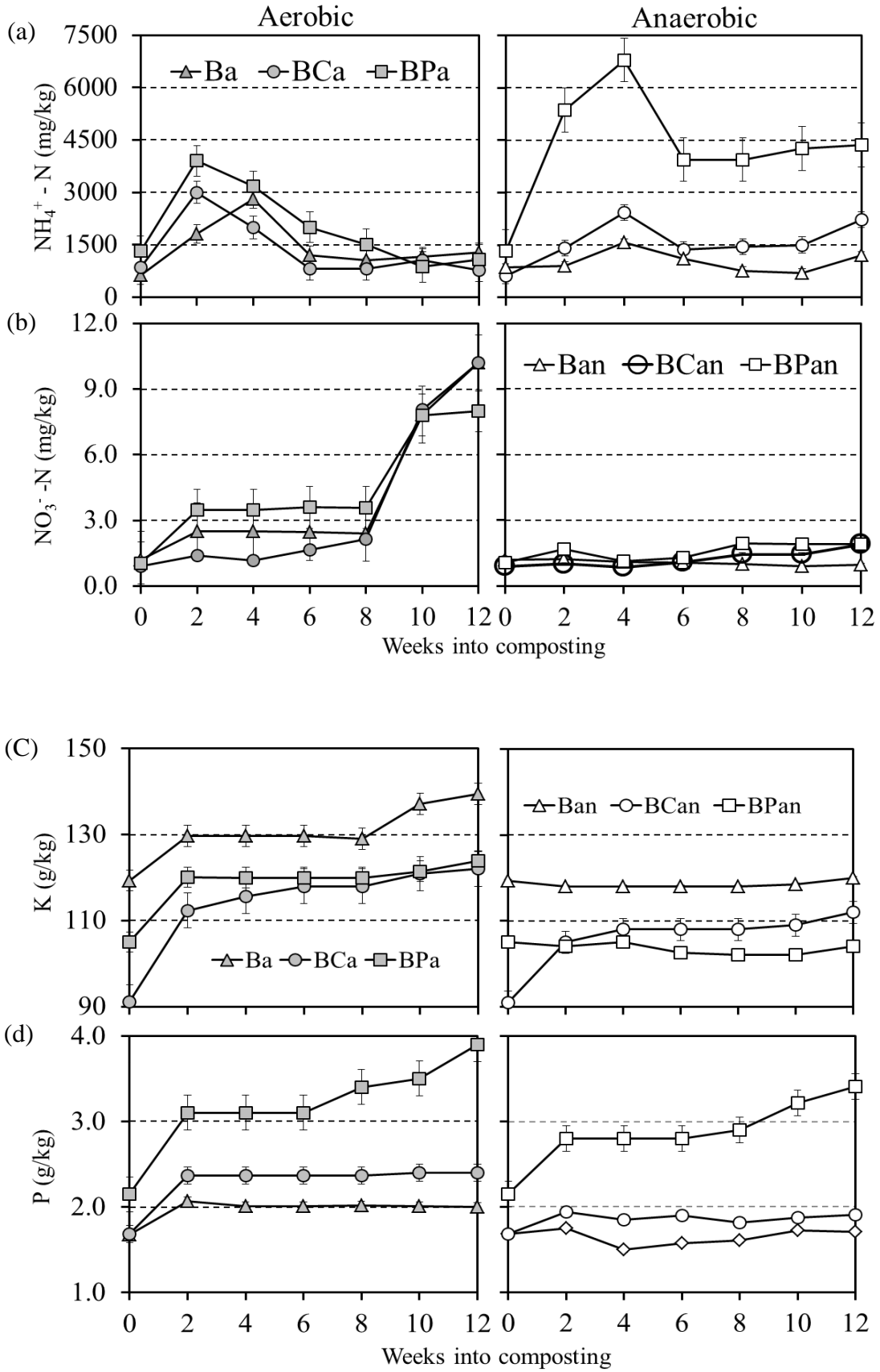


Figure 7. Available mineral nutrient patterns during composting

2.4.6 Phosphorus and Potassium

Phosphorus and K concentration in all treatments increased with composting time, with formulations under aerobic conditions showing significantly ($p < 0.05$) higher concentration than those under anaerobic conditions (**Figure 6c, d**). The increase in P and K during composting was possibly caused by concentration effect arising from the higher rate of carbon loss that occurs when organic matter is decomposed or mineralised into CH_4 or CO_2 (Chitsan, 2008). Among the inoculum treatments; P was in the order $\text{BP} > \text{BC} > \text{B}$, but K behaved exceptionally; it was significantly higher in plain peels than inoculated treatments in the order: $\text{B} > \text{BC} > \text{BP}$ under both composting conditions. Besides the higher microbial activity, higher P concentration in inoculated treatments was possibly also due to additive effect of P from the inoculums, especially poultry litter, which had the highest P content (14.8 g kg^{-1}). The unique K behaviour in the inoculated treatments might have been partly due to Potassium assimilation and immobilisation by microbes (Hankin et al. 1976). Overall, Potassium was notably and consistently highest in all treatments and of all other mineral nutrients ranging $>9.0\%$, probably due to the high inherent content in banana peels, suggesting that banana peel compost might be a good source of K fertilizer. The K content of banana-peel compost is much higher when compared to that of other composted materials such as: municipal solid waste compost – 7.1% (Mbarki et al. 2008), Olive-mill waste compost – 2.3% (Altieri and Esposito, 2010), and bovine manure – 2.1% (Gil et al. 2008).

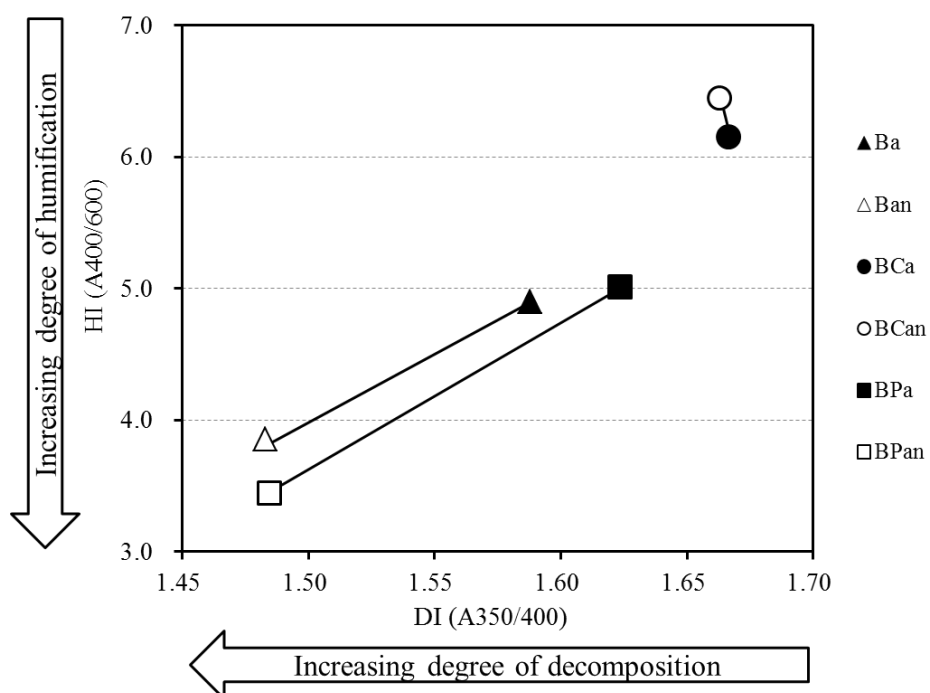
2.4.7 Calcium and Magnesium

Available Calcium (Ca) and Magnesium (Mg) showed similar trend under both aerobic and anaerobic composting conditions, with the aerobic attaining higher concentrations than anaerobic setup. Significantly higher Ca and Mg releases were observed

in the inoculated than plain banana peels. At the end of the composting period, Ca and Mg nutrient concentration was in the order; BP > BC > B under both composting conditions (**Table 8**).

2.4.8 Compost maturity

UV–Vis analysis of alkali compost extracts from the banana composts is shown in **Figure 8**. Yamamoto et al. (2000) proposed the two indices that could be used to signal compost maturity as: Humification index (HI) and decomposition index (DI). HI is the ratio of absorbance at wavelength 400 nm to that at 600 nm (A_{400}/A_{600}), while DI is the ratio of absorbance at 350 nm to 400 nm (A_{350}/A_{400}). A decrease in both indices implies an increase in the degree of humification and decomposition, and therefore an increase in compost maturity. In this study, anaerobically composted samples (especially Ban and BPan) showed higher degree of “maturity” as compared to those under aerobic composting. This result is in contrast with other composting progress parameters, such as temperature and C/N ratio in which aerobic composting appeared to progress faster and more efficiently as compared to anaerobic composting. This could have resulted from retention of the dark coloured easily decomposable compounds (such as polyphenolic acid in banana peels) under anaerobic conditions; these were likely greatly diminished under the more rapid aerobic composting conditions. The effect of inoculation showed a similar trend as aeration, with degree of compost maturity occurring in the order: Ba > BPa > BCa and Ban > BPan > BCan for aerobic and anaerobically composted samples respectively. Poultry litter inoculum could have facilitated faster degradation of the easily decomposable dark coloured compounds as described earlier.



“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

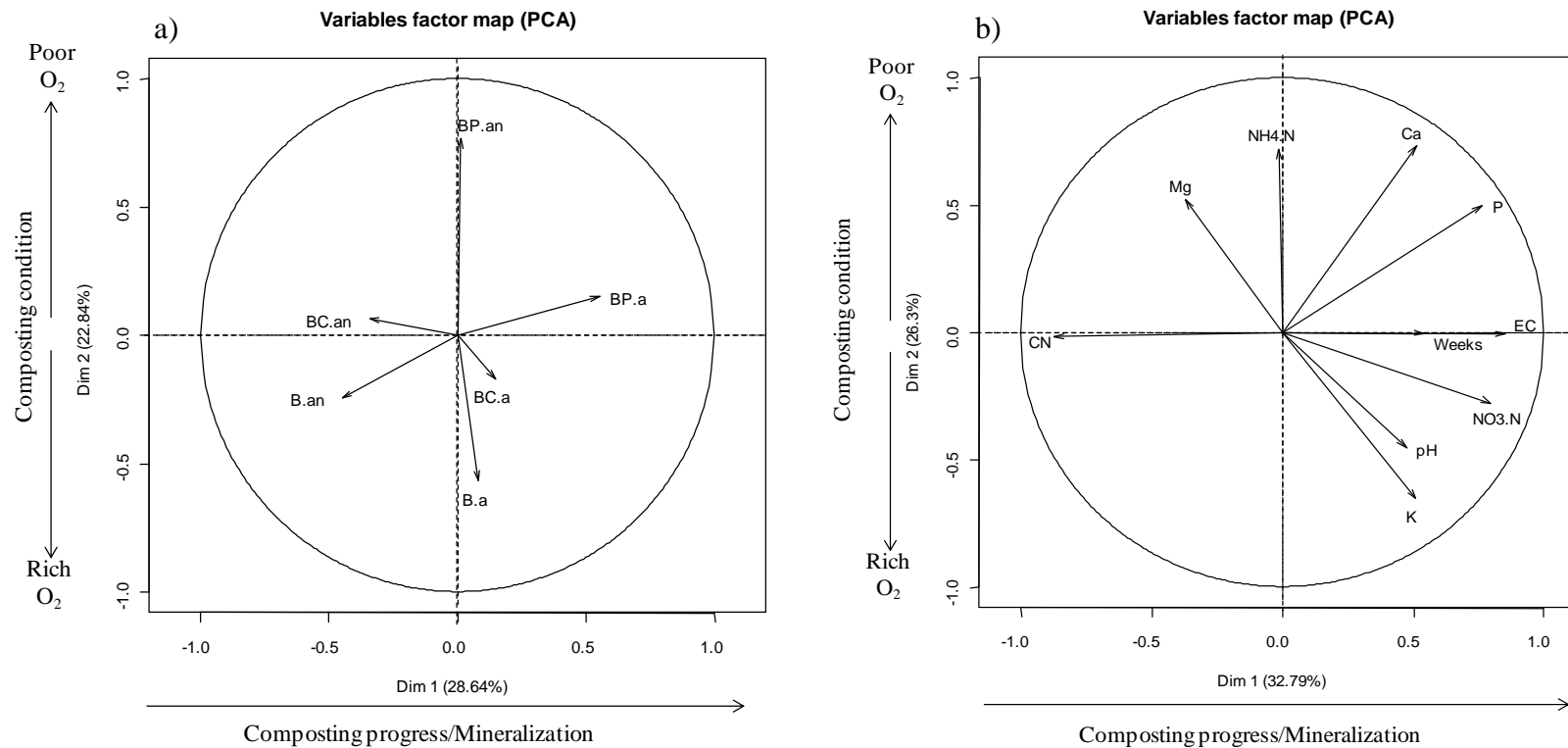
Figure 8. Humification and decomposition indices of alkali sample extracts at the end of composting

2.4.9. Overall physiochemical characteristics variability

Principal component analysis (PCA) of the total variation in the three compost formulations under aerobic and anaerobic composting conditions is shown in **Figure 9a**, and that among physiochemical characteristics in **Figure 9b**. Weeks of composting and C/N ratio showed very high factor loading, and are denoted by Dim 1 in this analysis. Dim 2 denotes the various physicochemical characteristics monitored during the composting period. Inoculated formulations and aerobic composting conditions had a significant positive effect on the composting process as compared to the un-inoculated formulations and anaerobic composting conditions. This reaffirms the significance of inoculation and aeration during the composting process as earlier described. Among the physiochemical interactions, K and pH, were strongly positively, but negatively correlated with $\text{NH}_4^+\text{-N}$. The strong positive correlation between K and pH further suggests that K might have been the precursor for the high pH recorded throughout the composting period. Such conditions favour $\text{NH}_4^+\text{-N}$ volatilization, hence the negative correlation observed.

2.5. Final compost characteristics

The final compost formulations had high N and K mineral nutrient concentrations ranging 2.04–2.18% and 12.2–13.9% under aerobic and 1.84–2.09 and 10.44–11.86% under anaerobic composting conditions respectively. Other nutrients were quite low: P (< 0.39%), Ca (< 0.46%), and Mg (< 0.39%) under both composting conditions (**Table 8**). The compost was also highly alkaline (pH > 9). These parameters are within the reported range for compost materials (Sanchez-Arias et al. 2008).



“B, BC and BP” are the compost formulations are earlier described, while “a” and “an” denote aerobic and anaerobic conditions respectively

Figure 9 (a). Variable factor map (PCA) for total variation in the three compost formulations with time, under aerobic and anaerobic composting conditions. **(b).** Variable factor map (PCA) for total variation in physiochemical characteristics with composting time

Table 8. Physiochemical characteristics of the final compost

Condition	Formulation	1:10 H ₂ O		g kg ⁻¹ d.wt basis		C:N ratio	Available nutrients (g kg ⁻¹) d.wt basis					
		pH	EC (dS m ⁻¹)	TC	TN		NH ₄ ⁺ -N	NO ₃ ⁻ -N	Olsen-P	K	Ca	Mg
Aerobic	Ba	9.7±0.10	0.77±0.03	224.4±0.19	20.4±0.09	11.0±0.71	1.27±0.69	0.01±0.01	2.01±0.39	139±5.96	1.62±0.31	1.10±0.06
	BCa	9.5±0.12	0.79±0.08	219.5±0.26	20.9±0.11	10.5±0.67	0.77±0.13	0.01±0.01	2.43±0.29	122±3.36	2.85±0.90	1.52±0.16
	BPa	9.6±0.04	0.80±0.08	222.4±0.21	21.8±0.13	10.2±0.67	1.07±0.09	0.01±0.03	3.90±0.03	123±4.27	3.71±0.50	1.41±0.01
Anaerobic	Ban	9.4±0.01	0.59±0.01	267.5±0.33	20.9±0.19	12.8±0.31	2.23±0.72	0.001±0.01	1.71±0.06	118±6.36	2.43±0.38	2.43±0.27
	BCan	9.5±0.05	0.57±0.01	231.8±0.19	18.4±0.18	12.6±0.29	1.22±0.64	0.002±0.05	1.92±0.09	111±7.75	3.72±0.41	3.91±0.53
	BPan	9.3±0.03	0.65±0.03	267.0±0.36	20.7±0.15	12.9±1.10	4.37±0.10	0.002±0.01	3.44±0.84	104±4.27	4.61±0.12	3.32±0.29

Values are means ±SD of three replicates

2.6 Pot cultivation

2.6.1 Seedling growth

Table 9 shows sorghum seedling growth under the different composts and chemical fertilizer treatments. Seedling emergence under K-base was similar to that under chemical fertilizer treatment, and significantly higher than the control (no additives). This shows that the banana peel compost (K-base) provided a conducive environment for germination as much as the chemical fertilizer. Meanwhile, there was 100% mortality of seedlings under the N-base treatment, likely due to toxic alkalinity, ($\text{pH} > 10$) that resulted from over application of K while trying to achieve the required 150 kgN in K-base treatment (**Figure 10**). Seedling growth was similar in K-base and chemical fertilizer treatments unlike in the control (no additives) where it was much lower. Biomass yield and LAI showed a similar trend; with K-base yielding as much biomass as the chemical treatment (**Table 9**). This suggested that banana peel compost effectively met the sorghum K requirements, and therefore could be a good source of K fertilizer.

Table 9. Sorghum seedling growth under K - and N - based applications

Treatment	Pre-cultivation	Post-cultivation	Germination (%)	Yield (mg/plant dwt)		Shoot/Root dwt /plant	Leaf length (mm)	LAI	
	pH (1:5 H ₂ O)			Shoot	Root				
CTRL	5.9	6.0	52.1	33.3	30.0	1.1	5.6	2.5	
CHEM	3.8	7.0	89.3	55.0	35.0	1.6	15.7	12.0	
K-base	Ba	7.4	7.3	93.2	46.7	33.3	1.4	12.7	9.3
	BCa	7.0	7.2	100.0	53.3	50.0	1.1	14.3	11.5
	BPa	7.6	7.1	85.2	56.7	46.7	1.2	13.7	10.5
N-base	Ba	10.7	10.2	0	-	-	-	-	-
	BCa	10.8	10.3	0	-	-	-	-	-
	BPa	10.8	10.3	0	-	-	-	-	-

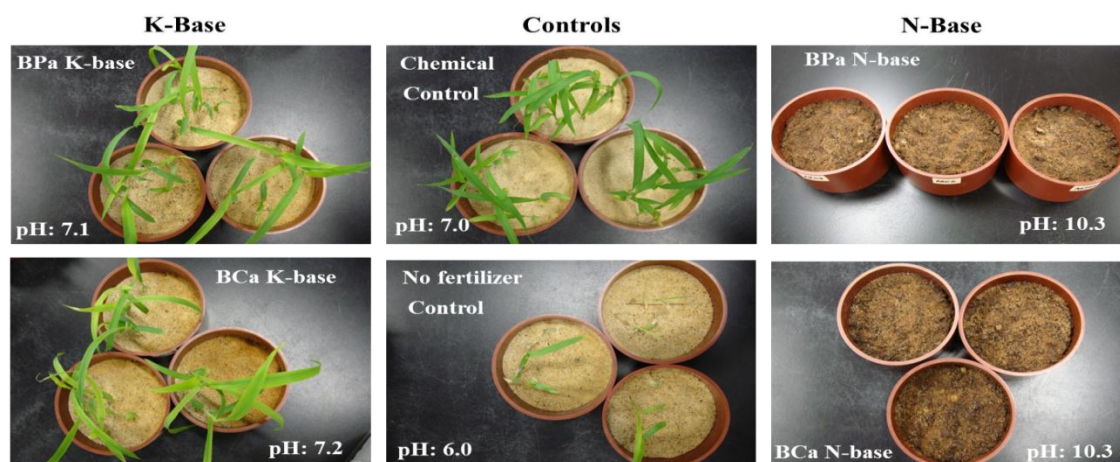


Figure 10. Sorghum seedling growth under the different composts and chemical fertilizer treatments

2.7. Conclusions

Banana peel compost is a good organic soil amendment as a K fertilizer (contains 130–175 g K₂O kg⁻¹). 1ton/ha of compost can supply the required 5070 kgK₂O ha⁻¹ for banana cultivation. Aeration and inoculation, especially with poultry litter are essential for an enhanced composting process, and subsequent production of good quality compost. The highly alkaline pH of banana peel compost could be useful in reducing liming requirements in acidic lands.

CHAPTER 3

Pyrolytic conversion of banana peel wastes into biochar for soil amendment and environment preservation

3.1 Introduction

Low cost technologies for beneficial and sustainable management of organic waste materials such as banana peels are still quite limited especially in the developing World. In the previous study, aerobic composting was proposed as a candidate pathway for sustainable management of banana peels, and indicated a high potential for use as a K and N fertilizer (Kalemelawa et al. 2012). Although this is of great potential agro-economic and environmental importance, it poses some challenges; composting takes long (> 10 weeks) and composts easily decompose, thus releasing greenhouse gases such as CO₂. Large scale composting is also cumbersome and the compost is bulky to transport and apply to intended fields. Biochar production may offer a second value-added approach for reusing a large amount of the wastes at the same time. Biochar contains recalcitrant carbon, sorptive for water and nutrients; ideal as a soil ameliorant for fertility enhancement and carbon sequestration (Inyang et al. 2010). It improves soil physical, chemical and biological properties through increased soil organic matter and nutrient content (Chan et al. 2007). Biochar usability however, is influenced by the efficiency and effectiveness of the process of their creation (by factors such as pyrolysis temperature, holding-time and MC) and the specific biomass sources used (McLaughlin et al. 2009). For instance, low processing temperatures (< 500°C) favour relative accumulation of a large proportion of available K, Cl (Yu et al. 2005), Si, Mg, P and S (Bourke et al. 2007), and alkalinity (Cao and Harris, 2010).

Therefore, processing temperatures $< 500^{\circ}\text{C}$ favour nutrient retention in biochar (Kim et al. 2012), while being equally advantageous in respect to yield (Ahmad et al. 2012). On the other hand, high pyrolysis temperatures ($> 500^{\circ}\text{C}$) lead to accumulation of aromatic carbon in the biochar (Kim et al. 2012), an increase in water sorption capacity (Ahmad et al. 2012), and alkalinity (Cao and Harris, 2010). The effect of holding-time was reported to be similar, but of less influence as temperature; for instance, aromatization increased in the order $1 < 2 < 3 < 5$ hours of holding-time in rice straw biochar production (Wu et al. 2012). Moisture is another critical factor of biochar production, as higher moisture content increases the costs of biochar production and transportation per unit of biochar produced. Pre-drying the biomass feedstock up to about 10% (by weight) appears to be desirable (Collison et al. 2009), however, its influence on biochar physiochemical characteristics remains unknown. Thus, different permutations of these processing conditions (pyrolysis conditions and moisture content) may affect differently each source material. The study on quantification biochar physiochemical characteristics under different pyrolysis conditions would be helpful for better understanding of the production process, and nature, composition and distribution of constituent mineral nutrients; this would form the basis for final biochar utility. In this experiment, baseline information on quality characteristics of banana peel biochar produced under different moisture and pyrolysis temperature conditions is presented. The variations in biochar agro-environmental properties such as; organic mass loss rate (yield), pH, EC, CEC, mineral nutrient content, and humification under the different production conditions are studied. The results of this work will have important implications for guiding appropriate biochar production conditions from banana peels, for agronomic and environmental benefit.

3.2 Materials and Methods

3.2.1 Experimental materials

Fresh banana peels were collected from Yamazaki Baking Co. Ltd, Okayama, Japan, sliced into small pieces (1–2 cm), and moisture content (MC) adjusted to 0, 50 and 80% (w/w) by air and oven-drying. The 80% MC sample was the near-fresh banana peel without any moisture adjustment.

3.2.2 Pyrolysis of banana peels

Approximately 150 g of the peels at each of the moisture levels (0, 50 and 80%) were loosely packed in 280 mL porcelain crucibles, covered with a fitting lid, and pyrolysed in a muffle furnace (KDF S-90, xx Co. Japan). Selected pyrolysis temperatures of 200, 400 and 600°C were applied at a heating rate of about 10°C min⁻¹ and held constant for 1, 2, 3 and 4 hours. An air-dried/un-charred peel sample served as a control; all treatments were replicated three times. The produced biochar solids in the crucibles, along with the control were then milled, sieved (< 1 mm) and the replicates mixed to make composite samples.

3.2.3 Biochar characterization

3.2.3.1 Yield

Yield was calculated as the mass of biochar generated from a unit dry mass of banana peel following the equation:

$$\text{Yield (\%)} = \frac{\text{Mass of biochar (g)}}{\text{Oven - dried mass of raw material (g)}} \times 100$$

3.2.3.2 Carbon recovery rate

The carbon recovery rate (CRR) was calculated from the formula:

$$CRR (\%) = \frac{\text{Carbon in biochar} \times \text{Yield} (\%)}{\text{Carbon in uncharred material}} \times 100$$

3.2.3.3 pH, Electrical conductivity and Cation exchange capacity

The pH and electrical conductivity (EC) were measured in 1:10; biochar: water extracts using digital meters (HM-30S and CM-30R-DKK, TOA Electronics Ltd, Japan), respectively. The cation exchange capacity (CEC) was measured by the ammonium acetate (NH₄OAc) extraction methods (Chapman, 1965)

3.2.3.4 Ash content

Biochar samples were oven dried at 105°C for 24 hours, then heated in open top ashing crucibles in a muffle furnace to 550°C for 30 minutes. Ash content was then calculated from the equation:

$$\text{Ash content} (\%) = \frac{\text{Mass of ashed material} (g)}{\text{Dry mass of biochar} (g)} \times 100$$

3.2.3.5 Total organic carbon and nitrogen

Total organic carbon (TC) and nitrogen (TN) content of the biochars were determined by the dry combustion method using an automated C/N coder (Model MT 700, Yonaco, Japan).

3.2.3.6 Total and extractable nutrient contents

Total nutrients: Potassium (K), calcium (Ca) and magnesium (Mg) were measured by atomic absorption spectrophotometer (Model Z-2300 Hitachi Co., Japan) after digestion with concentrated nitric acid, while total phosphorus (P) in the digests was determined colorimetrically on a spectrophotometer (Model U-2001, Hitachi Co, Japan) using phosphomolybdate blue method (Murphy and Riley, 1962). Water-soluble K, Ca, Mg and P were quantified after extraction with deionized water, using the same methods above.

3.2.3.7 Optical properties alkaline biochar extracts

Ultraviolet-visible (UV-vis) spectra were recorded on a UV-2200 (Shimadzu, Japan) spectrophotometer at A450, A520, A600 and A610 nm after extraction (shaking for 1 hour/room temperature) with a 1:1 mixture of 0.5 M NaOH and 0.1 M Na₄P₂O₇ (1:100; w/v). Spectrophotometric parameters; Pg index (PI) and Melanic index (MI) of the samples were calculated using the formulae; $PI = A_{610}/A_{600}$; $MI = A_{450}/A_{520}$ (Yamamoto et al. 2000)

3.2.3.8 *Fourier Transform Infrared (FTIR) spectroscopy*

FTIR analysis using Attenuated Total Reflectance (ATR) method with diamond crystal was performed on all samples using a spectroscope (FT/IR-4100, JASCO Co., Japan) set at a transmission mode between 4000 and 400 cm^{-1} , 32 scans and a spectral resolution of 4 cm^{-1} .

3.2.3.9 *Incubation test*

An incubation experiment was conducted using an ultisol soil (red-acidic, similar to the highly weathered tropical African soils) to assess the impact of banana peel-based biochar on soil properties (focus on pH – acidity remediation). Biochar (produced at 400 and 600 °C) was applied to soil at: 0, 1, 2, 5, and 10% by weight, and incubated at 25 °C at field capacity for a period of 7 days. Electrical conductivity and pH were then measured in 1:5 (w:v) – EC (H_2O) and 1:2.5 (w:v) - pH; biochar: water, KCl and hydrated CaCl_2 extracts using digital meters HM-30S and CM-30R-DKK (TOA Electronics Ltd, Japan), respectively.

3.3 **Statistical analysis**

Data on yield, pH, EC, CEC, ash and elemental concentration were subjected to analysis of variance using Stat View software for Windows (version 5.0). The treatment means were compared using least significant differences (Lsd) to determine the main effect of biomass feedstock MC, holding time and temperature; unless otherwise stated, the differences were significant at $p < 0.05$ level.

3.4 Results and Discussion

3.4.1 Biochar yield

The effect of pyrolysis temperature/HT and original biomass feedstock MC on yield is shown in **Figures 11**. An increase of pyrolysis temperature/HT and MC led to a decrease in the yields of biochar. For peels of 0% MC, yield decreased from a range of 80.4–83.2% at 200°C to 21.7–38.5% at 600°C; at 50% MC, it decreased from 79.0–79.4 to 21.7–38.5, while peels of 80% MC experienced a yield decline from 21.3–27.3 at 400°C to 20.1–19.2% at 600°C. It was impossible to produce biochar under very low temperatures/HT and high MC permutations. Semi-charred materials under 0%MC/200°C/1 hr were however air-dried and subsequently characterized for thermochemical transformation studies. For moisture: samples of 80% MC yielded least; nearly half that at 0 and 50% MC, suggesting that moisture reduction prior to charring might be a desirable practice to boost yield. The decrease in biochar yields with increasing temperature could either be due to greater primary decomposition or through secondary decomposition of biochar residues. The high yield of biochar at low temperatures indicates that the material has been only partially pyrolysed (Katyal et al. 2003). The effect of HT was more important at low temperatures, while at high temperatures, HT showed a similar trend with respect to biochar yields. Overall, banana peel biochar yielded similarly to that from other feedstock sources; safflower seed cake biochar 25–34% at 400– 600°C (Kim et al. 2012) and pitch pine biochar 14.4– 60.7% at 300–500°C (Angin, 2012).

3.4.2 Carbon recovery rate

Carbon recovery rate represents the proportion of carbon that is retained in the biochar after pyrolysis. The effect of pyrolysis temperature/HT and original biomass feedstock MC on CRR is shown in **Figures 12**. CRR trends were similar to yield, where an increase in pyrolysis temperature/HT, and MC led to a decrease in the CRR likely due to same reason as described in yield above. Pre-charring withering also appeared to boost CRR.

3.4.3 Agronomic characteristics of produced biochars

Agronomic properties of produced biochars are shown in **Figure 13**. At lower temperatures (200°C), biochars were acidic (pH 4.9–6.9), shifting to strongly alkaline at 400 and 600°C (pH 9.4–12.7) (**Figure 13a**). This range is slightly higher than that of biochars from other common materials such as peanut hulls and pine chips through 400 °C pyrolysis which had pH of 10.5 and 7.6, respectively (Gaskin et al. 2009). Variations among the holding hours and moisture regimes were quite narrow. Acidity at 200°C was likely due to organic acids and phenolic substances produced from thermal-decomposition of cellulose and hemicellulose (Abe, 1998), while the strong alkalinity at 400 and 600°C might have been caused by increased concentration of alkali salts following C-ashing (Shinogi and Kanri, 2003). The high banana peel biochar pH presents a high potential for its use in soil acidity amelioration. The EC of all samples was generally low ($< 5.5 \text{ dS m}^{-1}$); increasing slightly with pyrolysis temperature and holding time, and decreasing with MC. EC of the uncharred sample was 1.2 dS m^{-1} , and ranged 1.4–1.6 at 200 °C and 3.1–5.4 dS m^{-1} at 600 °C (**Figure 13a**). This trend is similar to a study by Singh et al. (2010) in which EC of charred materials increased at 400 and 550 °C. Cation exchange capacity of the biochar samples was in the order: $200 > 400 > 600 \text{ °C}$, and ranged 5.1–16.5 cmolc kg^{-1} (at 200°C) to 4.1–15.5 cmolc kg^{-1}

(at 400/600°C (**Figure 13b**)). Guo and Rockstraw (2007b) had reported a decrease in the number of acidic functional groups with increasing temperature during thermolysis. Presence of moisture (50%) was observed to enhance CEC build-up, further studies are necessary to confirm this phenomenon and determine mechanism of action. The ash content is a measure of the non-volatile matter and non-combustible component of the biochar. Ash content increased with pyrolysis temperature (**Table 10**) likely due to volatilization accompanied by relative enrichment of various inorganic components.

3.4.4 Nutrient contents of banana peel biochar

The biochars contained moderate amounts of C and low N with TC concentration generally decreasing while that of TN more or less remained constant with increasing pyrolysis temperature/HT and MC. At 200°C, TC ranged 377.1–410.2, decreasing to 229.0–389.3g kg⁻¹ at 600°C. Weiping and Mingxin (2012) had reported a decreasing tendency in TC with increase in pyrolysis temperature during poultry litter biochar production. TN varied marginally between 10.2–12.2 g kg⁻¹ at 200°C and 11.2–13.0 g kg⁻¹ at 600°C (**Table 10**). This content is moderate and comparable to that of biochars from other biomass feedstock sources such as rapeseed and sunflower that contained TN of 7.6 and 11.9 g kg⁻¹, respectively (Sanchez et al. 2009). The C/N ratio of all produced biochars was quite high (> 24), suggesting that N release would potentially be slowed for more efficient plant utilization. Both TC and TN were, however, lower than that of uncharred material (TC: 320.2 and TN: 13.1 g kg⁻¹), likely due to the increasing biomass combustion and organic volatilization with increasing temperature. Produced biochars showed high content of mineral elements K and P, but low Ca and Mg. Potassium was the most predominant; likely due to high inherent K content in banana peels (Kalemelawa et al. 2012).

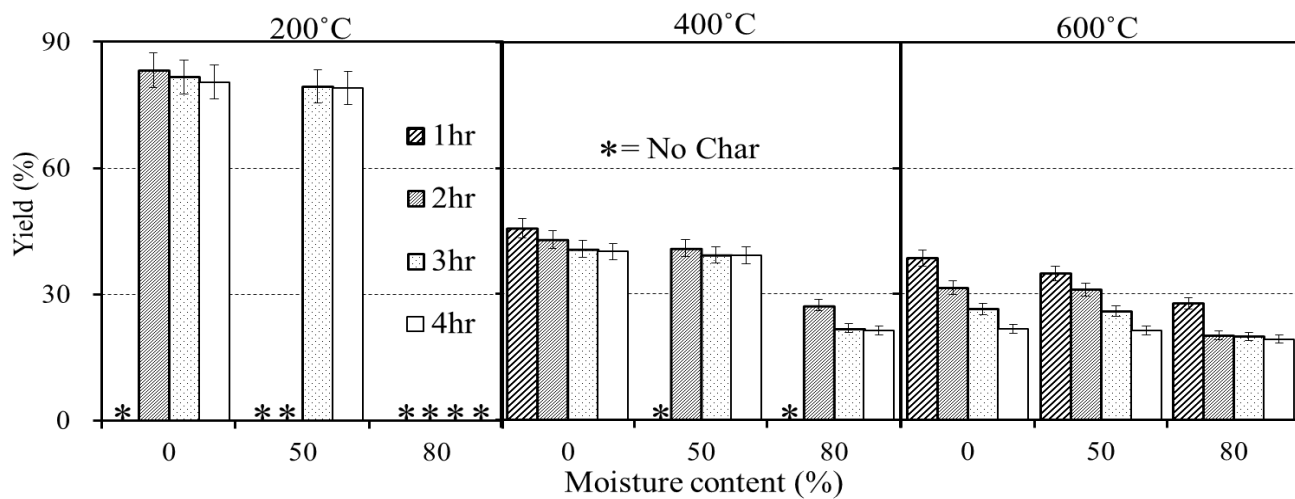


Figure 11. Banana peel biochar yield under different biomass feedstock moisture and pyrolysis conditions

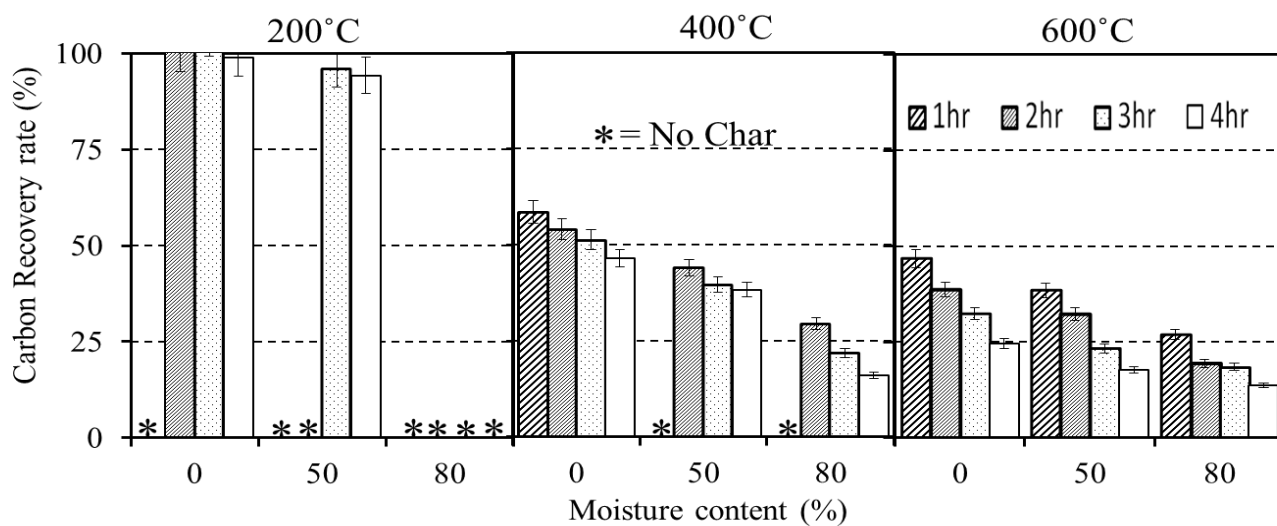


Figure 12. Banana peel biochar carbon recovery rate (CRR) under different biomass feedstock moisture and pyrolysis conditions

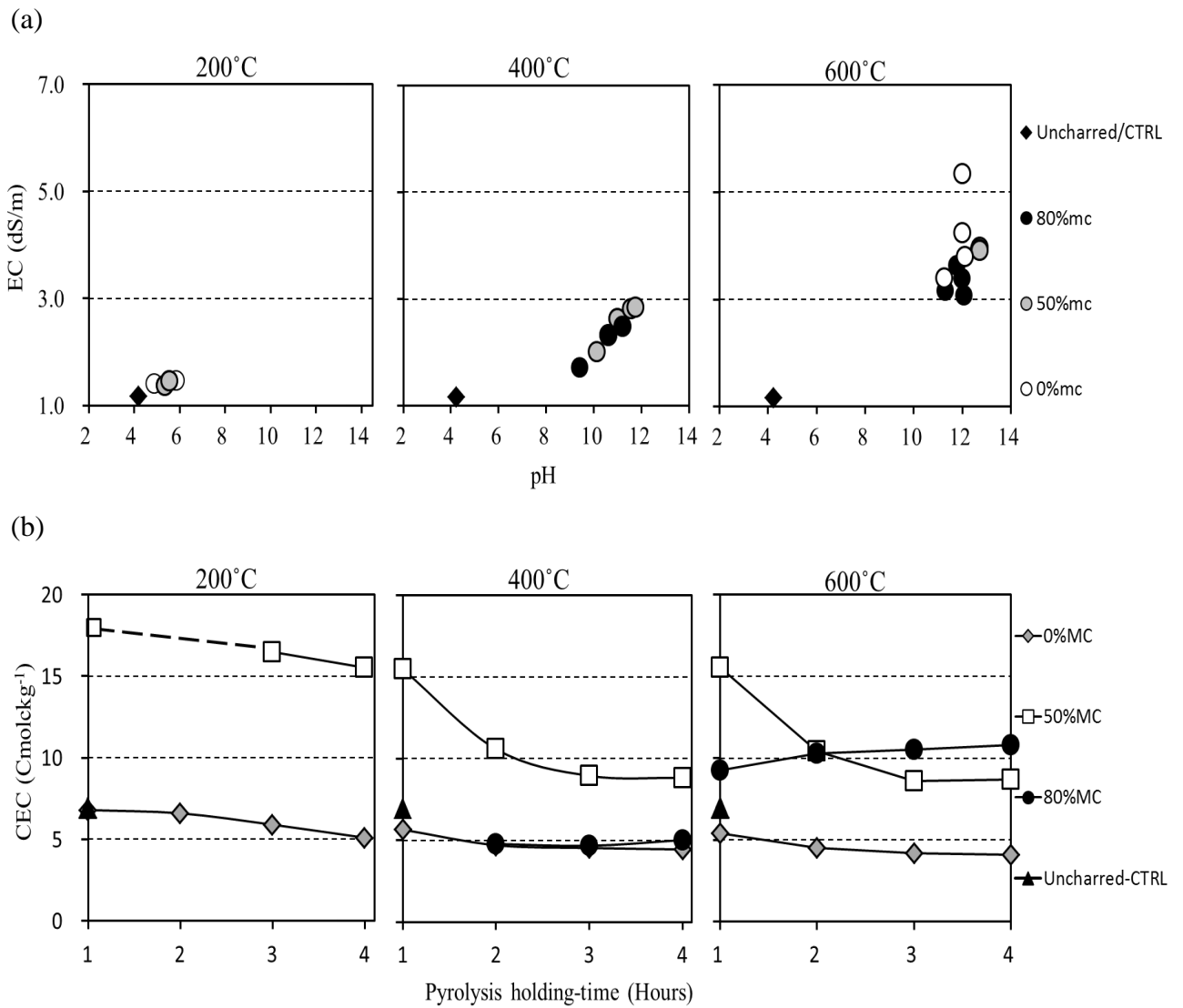


Figure 13 (a) EC-pH and (b) CEC of banana peel biochar produced under the different pyrolysis conditions

Heat treatment reduced biomass and MC, consequently increasing concentrations of P, K, Ca, and Mg in the biochars (**Figure 14 a-d**). Total P and K concentration ranged 11.2–15.2 and 113.1–152.4 g kg⁻¹ at 200°C, and 14.3–30.4 and 130.0–216.3 g kg⁻¹ at 600°C, respectively. Phosphorus content in the biochar is comparable to that from other feedstocks such as; peanut straw (15.0 g kg⁻¹) and slightly higher than that from; soybean (5.8 g kg⁻¹) and corn (6.8 g kg⁻¹) straw (Yuan et al. 2011); meanwhile K content is much higher as compared to that from other K-rich feedstocks such as; sawdust (14.9 g kg⁻¹) and rice paddy husk (12.35 g kg⁻¹) (Mankasingh et al. 2011). Total Ca and Mg concentration varied from between 2.1 and 5.1 for the uncharred peels, through to 1.1–6.2 and 2.1–4.1 g kg⁻¹ at 200°C, and 9.1–18.0 and 4.0–8.3 g kg⁻¹ at 600°C, respectively.

Water soluble fractions also generally increased with pyrolysis temperature, however, the rate declined at 600°C. Increase in water solubility at moderately elevated temperatures could have been due to increased concentration arising from biomass reduction. Reduced solubility (especially P, Ca, Mg) at 600°C (**Figure 14 b-d**) was likely caused by formation of less soluble forms following crystallization of amorphous P–Ca–Mg (Josan, 2007). High water soluble K in all chars and under all production conditions (ranging: 65.4–205.0 g kg⁻¹) indicated that banana peel biochar could be potentially useful as a source of readily available K fertilizer. Moisture presence appeared to enhance nutrient water solubility.

Table 10. Banana peel biochar physiochemical properties derived under different biomass feedstock MC and pyrolysis conditions

Temperature (°C)	MC (%)	HT (Hours)	pH (1:10 H ₂ O)	EC (dS m ⁻¹)	CEC (cmolc kg ⁻¹)	Ash (%)	TC (g kg ⁻¹)	TN	
Air-dried	0	na	4.2	1.2	6.9	2.3	320.2	13.1	
200°C	0	1	4.9	1.4	6.8	2.4	377.1	10.0	
		2	5.9	1.5	6.6	2.5	386.3	10.1	
		3	6.6	1.5	5.9	3.0	410.2	11.0	
		4	6.9	1.6	5.1	3.1	394.1	12.2	
	50	3	5.4	1.4	16.5	2.3	386.9	12.2	
		4	5.6	1.4	15.5	2.4	382.0	11.3	
	400°C	0	1	10.6	2.2	5.7	2.7	410.1	12.2
			2	10.9	2.4	4.7	3.2	403.2	13.1
3			11.1	2.5	4.5	3.3	403.4	13.1	
4			11.1	2.7	4.4	3.5	371.1	13.1	
50		1	10.1	2.0	15.5	2.5	362.1	13.2	
		2	11.0	2.6	10.6	3.0	344.9	13.1	
		3	11.6	2.8	8.9	3.2	323.8	13.0	
		4	11.8	2.8	8.8	3.3	313.1	13.0	
80		2	9.4	1.7	4.8	1.6	345.6	13.0	
		3	10.6	2.3	4.7	1.7	320.5	13.0	
		4	11.2	2.5	5.0	2.7	241.1	13.0	
		1	11.3	3.4	5.4	3.0	389.3	11.2	
600°C	0	2	12.0	3.8	4.5	3.7	392.9	11.2	
		3	12.0	4.2	4.2	5.0	392.7	11.2	
		4	12.0	5.4	4.1	5.1	363.0	11.2	
		1	12.7	3.3	15.5	3.6	353.2	12.1	
	50	2	12.7	3.3	10.4	3.4	333.4	12.0	
		3	12.7	3.6	8.6	3.6	289.1	12.0	
		4	12.7	3.9	8.7	3.7	267.0	11.0	
		1	11.3	3.1	9.2	3.4	310.9	13.0	
80	2	12.1	3.1	10.3	3.4	309.0	12.0		
	3	12.0	3.4	10.5	3.5	298.7	12.0		
	4	11.8	3.6	10.8	3.5	229.0	12.0		

Values are means of three triplicate measurement

MC = Moisture content, HT = Holding time, CEC = Cation exchange capacity

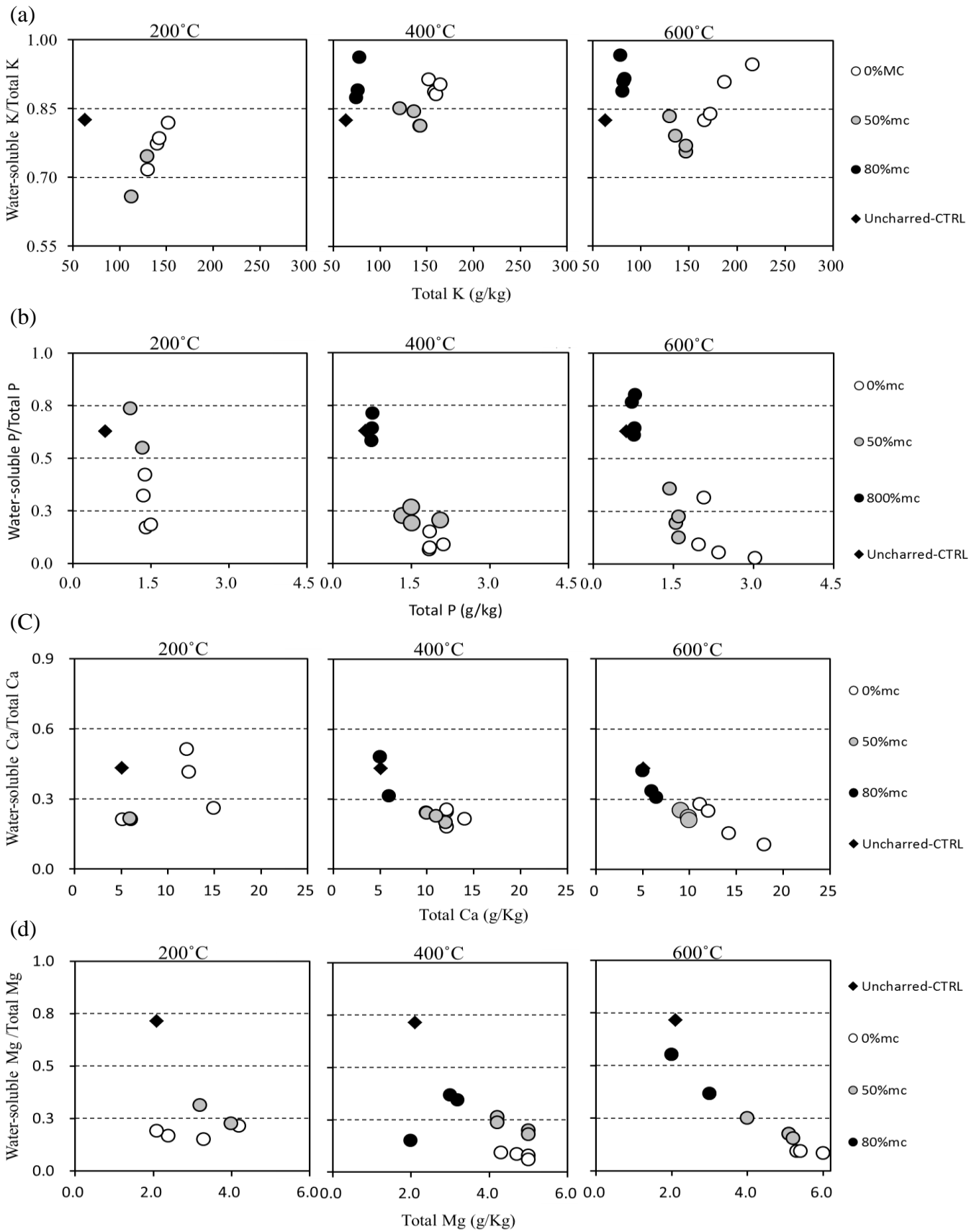


Figure 14. Total and water-soluble mineral nutrient fractions of produced biochars

3.4.5 Optical properties alkaline biochar extracts

UV–Vis analysis of alkali extracts from banana peel biochar is shown in **Figure 15**. Kumada (1987) classified humic acids (HA) into four types: A, B, P and Rp basing on relative color density (RF) and color coefficient ($\Delta \log K$) of alkali HA extracts. A-type HA is the darkest and most humified, with more aromatic and carbonyl, and less aliphatic groups (Yonebayashi, 1988); B-type HA is brownish, with more aliphatic and less carbonyl group content, while P is characterized by high Pg content (Pg is a type of green pigment present in HA). Rp-type HA is presumed to be formed during the rotting process of plant residues, and constitutes the initial stage of humification (Yonebayashi, 1988). Meanwhile, Pg index (PI) is depicted by a remarkable strength of absorbance at two spectral curves at wavelengths: 610 and 600 nm, and reflects the density of Pg pigment present in HA. It is used to differentiate P+ ~ +++ type of HA from other types (Yamamoto et al. 2000). A graph plot of the absorbance ratios: MI = (A450/A520) against Pg index = (A610/A600) shows the overall qualitative degree of humification of organic matter in a material. In this study, degree of humification increased with increase in charring temperature and holding time; with samples at 200°C remaining nearly as humified as the uncharred material, while those at 600°C where all transformed into the A-type HA (**Figure 15**). This was probably due to increase in aromatization and density of conjugated double bonds at elevated temperatures (Kim et al. 2012); thus implying that biochar stability increased with pyrolysis temperature. The effect of MC on humification varied widely, but appeared to promote humification. Besides pyrolysis temperature and holding time, biomass feedstock moisture content significantly influences biochar quality, with respect to humification. Quantities of produced humic substances were estimated as a function of optical density of undiluted alkali biochar extracts at 600 nm (**Figure 16**).

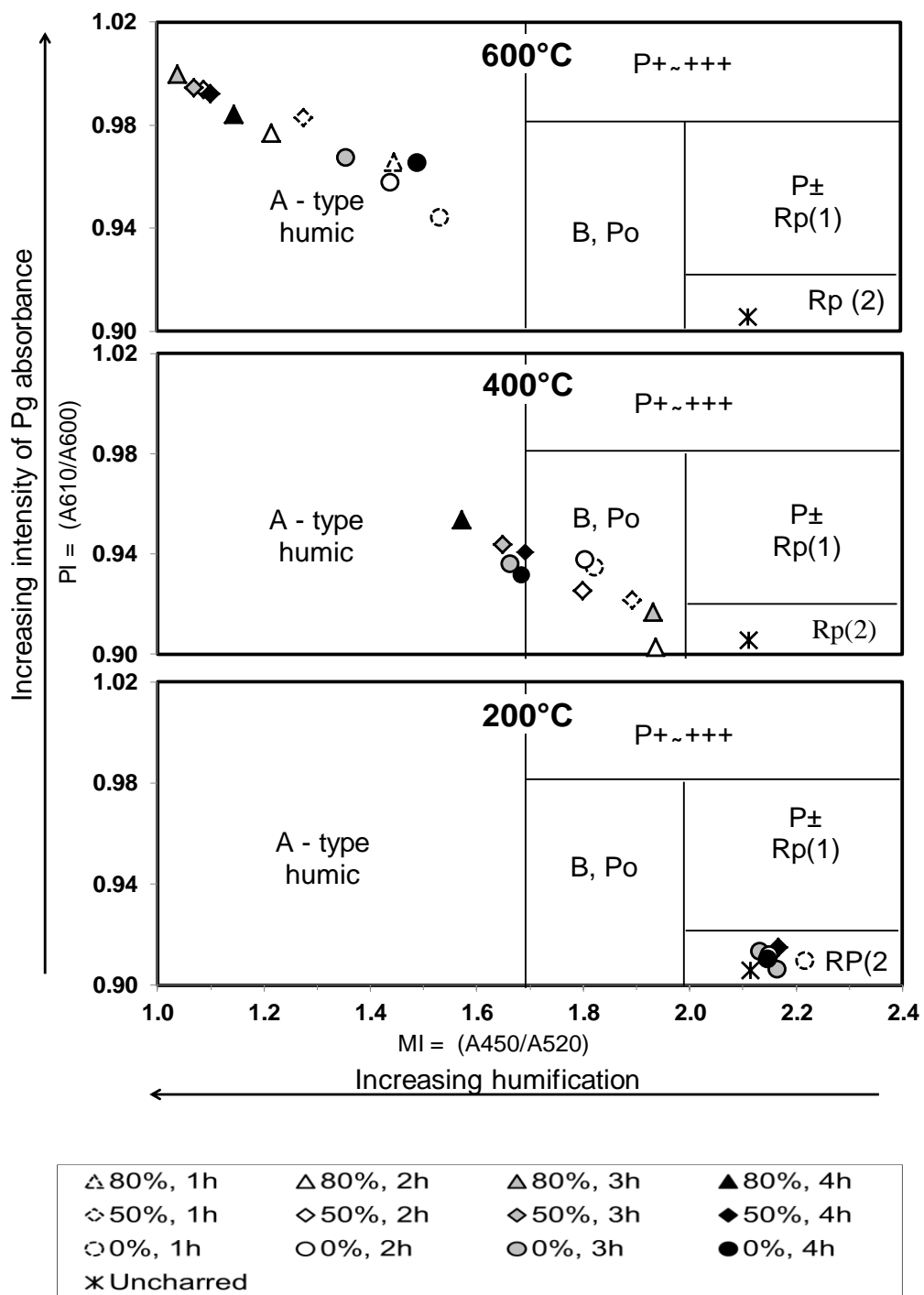


Figure 15. Optical properties of alkali extracts from banana peel biochar

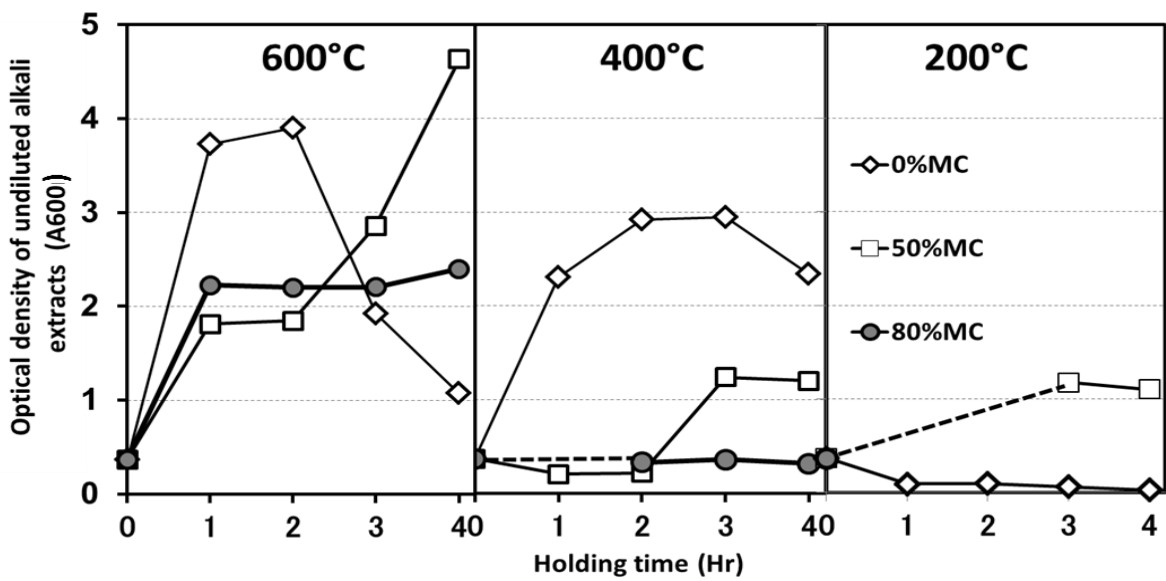


Figure 16. Optical density of undiluted alkali biochar extracts at 600nm

Yamamoto et al. (2000) had illustrated that optical absorbance of undiluted alkali extracts at 600 nm is proportional to the quantity of produced humic substances. Formation of humic substances was in the order: 600 > 400 > 200°C. At 600°C/0%MC, shorter holding time (2 hours) is sufficient to produce highly humified biochar, while a longer period leads to a decline in humic substances, likely due to thermo-chemical degradation. Presence of moisture requires longer holding time, but produces a higher amount of humic substances.

3.4.6 ATR-FTIR spectroscopy

FTIR spectra of the uncharred material and banana peel biochars derived under varying MC and pyrolysis conditions are shown in **Figure 17(a,b)**. Spectral patterns reflect physiochemical transformation during the charring process mainly arising from: dehydration, organic matter combustion and the consequent mineral content concentration (Chen et al. 2012). The spectrum for the uncharred sample showed predominance of organic functional groups, with the peak at 3298 cm⁻¹ likely due to OH or NH vibrations from organic matter. This band diminished with increasing pyrolysis temperature due to the cleavage of organic groups during combustion. The peaks at about 3700 cm⁻¹ and 3600 cm⁻¹ corresponding to vibration of OH groups in the mineral matter were present even at elevated temperatures, thus confirming the stability of the mineral over the organic components. The bands at 2918 cm⁻¹ and 2849 cm⁻¹ correspond to aliphatic CH₃ asymmetric and symmetric stretching vibration respectively. Methyl groups (CH₃) just like the OH and NH groups, are the weakest functional groups and break at low temperatures. The cleavage of these groups is contributing to char yield loss during thermal decomposition.

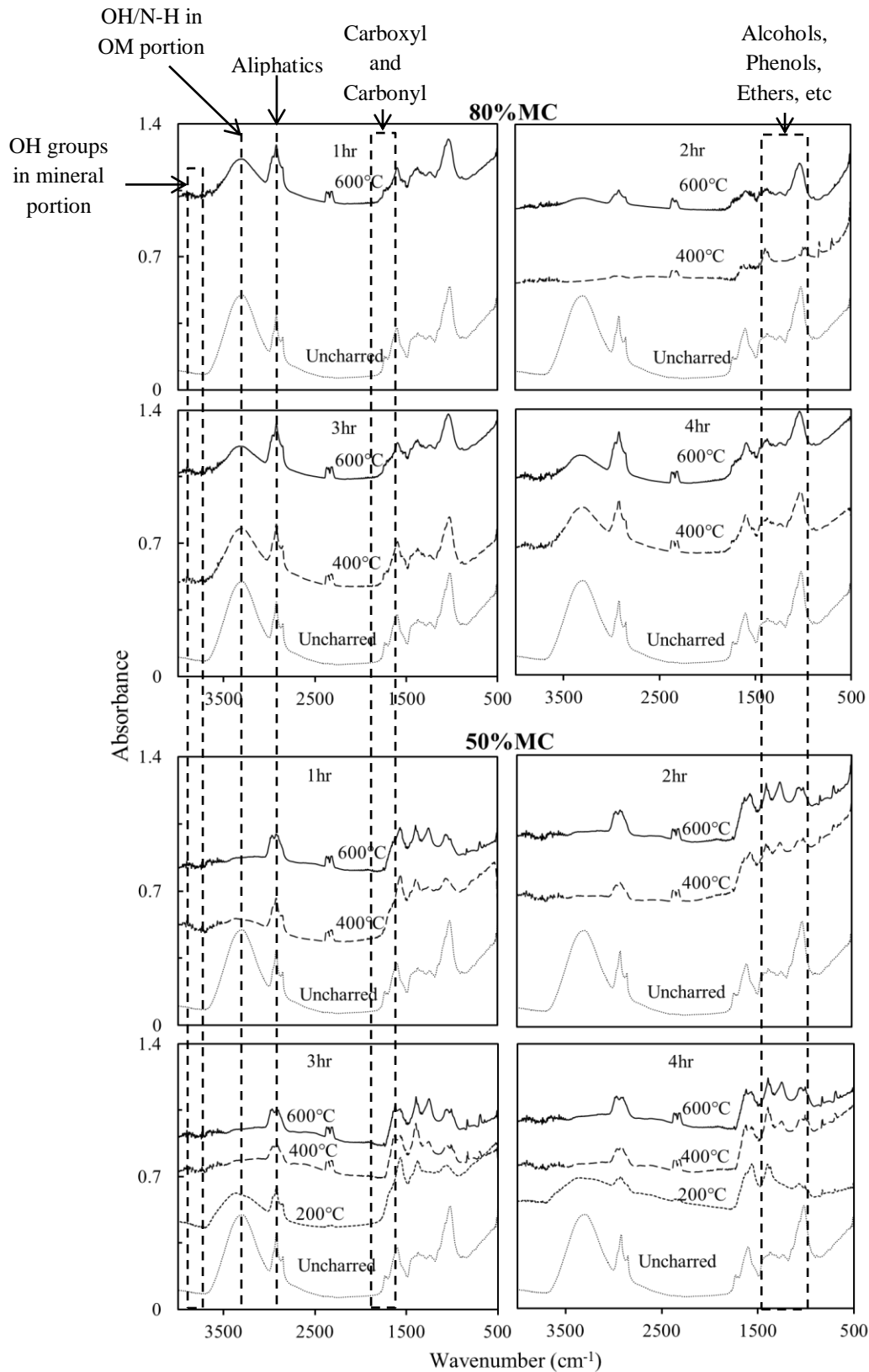


Figure 17a. ATR-FTIR spectra of banana peel biochar prepared under different biomass feedstock moisture and pyrolysis conditions

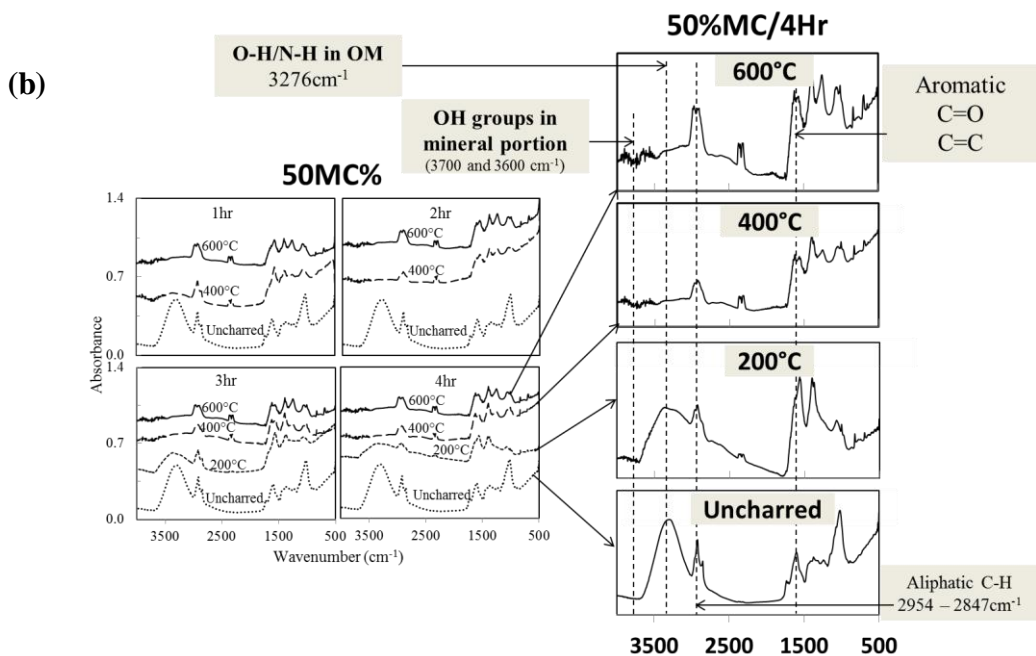
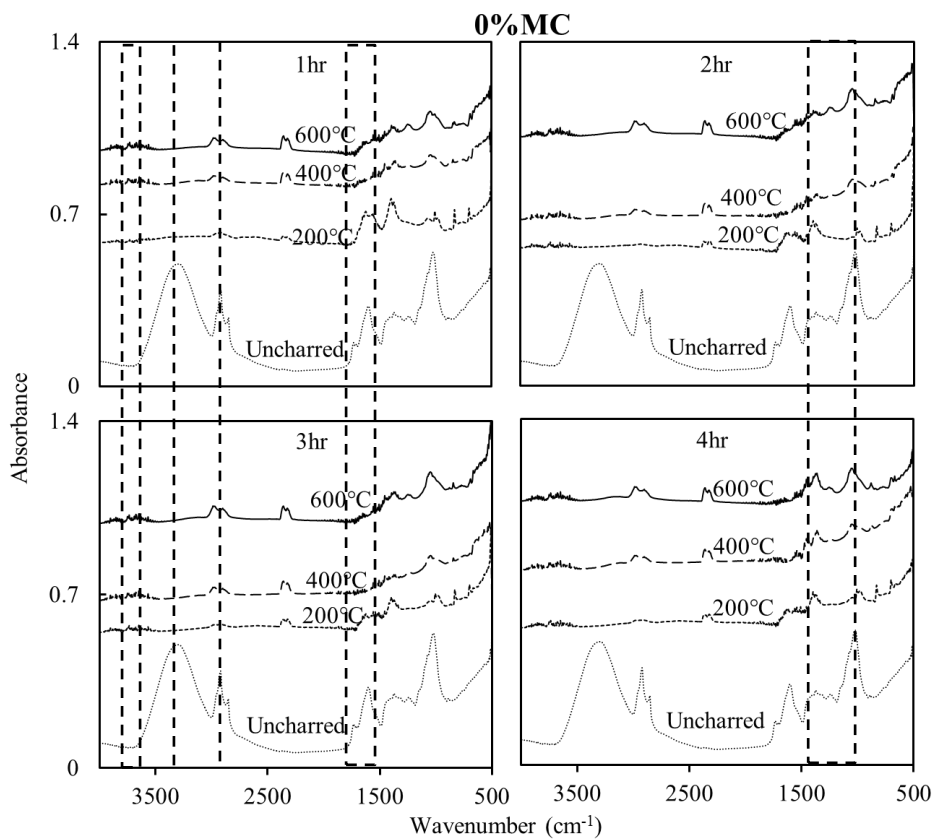


Figure 17b. ATR-FTIR spectra of banana peel biochar prepared under different biomass feedstock moisture and pyrolysis conditions

Aromatic and hetero-aromatic compounds are confirmed by C-H wagging vibrations in the region between 800 and 600 cm^{-1} . The intensity of these peaks increases with temperature and holding time, thus indicating the stability of aromatic and hetero-aromatic compounds and possible cyclisation. These results are in agreement with those of optical properties, in which humification/char stability increased with pyrolysis temperature.

3.4.7 Incubation test

The EC and pH of incubated soil-biochar extracts are shown in **Figure 18(a, b)** and **Table 11**. Both parameters significantly increased with application rate for both types of biochars (produced at 400 and 600 °C), likely due to increase in inorganic salt loading. EC increased from 0.04 (soil only) to 2.1 and to 3.0 dS/m (at 10% application rate) for the biochars produced at 400 and 600 °C respectively (**Figure 18a**). Similarly, pH ranged 3.7–4.5 (soil:H₂O, KCl, CaCl₂·2H₂O), increasing to 6.7–7.6 and 7.8–8.4 at 10% application rate for biochars produced at 400 and 600 °C, respectively (**Figure 18b**). Whereas this biochar successfully remediated soil acidity, the necessary application rates were high, and if applied in the field, could lead to excess nutrient application, especially K. For instance, to raise pH (H₂O) from 4.5 to 7.0, it would require an application rate of about 7.8 and 9.5% for the two different biochars respectively. This is considered quite high, as compared to 1–2% application rates commonly used, and would definitely result in excess K supply. Therefore, banana peel biochar is not advisable for use in soil acidity remediation, but would certainly reduce liming requirements when applied as a K–nutrient source.

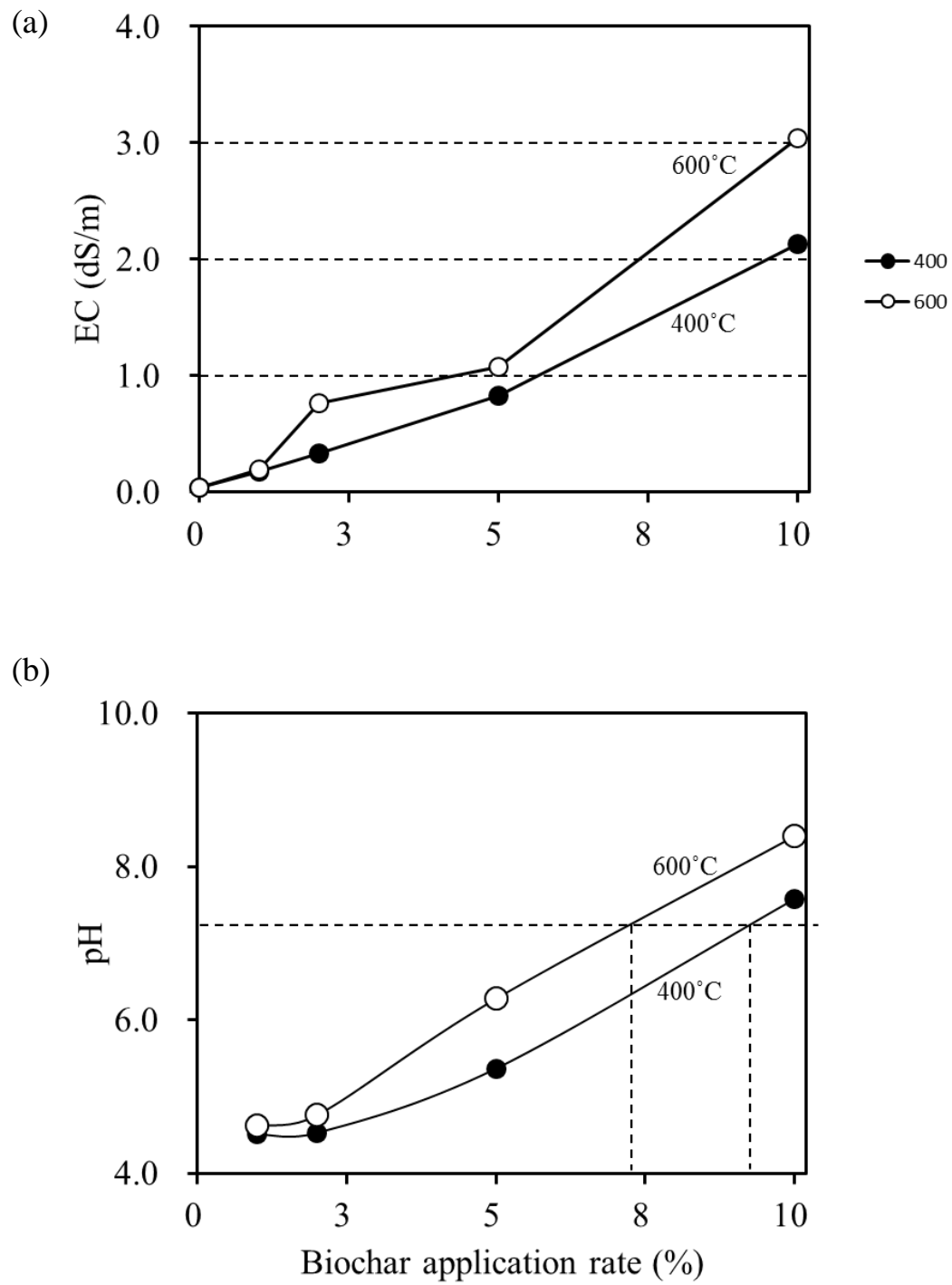


Figure 18 (a) EC and (b) pH (H₂O) of incubated soil-biochar mixtures

Table 11. EC and pH of incubated soil/biochar mixtures

Pyrolysis Temperature (°C)	Application rate (%)	EC (1:5) (mS/m)	pH (1:2.5 w/v)		
			H ₂ O	KCl	CaCl ₂ .2H ₂ O
400	0	3.79	4.50	3.72	3.85
	1	17.16	4.51	3.84	3.97
	2	33.05	4.53	3.94	4.13
	5	82.57	5.37	4.61	4.98
	10	213.33	7.58	6.79	7.02
600	1	19.52	4.62	3.90	4.06
	2	75.97	4.76	4.75	4.30
	5	107.20	6.28	5.59	6.11
	10	303.67	8.40	7.84	7.90

Values are means of three triplicates

3.5 Conclusions

Initial biomass feedstock MC and pyrolysis conditions significantly influenced the thermo-decomposition process; thus determining the possible biochar functionality and stability. Yield under the different feedstock moisture and temperature conditions was in the order: 0 > 50 > 80%, and 200 > 400 > 600°C, respectively. Holding time had a similar, but less significant influence on biochar physiochemical characteristics as compared to pyrolysis temperature. Choice of particular pyrolysis conditions would depend on ultimate usage; for instance biochar for use in low fertility soils, moderate conditions of 50% MC and temperature of 400°C/1–2 hrs would be ideal.

Though highly alkaline, banana peel biochar is not advisable for use as a soil acidity remediation agent due to risk of over application of K. Instead, this biochar could be used as K fertilizer (> 10% K).

CHAPTER 4

General discussion and conclusion

4.1 Banana peel composting

This work evaluated compost and biochar production concepts as candidate pathways for sustainable and profitable management of banana peel wastes. The composting process took 12 weeks, and reported on agronomic characteristics of banana peel-based compost under different inoculation and aeration conditions. Inoculation and aeration were found to be essential for an efficient composting process due to their roles in enhancing microbial activity and composting environment. Earthworm inoculation was unsuccessful, due to “hash” environmental conditions for their survival; however, this could be mitigated with “relay” inoculation, where earthworms would be introduced at a later stage of the composting cycle; in essence after the mesophilic and thermophilic stages, where temperatures rise to lethal levels of over 70°C. The high toxic alkalinity could also be remediated through administration of buffer agents such as ash during composting. This would have additional benefits of mitigating the high NH₃ volatilization that was observed during composting. High alkalinity is also toxic to the nitrifying bacteria; therefore its remediation would boost nitrification. Additionally, although aeration supports composting, the pressurized air supply system appeared to exacerbate nitrogen loss through NH₃ volatilization; therefore, caution ought to be taken while setting up pressurized air supply systems for composting in order to conserve nitrogen. Overall, banana peel-based compost showed potential for use as source of N and K fertilizer; and also owing to its high alkalinity could be useful in soil acidity

remediation. For small scale on-farm banana waste management, a composting pile, covered with polythene material (for heat retention) and fitted with a perforated pipe at an angle (about 45°C - for aeration) could produce good quality compost for soil amelioration.

4.2 Banana peel biochar production

The biochar study assessed the agronomic- and eco- value of banana peel-based biochar. Biochar was produced under different moisture and pyrolysis temperature conditions, and a significant influence of the production conditions on produced biochar properties and potential utility was reported. Pyrolysis temperature of 400°C appeared ideal for agricultural-use biochar production; besides, 400°C is attainable using low-cost field-based equipment for poor farmers. 600°C was recommended for carbon sequestration; however, attainment of this temperature requires more advanced/expensive equipment. In both cases, presence of moisture in the peels was shown to facilitate humification. Further studies are necessary to confirm this phenomenon, and clarify the mode of action. Banana peel biochar showed high K mineral nutrient enrichment, thus its potential utility for the same as fertilizer.

4.3 Comparison between banana peel-based compost and biochar

A summarized comparison between banana peel-based compost and biochar is shown in **Table 12**. The two products have common and special attributes, suggesting that choice needs to be guided by the ultimate/preferred goal. For instance, composting retains relatively higher N, while charring literally loses most it. Conversely, other mineral nutrient contents are more enriched in biochar as compared to compost. Due to high energy and equipment

requirements, biochar production may be unsuitable for the poor rural farmers, who instead should employ composting. For large scale banana waste management, especially in urban centers, charring is recommended as the waste volume reduction is higher as compared to composting. The produced biochars are cheaper to transport back to the rural production areas and easier to apply in the field. Integrated use of banana peel-based biochar and compost is a possibility, as studies have shown potential beneficial synergy in the practice. Combining compost and biochar potentially improves the overall quality of the additives; enhanced nutrient fertility, increased CEC, increased pH, liming effect and improved buffering capacity, immobilization of soil heavy metals/biochemicals, Improved air balance, improved pore volume and hydraulic conductivity, and increased aggregate stability. This concept however, requires specialized studies using intended materials prior to adoption.

4.4 Overall conclusion

Compost and biochar production are viable pathways for sustainable banana peel waste management as K fertilizer. The 0.4 million tons of peels produced in Uganda annually could yield an estimated 96,000 t compost, enough for 96,000 ha for banana cultivation. 64,000 t of biochar is attainable, and could supply 19,200 tK₂O enough for about 275,000 ha for banana cultivation

Table 12. Comparison between banana peel based biochar and compost

Parameter	Banana peel-based	
	Compost	Biochar
Nutrient supply potential	Moderate-low, but Largely bio-available	Highly enriched (except N), but largely fixed
Soil pH remediation potential	Moderate acidity remediation	Variable, influenced by temperature
Waste volume reduction	Moderate	Higher/more suitable
Production time	12 weeks	A few hours
Energy/equipment requirement	Low/cheaper	High/more expensive
Location suitability	On-farm/rural	Urban

CHAPTER 5

Summary

Soil fertility depletion through erosion and “low in-put agriculture” is the major obstacle to increased crop production and productivity, and household incomes in Sub-Saharan Africa. Chemical fertilizer usage for soil fertility enhancement is quite low due to social-economic constraints. Meanwhile, a large volume of banana, and therefore banana wastes is produced in Uganda (20th World-leading banana producer). The wastes could be processed into potentially beneficial products for soil amendment and C-sequestration. The current disposal practices (dumping and landfill) are both wasteful and environmentally hazardous. This work evaluated two concepts (i.e. compost and biochar production) with potential for sustainable and profitable management of banana wastes. Evaluation encompassed compositional analysis of the products for soil additive potential, and recalcitrance for carbon sequestration. The first study aimed to evaluate the efficacy of aerobic and anaerobic composting methods for banana peels and the effect of poultry litter, cow dung and earthworm as starter inoculums on composting, as well as to determine the dominant mineral nutrient components of banana residue-based compost. 5 kg aliquots of withered banana peels (60%MC) were placed in two different sets of compost boxes (aerobic and anaerobic). These were then inoculated and thoroughly mixed with 0.5 kg of either cow dung (C), poultry litter (P) or earthworm (E) at 1.6 kg m⁻³ density to obtain the formulations: (i) plain banana peels (B) serving as control, (ii) banana peel + cow dung (BC), (iii) banana peel + poultry litter (BP) and (iv) banana peel + earthworm (BE). For the aerobic setup, boxes were fitted with a vent pipe at the top and an air-supply tube connected to a 1.5 L. min⁻¹

air pump at the bottom, while the boxes under anaerobic composting were completely sealed. The experiment was set and left to run in an incubation room (40°C) for a 12-weeks period. Bi-weekly monitoring of the physiochemical characteristics of compost samples revealed that inoculation and aeration are essential for an enhanced composting process. Effect of inoculation was in the order: poultry litter > cow dung > plain peels. Earthworm inoculation was unsuccessful, as earthworms died two days into composting, likely due to unfavourable environmental conditions (temperatures > 40°C, pH > 7 and moisture content > 45%). Accelerated composting under inoculated conditions was likely due to increased microbial activity; as a diverse population of organic matter degrading microorganisms, including *Pseudomonas* had been reported in animal wastes. Additionally, mineral nutrients N and P in the inoculum formulations might have promoted prolific growth and activity of the microbes. These are believed to be essential in the biodegradation of organic compounds. Higher decomposition rate under aerobic as compared to anaerobic conditions was likely due to increased bio-oxidative activity. Bernal et al. (2008) had found that during the different stages of biodegradation, organic compounds are degraded to CO₂ and NH₃, with consumption of copious amount of oxygen. The final compost formulations were especially rich in N and K mineral nutrient concentrations ranging 2.04–2.18% and 12.2–13.9% under aerobic and 1.84–2.09 and 10.44–11.86% under anaerobic composting conditions respectively; thus suggesting potential for use as N and K fertilizers. Pot cultivation trials however, revealed a risk of alkalinity toxicity when compost is used to supply N. The composts were also highly alkaline (pH > 9), indicating their potential usability in liming in some of Uganda's highly weathered/acidic soils. This result constitutes the core of this study's novelty, as no other had reported on the physiochemical characterization and potential utilization of banana waste-based compost. Summarily, although composting under aerobic was generally more efficient than that under anaerobic conditions, nitrification was

largely inhibited in both setups; there was massive loss of N through NH_3 volatilization likely caused by the high composting pH. Use of appropriate pH correction additives during composting might help minimize NH_3 loss and enhance nitrification. Also, due to high compost alkalinity, appropriate nutrient supply management might be necessary especially if applied at germination to protect plants. The compost is also low in other useful nutrients, such as P, Ca and Mg; thus the need for supplementary supply of deficient nutrients.

Despite its high potential agro-ecological value, composting poses some challenges; such as the long composting period (> 10 weeks), and composts' easy decomposability (low stability). A second study was therefore undertaken to assess biochar production as a second value-added approach for sustainable and profitable management of banana wastes. The study aimed to characterize and compare physiochemical properties (mineral nutrient content, pH, EC, CEC, humification) of banana peel biochar produced under different biomass feedstock moisture content (MC), pyrolysis holding time (HT) and temperature conditions. Additionally, the study also served to fill in an information gap on physiochemical characterization of banana waste-based biochar, which had not been reported on. Biochar was made from banana peels of 0, 50 and 80% MC by heating at 200, 400 and 600°C for 1, 2, 3 and 4 hours of HT. Resultant biochars varied widely in physiochemical properties, with 200°C producing the least transformed biochar, and in some cases (high MC/short HT such as: 80%MC/1-4 hrs HT, 50%MC/1-2 hrs HT, 0%MC/1 hr), the conditions were insufficient for carbonization (no biochar formed). Initial biomass feedstock MC and pyrolysis conditions significantly influenced the thermo-decomposition process; thus determining the possible biochar functionality and stability. Moisture content affected physiochemical characteristics (mineral nutrient content, pH, EC) in the order: 0 > 50 > 80 % MC; humification and CEC however, behaved differently, with presence of moisture (50 and 80%MC) appearing to enhance humification and CEC build-up as compared to no-moisture conditions (0%). This

suggested that presence moisture might be essential for enhanced humification and CEC build-up during charring. Yield under the different feedstock moisture conditions was in the order: 0 > 50 > 80%. This work is the first to delve into the effect of initial feedstock biomass moisture content on physiochemical properties of produced chars; further studies are required to confirm these findings, and understand the mode of action. Temperature generally affected biochar properties in the order: 600 > 400 > 200°C, except for yield. At 600°C, biochars were the most humified, containing the highest degree of condensation, thus likely the most stable. Effect of HT on charring was similar, but of less significance as compared to temperature. The key nutrient contents and characteristics (P, K, pH, CEC) of produced biochars were moderate and in some cases slightly less at 400°C as compared to 600°C. Choice of particular pyrolysis conditions would depend on ultimate usage; for instance biochar for use in low fertility soils, moderate conditions of 50% MC and temperature of 400°C/1–2 hrs would be ideal. Though highly alkaline (at 400 and 600 °C, pH > 10), banana peel biochar is not advisable for use as a soil acidity remediation agent due to risk of over application of K. Instead, this biochar could be used as K fertilizer (> 10%K).

In this work, UV-vis spectrophotometric analytical technique on humic substances by Kumada(1987) and later modification by Yamamoto et al. (2000) has been further validated (on biochar humification); the procedure had previously been used on soil and compost humification analysis. It is much simpler and uses less advanced equipment. UV-vis Spectral data on degree of humification under the different treatments strongly correlated with and were supported by those on the chemical bonding patterns/functional groups' variation from the ATR/FTIR spectroscopic analysis.

The two products have common and special attributes, suggesting that choice needs to be guided by the ultimate goal. For instance, composting retains relatively higher N, while

charring literally loses most it. Conversely, other mineral nutrient contents are more enriched in biochar as compared to compost. Due to high energy and equipment requirements, biochar production may be unsuitable for the poor rural farmers, who instead should employ composting. For large scale banana waste management, especially in urban centers, charring is recommended as the waste volume reduction is higher as compared to composting. The produced biochars are cheaper to transport back to the rural production areas and easier to apply in the field. Integrated use of banana peel-based biochar and compost is a possibility, as studies have shown beneficial synergy in the practice. Combining compost and biochar potentially improves the overall quality of the additives; enhanced nutrient fertility, increased CEC, increased pH, liming effect, improved air balance, improved pore volume and hydraulic conductivity, and increased aggregate stability. This concept however, requires specialized studies using intended materials prior to adoption.

Summarily, compost and biochar production are viable pathways for sustainable banana peel waste management as K fertilizer. The 0.4 million tons of peels produced in Uganda annually could yield an estimated 96,000 t compost, enough for 96,000 ha for banana cultivation. 64,000 t of biochar is attainable, and could supply 19,200 tK₂O enough for about 275,000 ha for banana cultivation

要約

サブサハラ地域の土壌肥沃度向上は、急増する人口を賄う食糧の持続的確保のために喫緊の課題である。そのためには有機物の物質循環を基本とした土壌管理による持続的な農業生産システムの構築が必須である。アフリカ第三位のバナナ生産国であるウガンダ共和国は、その大半が国内消費され、都市部においては大量のバナナ廃棄物（バナナ果実不可食部、主に皮部分）が環境問題を誘発している。バナナ生産農地は不十分な養分還元により肥沃度低下が深刻化している一方、バナナ廃棄物を農業利用するための知見は未だ不十分である。本研究では、土壌肥沃度改善のためのバナナ廃棄物の持続的および有効な利用法を提言するために、堆肥化および炭化処理の2つの方法について評価し、以下の新しい知見を得た。

1. バナナ廃棄物の堆肥条件と堆肥の特性を調べ、有機物資材としてのバナナ堆肥の特性を明らかにした。

バナナ廃棄物の堆肥化は好気条件と副資材添加で大きく促進された。好気条件においては最高温度が77~85°Cに達したが、嫌気条件では50~60°Cにとどまった。また、両区とも鶏ふん添加区の温度が最も高くなった。ウガンダには土抗中で有機物を嫌気発酵させる伝統的方法があるが、大量の廃棄物処理のためには好氣的な堆肥化が適することを示した。バナナ廃棄物のpHは9.2と高く、堆肥化が9以上の強アルカリ性下で進行したため、硝化作用が両条件区とも抑制され、アンモニアが集積していた。

バナナ堆肥（12週間堆肥化）は好気、嫌気条件ともpHが高く（9以上）、カリウムに富んでいた（有効態として130~175g K₂O kg⁻¹）。リン、カルシウム、マグネシ

ウムの有効態含量は低く、カリウムの 1/100 オーダーであった。堆肥の現物 1 トンを 1ha に施与すると有効態カリウムがバナナ栽培に十分な量 (50~70kg K_2O) を供給できると見積もられた。バナナ堆肥の全窒素は 2%程度あり、堆肥として低いレベルではないが、カリウム含量が高いため、窒素必要量を基準とする施与においては、土壌が強アルカリ性化し、幼植物栽培試験における発芽も認められなかった。よって、本堆肥は、有機物供給資材、窒素供給資材ではなく、カリウム供給資材 (緩効的な有機質カリウム肥料) として取り扱うべきと結論した。

2. バナナ廃棄物の炭化条件 (炭化温度: 200, 400, 600°C, 加熱時間: 1~4 時間, 材料の水分含量: 0, 50, 80%) と炭化物の特性との関係を調べ、バナナ炭化物の土壌改良資材としての特性を明らかにした。

炭化物収率 (BCY), 炭素残存率 (CRR) には、炭化温度、水分条件が大きく影響した。200°Cの高水分条件では炭化物が生成しない場合があった。400, 600°Cでは、水分条件の影響が大きく、水分含量 80% (新鮮物相当) 区において BCY, CRR が顕著に低下した (0%区に対し最大 50%低下)。また、低水分条件における長時間の炭化は BCY, CRR を顕著に低下させたが、高水分条件においてはその変化が小さかった。

バナナ炭化物は高 pH, 高カリウム資材であった。炭化物の pH は、200°Cでは 5 程度であったが、400°Cでは 10~11, 600°Cでは 12 以上に上昇した。炭化物の全窒素はいずれも 10~15 g kg^{-1} の範囲にあった。カリウム含量が最も高く 150~300 g K_2O kg^{-1} にも達し、材料の水分含量が高いほど可給度が上昇する傾向が認められた。本資材は、土壌酸性矯正のために使用するとカリウムの過剰施与になるため、カリ肥料としての取り扱いを推奨した。

バナナ廃棄物は水分共存下で炭化させると CEC の上昇が認められ (5→10~15 cmolc kg⁻¹) , 炭化過程における生成される腐植物質との関連が示唆された。腐植物質の生成と腐植化度には炭化温度と水分条件が大きく影響し、600°Cにおいてはすべての条件で腐植化度の最も高い A 型腐植酸を含む炭化物が生成し、水分含量 50, 80%で腐植化度が最高となった。炭化条件によって有機物変化の過程が異なり、養分保持等の機能性、より高い生物分解抵抗性を付与できることを明らかにした。酸性低肥沃度土壌の高い改良効果を持つ炭化物を調整するためには、適度な水分を含む材料を用いことが重要であり、炭化温度は 400°C以上で、炭化時間は 1~2 時間で充分であると結論された。

以上のことから、これまで知見が不足していたバナナ廃棄物の堆肥、炭化物の効果的調製方法とその特性が明らかにされ、これらを踏まえた適切な利用方法を示すことができた。この研究成果は、有機性廃棄物の地域内循環を基本にした開発途上国における持続的農業生産システムの構築に活用し、ウガンダ国のみならずアフリカ諸国等の途上国における持続的な食料生産にも大きく貢献するものであると考えられた。

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List of publications

1. F. Kalemelawa, E. Nishihara, T. Endo, Z. Ahmad, R. Yeasmin, M.M. Tenywa, S.Yamamoto. An evaluation of aerobic and anaerobic composting of banana peels treated with different inoculums for soil nutrient replenishment. *Bioresource Technology* 126 (2012) 375–382 (See Chapter two)
2. F. Kalemelawa, S. Yamamoto, E. Nishihara, M.M Tenywa, T. Endo, H. Matsumoto. Pyrolytic conversion of banana peel wastes into biochar for soil amendment and carbon sequestration. *The Wood Carbonization Research Society* Accepted on June 9 2013 (See chapter three)