THE USE OF BIOCHAR AND CHARCOAL AS SOIL AMENDMENTS TO IMPROVE ALLELOCHEMICAL-LADEN SOILS IN THE LANDSCAPE

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A THESIS SUBMITTED TO THE SCHOOL OF RESEARCH AND GRADUATE STUDIES, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY (MPhil LANDSCAPE STUDIES) DEGREE

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DECLARATION

I hereby declare that this work entitled, “The Use Of Biochar And Charcoal As Soil Amendments To Improve Allelochemical-Laden Soils in the Landscape” is a true account of my own work except for the references which have been duly acknowledged.

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(HEAD OF DEPARTMENT)

DEDICATION

This work is dedicated to my sweet mother, Madam Charlotte Buerkie Nubuor for her unflinching prayers, guidance, support, advice and undying love throughout my schooling period.

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My most heartfelt gratitude goes to God Almighty and His Host of Angels for seeing me through this phase of my life successfully.

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ABSTRACT

The landscape and turf industries are based on beauty. Some trees in the landscape suppress the growth of any other plant species beneath them. This is reported to be caused by the presence of allelochemicals which are released into the soil by the plants, a mechanism known as allelopathy. Soil amendment is therefore needed to curb the effects of these allelochemicals and make the nutrients in the soil available to other plant species that may be planted beneath the allelopathic trees. There is evidence from thousands of years of traditional use of charcoal as amendment in the terra preta soils of Brazil. Biochar, a pyrolised biomass, is a fine-grained, highly porous charcoal substance that is used as a soil amendment. The study was conducted to find out the ameliorative effect of biochar and charcoal in allelochemical-laden soils to improve on the physicochemical properties of the soil. Charcoal produced from *Tectona grandis* tree, biochar produced from four different types of sawdust (*Tectona grandis*, *Celtis mildbraedii*, *Entandrophragma cylindricum* and *Khaya senegalensis*) and absolute control were the treatments used. The study was carried out beneath three trees suspected to be allelopathic (*Tectona grandis, Eucalyptus grandis* and *Bambusa sp.*). St. Augustine's grass was used for the study because it prefers shaded growing environmental conditions. The experimental design employed was Randomized Complete Block Design (RCBD) and the experiment was replicated three times. Data collected over a period of twelve weeks included presence of allelochemicals in the soil and in the tree species, rate of spread and rate of growth of grass, weed count, soil nutrient analysis, soil water-holding capacity, presence of soil microorganisms and soil pH. The results of the study indicated that the three landscape trees are allelopathic. The biochar and charcoal were able to ameliorate the effects of the allelochemicals and hence allowed the grass to grow well

under the trees. Significant differences were observed in the rate of spread of grass as well as the rate of growth. Available phosphorous and soil potassium were increased in the biochar amended plots whereas total nitrogen was reduced due to adsorption of NH^{3-} and NH^{4+} from the soil solution onto the biochar surface. Soil organic carbon was reduced due to the priming effect of biochar. Water-holding capacity was increased tremendously in all amended plots due to the porous nature of the charcoal and biochar. Both amendments were able to improve soil pH to an optimum range for most plants. It was recommended that other feedstock types for biochar and charcoal production should be considered in further studies to find out which feedstock type can also improve the soil where allelochemicals have been found.

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LIST OF ACRONYMS

SOM	Soil Organic Matter
SOC	Soil Organic Carbon
T_{TB}	Teak biochar
T_{EB}	Esa biochar
T_{MB}	Mahogany biochar
T_{SB}	Sapele biochar
T_{CH}	Charcoal
T_{CT}	Control
CEC	Cation Exchange Capacity
WAP	Weeks After Planting

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CHAPTER ONE

1.0 INTRODUCTION

Trees have developed in ecological systems filled with many other organisms. The environment, shared by all, contains limited resources and less-than-ideal growth conditions. All living things have strategies to thrive in this intense struggle for life and allelopathy is one such strategy of life (Coder, 1999a). The term "allelopathy" is from Greek literally meaning "to suffer from each other." Allelopathic plants release allelochemicals into the environment and in most cases the release of these chemicals results in more resources available to the allelopathic plant for uptake (Pisula and Meiners, 2010). To allow other plants to survive in allelopathic soils, it is important to amend allelochemical-laden soils to nullify the effects of the allelochemicals and boost the resistance of the plant.

According to Davis and Wilson (2005), a soil amendment is any material added to a soil to improve its physicochemical properties. The goal is to provide a better environment for roots. To do its work, an amendment must be thoroughly mixed into the soil. There is evidence from thousands of years of traditional use of charcoal as amendment in soils. The most well-known example is the fertile Terra Preta soils in Brazil. The use of charcoal extends back as far as human history itself. In more recent times however, charcoal has remained a technologically important material, primarily as a result of its adsorptive properties. In present times, charcoal is used on an enormous scale for the purification of air and water (Harris, 1999). Biochar is a name for charcoal when it is used for particular purposes, especially as soil amendment. Like all charcoal, biochar is

created by pyrolysis of biomass mostly from organic matter (Lean, 2008). 'Biochar' is however much broader than traditional charcoal. It encompasses black carbon produced from any biomass feedstock (Woolf, 2008). Like other pyrolysis products (black carbon, activated carbon, charcoal), biochar are expected to be highly surface active materials that strongly adsorb organic compounds.

The addition of strong adsorbents such as biochar or charcoal to soil may disrupt the function of allelochemicals. It is therefore reasonable to assume that these amendments could become a useful management option for landscape designers and amenity horticulturists.

The landscape and turf industries are however based on aesthetics. A well-landscaped area should therefore look sightly and full with no bare patches in lawns and flower beds beneath and around trees. These patches allow weed growth and make the landscape not fully functional. Weeds in the landscape detract from the beauty of landscape plantings and disrupt the effect of good landscape designs.

Again, some common landscape plants which are used in Ghana are allelopathic. These include *Azadirachta indica* (Neem), *Eucalyptus sp* (Eucalyptus), *Tectona grandis* (Teak), *Acacia nilotica* (The Neem Foundation, 1997), *Bambusa sp* (Bamboo), and *Mangifera indica* (Mango) (Yan *et al.,* 2006). These landscape plant species are preferred at the same time because of certain properties they possess. For instance, the Neem tree is used for the treatment of malaria, as an insect repellent and as an insecticide and is also used in land reclamation and can therefore be able to avert problems posed in the landscape by erosion (The Neem Foundation, 1997). The eucalyptus species is also planted as an

ornamental and shade tree as well as windbreaks. Teak is desired for its appearance and durability (Miro Forestry Company, 2012). Mango is largely preferred because of its fruits and also as a good shade tree and is one of the most common landscape tree in Ghanaian homes.

Hence if there are large trees in the landscape serving such functions it will not be reasonable to remove them from the landscape just because they have allelopathic properties. Soil amendment is therefore required to enable allelopathic tree species to cope well with other landscape plants to make the landscape fully functional and aesthetically pleasing.

This study therefore aimed at using biochar and charcoal as soil amendments to improve on the effects of allelochemicals in soils laden with these chemicals to enable other landscape plants to do well under allelopathic trees.

The objectives of this study were to determine the specific allelochemicals present in selected allelopathic plants and determine the efficiency of charcoal and biochar amendments in the adsorption of allelochemicals to improve the soil physicochemical properties and the potential of biochar and charcoal in improving the nutrient status, texture and water-holding capacity of allelochemical-laden soils were also assessed.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 ALLELOPATHY

The term allelopathy is from the Greek-derived compounds *allelo-* meaning “mutual harm” or “of each other” and *-pathos* meaning "suffering". It was first detected by Davis (1928) in black walnut tree (*Juglans nigra*) whose foliar leachate containing juglone was found to damage germination and seedling growth of crops beneath the tree (Mirza, 2012). It was used in 1937 by the Austrian professor Hans Molisch in the book *Der Einfluss einer Pflanze auf die andere - Allelopathie* (The Effect of Plants on Each Other) (Willis, 2007). Allelopathy refers to the beneficial or harmful effects of one plant on another plant (both crop and weed species) by the release of chemicals from plant parts by leaching, root exudation, volatilization, residue decomposition, seed extraction and other processes in both natural and agricultural systems (Ferguson *et al.*, 2003). It is therefore a biological phenomenon and a chemical process that a plant uses to keep other plants from growing too close to it. In essence, plant allelopathy is used as a means of survival in nature, reducing competition from plants nearby. Allelopathic plants can also be affected by their own chemicals (autoallelopathy), resulting in reduced growth (Pisula and Meiners, 2010).

Chemicals released from plants and imposing allelopathic influences are termed allelochemicals. Most allelochemicals are classified as secondary metabolites of the plant (Kruse *et al.*, 2000; Stamp, 2003). Secondary metabolites are organic compounds that are not directly involved in the normal growth, development, or reproduction of an organism but are produced as offshoots of the primary metabolic pathways of the plant. It is well

documented that the production of secondary metabolites is characterized by the plant's genetic and environmental conditions during its growth (Quader *et al.,* 2001). However, these stimulatory and inhibitory effects depend on the concentration of the compounds (Bhowmik and Inderjiit, 2003). Secondary metabolites include both simple molecules such as alcohols, sugars and organic acids as well as complex compounds such as polyketides, flavonoids, terpenoids, non-ribosomal peptide compounds (Medentsev and Akimenko 1998), phenols, tannins, alkaloids, polyacetylenes, fatty acids and steroids, which have an allelopathic effect on the growth and development of the same plant or neighbouring plants. Considerable knowledge has been obtained concerning the chemicals involved in allelopathy (Rice, 1984; Narwal and Tauro, 1994).

Allelochemicals can be present in any part of the plant – in the leaves, flowers, roots, fruits, or stems – and in the surrounding soil (Anon, 2005). Allelochemicals inside a tree can produce major changes in the survival, growth, reproduction and behaviour of other organisms if they escape into the environment. The effects can be positive or negative (Coder, 1999b).

2.1.1 Release of Allelochemicals

Allelochemicals can be released or escape from a tree by several means. Mirza (2012) grouped the release pathways of allelochemicals into the following:

- Volatilization: Allelopathic trees release a chemical in a gas form through small openings in their leaves. Other plants absorb the toxic chemical and die.
- Leaching: All plants loose leaves. Some plants store protective chemicals in the leaves they drop. When the leaves fall to the ground, they decompose and give

off chemicals that protect the plant. Fall foliage tends to release more potent allelochemicals than fresh, spring foliage. Water-soluble phytotoxins may be leached from roots or aboveground plant parts or they may be actively exuded from living roots.

- Exudation: Some plants release defensive chemicals into the soil through their roots. The released chemicals are absorbed by the roots of nearby trees. Exuding compounds are selectively toxic to other plants. Exudates are usually various phenolic compounds such as coumarins that tend to inhibit development.

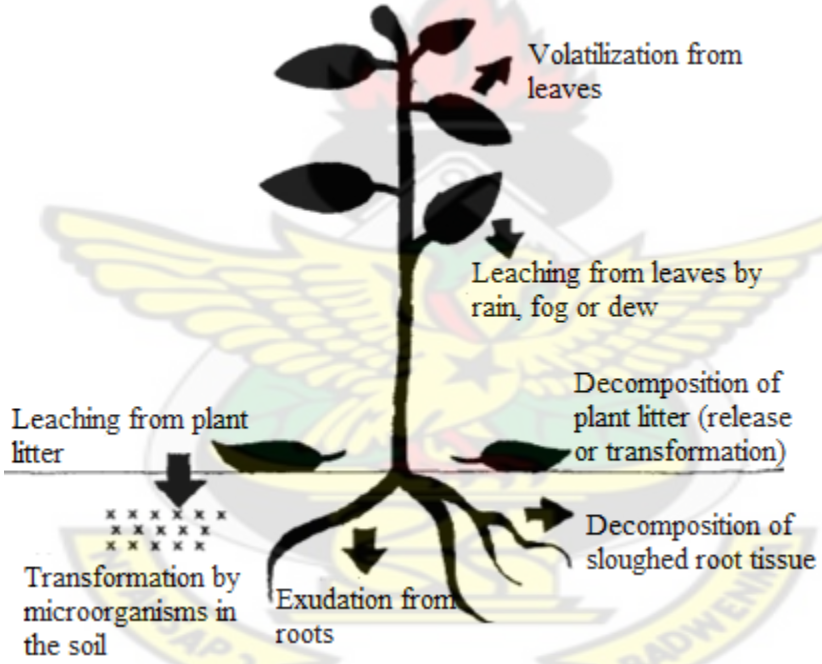

Plate 2.1: Environmental Routes of Entry of Allelochemicals (modified from Burke 1987, in Chick 1991).

Allelochemicals can also be produced when an organism is under stress. Nitrogen, phosphorus, water, and temperature extremes can all accelerate allelopathic chemical production (Coder, 1999b). Injury and pests can also rapidly increase base-level concentrations of allelopathic chemicals. Allelopathic chemicals are not newly induced in

the tree by stress, but are always present. Their concentrations change continually from day to day, (and from tree part to tree part), as their synthesis and degradation are enhanced or reduced (Coder, 1999b). Allelopathic chemicals are bundled or concentrated in many forms. Some are tied to sugar molecules which are inactive until bacteria split-off the sugar, releasing the chemical. Other allelopathic compounds are held in unoxidized forms inside cells and only produce an active agent when oxidized by injury or expulsion. Still other compounds are active, but kept sealed in special compartments or along transport corridors until needed. Allelopathic compounds can be made faster at the site of use or can be transported to the site, depending upon the chemical. These chemicals are a significant investment and biologically dangerous for an organism, and are carefully controlled (Coder, 1999b).

2.1.2 Responses of Organisms to Allelochemicals

Many organisms respond quickly to allelopathic attack by breaking-up the chemicals or transforming them into non-damaging forms. Once an allelopathic chemical is outside its producer (conveyor), the chemical is easily modified, torn-apart, reassembled, and/or used by other organisms. As a general rule, the longer species have lived together, the less allelopathy affects their interference. New species combinations, rapid successional changes, and introduced exotic species can generate a large allelopathic effect. Under good growing conditions, allelopathy usually can represent 5-10% of the total interference between species. As stress becomes great, allelopathy increases in importance. Allelopathy is an important consideration in the overall stress in any tree-containing landscape (Coder, 1999b).

Allelopathic chemicals usually have short lives in the environment. Other living things, soil chemistry and physical processes, and organic matter decay rates all can change the form and concentration levels of any compound. The original materials produced in a tree may be modified into other active allelopathic compounds in the soil (Coder, 1999a).

2.1.3 Effects of Allelochemicals on Other Plants

Commonly cited effects of allelopathy include reduced seed germination and seedling growth. Like synthetic herbicides, there is no common mode of action or physiological target site for all allelochemicals. However, known sites of action for some allelochemicals include cell division, pollen germination, nutrient uptake, photosynthesis, and specific enzyme function (Kruse *et al.*, 2000).

Allelopathic inhibition is complex and can involve the interaction of different classes of chemicals like phenolic compounds/acids, coumarins, flavonoids, terpenoids, alkaloids, steroids, carbohydrates, cyanogenic glycosides, glucosinolates and amino acids, with mixtures of different compounds sometimes having a greater allelopathic effect than individual compounds alone (UD, 2009; Mirza, 2012).

Allelopathic effects might depend on a number of factors that might be important in any given situation. These include:

- Varieties: There can be great differences in the strength of allelopathic effects between different crop varieties (Mirza, 2012).
- Autotoxicity: Allelopathic chemicals may not only suppress the growth of other plant species, they can also suppress the germination or growth of seeds and

plants of the same species. For instance the toxic effect of wheat straw on following wheat crops is well known (Ferguson *et al.*, 2003).

- Crop on crop effects: Residues from allelopathic crops can hinder germination and growth of following crops as well as weeds (Mirza, 2012).
- Environmental factors: Several factors impact the strength of the allelopathic effect. These include pests and disease and especially soil fertility. Low fertility increases the production of allelochemicals (Mirza, 2012).
- Furthermore, physiological and environmental stresses, pests and diseases, solar radiation, herbicides, and less than optimal nutrient, moisture, and temperature levels can affect allelopathy (Ferguson *et al.*, 2003).
- Soil type: Clay soils and poorly drained sandy soils tend to retain and build up concentrations of allelochemicals whereas well-drained sandy soils are likely to leach allelochemicals (Mirza, 2012).

Although allelochemicals occur commonly in nature, biological, chemical, and environmental factors can influence the ability of a toxin to affect the growth of a particular plant (Chick and Kielbaso, 1998). Five factors merit consideration.

- First, specific plant toxins affect only particular species. The presence of species that have been reported as allelopathic should be cause for concern when they are growing in the rooting zone of trees. For example, *Leucaena leucocephala*, the miracle tree promoted for revegetation, soil and water conservation and animal improvements in India, also contains a toxic, non-protein amino acid in leaves and foliage that inhibits the growth of other trees but not its own seedlings. *Leucaena*

species have also been shown to reduce the yield of wheat but increase the yield of rice.

Allelochemicals concentrations in the producer plant may also vary over time and in the plant tissue produced. Foliar and leaf litter leachates of *Eucalyptus* species, for example, are more toxic than bark leachates to some food crops (Rizvi *et al.*, 1999).

- A second factor involves the size of a toxin producing plant and its proximity to a sensitive plant (Chick and Kielbaso, 1998).

- Seasonal variation in the toxicity of allelochemicals is a third well-reported factor. Fall foliage tends to release more potent allelochemicals than do fresh, green, spring foliage (Fisher *et al.*, 1978; Petranka and McPherson, 1979). Because unmaintained areas such as low use parks, vacant lots, and rights-of-way tend to accumulate decaying ground-cover vegetation, substantial amounts of potent allelochemicals may be released, which could inhibit other plant growth (Chick and Kielbaso, 1998).

- A fourth factor involves chemical magnification. The concentration of specific allelochemicals, when applied singly, may be insufficient to cause injury to a sensitive plant. However, numerous experiments have shown that combinations of these same compounds can produce additive or synergistic effects that are inhibitory. Therefore, ground covers consisting of several species of allelopathic plants may produce a more toxic association than any of the individual species alone (Chick and Kielbaso, 1998).

- The last factor involves the mediation of allelochemicals in the soil. Except for some volatiles, edaphic factors are crucial in determining the fate of a toxin in the soil and its potential impact on sensitive plants (Chick and Kielbaso, 1998).

Not all plants have allelopathic tendencies. Some, though they exhibit these tendencies, may actually be displaying aggressive competition of a non-chemical form. Much of the controversy surrounding allelopathy is in trying to distinguish the type of competition being displayed. In general, if it is of a chemical nature, then the plant is considered allelopathic.

2.1.4 Allelopathy in Eucalyptus species

Eucalyptus is a diverse genus of flowering trees and shrubs (including a distinct group with a multiple-stem mallee growth habit) in the myrtle family, Myrtaceae (Gledhill, 2008). Members of the genus dominate the tree flora of Australia. There are more than 700 species of eucalyptus, and a very small number are found in adjacent areas of New Guinea and Indonesia and one, *Eucalyptus deglupta*, ranges north to the Philippines (Gledhill, 2008). Eucalyptus is one of three similar genera that are commonly referred to as "eucalypts", the others being *Corymbia* and *Angophora*. Many species, but far from all, are known as gum trees because they exude copious sap from any break in the bark (Gledhill, 2008).

Some eucalyptus species have attracted attention from global development researchers and environmentalists because of desirable traits such as being fast-growing sources of wood, producing oil that can be used for cleaning and as a natural insecticide, or an ability to be used to drain swamps and thereby reduce the risk of malaria (Luzar, 2007).

Outside their natural ranges, eucalypts are both lauded for their beneficial economic impact on poor populations (World Watch Institute, 2007).

Nearly all eucalyptus are evergreen but some tropical species lose their leaves at the end of the dry season. As in other members of the myrtle family, eucalyptus leaves are covered with oil glands. The copious oils produced are an important feature of the genus (Brooker and Kleinig, 2001).

Allelopathy is not specific to Eucalyptus species, and has been demonstrated in many commercially important tree species (ArborGen, 2008). Baker (1966) reported that *Eucalyptus globulus* produces volatile materials that inhibit the root and hypocotyl growth of cucumber seedlings. A similar lack of herbaceous species under *E. globulus* and *E. camaldulensis* due to their allelopathic effects was also reported by del Moral and Muller in 1969 (Sasikumar *et al.*, 2001). *E.microtheca* compared to *Casuarina cunninghamiana* was reported to possess a poor under-storey due to allelopathic effects in central Iraq (Al-Mousawi and Al-Naib, 1976). So, Eucalyptus though a potential industrial crop is not being recommended as an intercrop in agroforestry systems (Bansal, 1988; Suresh and Rai, 1987), presumably due to the release of inhibitory compounds from the trees (Lisanework and Michelson, 1993). The release of phenolic compounds adversely affects the germination and growth of plants through their interference in energy metabolism, cell division, mineral uptake and biosynthetic processes (Rice, 1984). Leachates from stem flow and litter fall are responsible for such an effect (Molina *et al.*, 1991).

2.1.5 Allelopathy in Teak

Teak (*Tectona grandis*) is native to South and Southeast Asia, mainly India, Indonesia, Malaysia, and Burma, but is naturalized and cultivated in many countries, including those in Africa and the Caribbean. It is commonly called teak which is from the Tamil word thekku (Anon, 2010). Teak is a large, deciduous tree up to 40 m (131 ft) tall with gray to grayish brown branchlets and is dominant in mixed hardwood forests. Leaves are ovate-elliptic to ovate, 15–45 cm (5.9–17.7 in) long by 8–23 cm (3.1–9.1 in) wide, and are held on robust petioles that are 2–4 cm (0.8–1.6 in) long. Leaf margins are entire (Anon, 2010).

Tectona grandis is one of three species in the genus *Tectona*. The other two species, *T. hamiltoniana* and *T. philippinensis*, are endemics with relatively small native distributions in Myanmar and the Philippines, respectively (Tewari, 1992). Teak is found in a variety of habitats and climatic conditions from arid areas with only 500 mm of rain per year to very moist forests with up to 5,000 mm of rain per year. Typically, though, the annual rainfall in areas where teak grows averages 1,250-1,650 mm with a 3-5 month dry season (Kaosa-ard, 1981).

Teak is desired for its appearance and durability (Miro Forestry Company, 2012) and as a shade tree. It may also be used as a noise buffer. Teak, a valuable timber tree of Asia has been successfully used as a partner in agroforestry. In the second half of 19th century teak and maize were inter-cultivated in Indonesia and other tropical countries in Asia (Evangeline *et al.,* 2012). Since then, this species has been used successfully in rotation

and is combined with agricultural species such as mountain rice, cotton, tapioca, chilli and ginger.

Allelopathy in teak has been studied in various fields over the years. In India it was found that teak plantations with groundnut and soybean were very successful (Mishra and Prasad, 1980). However, later studies showed that leaves of teak had allelopathic effect on several crop plants. Jayakumar *et al.* (1987) demonstrated the allelopathic effects of teak leaves on the germination of peanut and maize. Macias *et al.* (2000) reported the phytotoxic activity of aqueous extracts from bark and leaves of teak between 1000-125 ppm, on the germination, root and shoot length of *Lepidium sativum L.*, *Lactuca sativa, Lycopersicum esculentum, Allium cepa* and *T. aestivum* L. Bioassay results showed that bark extract of teak had higher phytotoxicity. The most affected parameters were root length of tomato, onion and wheat. The allelopathic extracts from teak leaves significantly inhibited germination and growth of tomato (*Lycopersicum esculentum*), eggplant (*Solanum melongena*) and pepper (*Capsicum annum*) (Krishna *et al.,* 2003). Teak has also shown high allelopathic activity on *Triticum aestivum* (Krishna *et al.,* 2003). Sahoo *et al.* (2007) reported that teak as a potential harmful allelopathic plant to maize and the toxic effect of teak followed the order: leaf litter >crushed seeds >soil root zone. This study had also showed that leaf, bark and seed extracts and soil from the root zone of teak had suppressive effects on germination, radical length and yield of maize.

2.1.6 Allelopathy in Bamboo

Bamboo (Bambuseae) is a type of grass and is among the fasters growing plants on the planet due to a unique rhizome-dependent system. One Japanese species grows at a rate

of a metre a day. Some bamboos can reach a lofty 35m in height while others are only half a meter tall (BBC, 2013). It is a tribe of flowering perennial evergreen plants in the grass family Poaceae, sub-family Bambusoideae, tribe Bambuseae. Giant bamboos are the largest members of the grass family. Bamboos flower en-mass, the whole population coming into bloom simultaneously. There are about 1500 different species of bamboo, occurring naturally in every continent except Europe and Antarctica (BBC, 2013).

In bamboos, the internodal regions of the stem are hollow and the vascular bundles in the cross section are scattered throughout the stem instead of in a cylindrical arrangement. The dicotyledonous woody xylem is also absent. The absence of secondary growth wood causes the stems of monocots, even of palms and large bamboos, to be columnar rather than tapering. Bamboos have strong culms, have greater density than oak, and yet are light weight and flexible (Bell, 2000).

Bamboo species are found in diverse climates, from cold mountains to hot tropical regions. They occur across East Asia, from 50°N latitude in Sakhalin through to Northern Australia, and west to India and the Himalayas (Bystriakova *et al.*, 2003). They also occur in sub-Saharan Africa, and in the Americas from the Mid-Atlantic United States to Argentina and Chile, reaching their southernmost point anywhere, at 47°S latitude.

The growth rate of bamboo is dependent on local soil and climatic conditions, as well as species. Bamboo growing in a slightly acidic soil with a healthy amount of water and partial shade can grow about 2inches per hour. On the slower side, most estimates place bamboo at about 24inches in a single day (Bambooki, 2011). Some of the largest timber bamboo can grow over 30 m (98 ft) tall, and be as large as 15–20 cm (5.9–7.9 in) in

diameter. However, the size range for mature bamboo is species dependent, with the smallest bamboos reaching only several inches high at maturity.

Bamboo has a multitude of uses. It is used in the landscape to create a natural, tall privacy screen. It also creates a decorative appeal with dazzling array of colours and graceful, evergreen foliage. The pulp can be made into paper, culms into timber, and are used by some architects to build earthquake resistant houses (Bell, 2000).

2.2 SOIL AMENDMENT

Davis and Wilson (2005) defined soil amendment as any material added to a soil to improve its physical properties, such as water retention, permeability, water infiltration, drainage, aeration and structure. The goal is to provide a better environment for roots. To do its work, an amendment must be thoroughly mixed into the soil. The best soil amendments increase water and nutrient holding capacity and improve aeration and water infiltration. While fertilizer improves soil by adding nutrients only, soil amendments improve soil by making its texture or drainage more conducive to plant health. Soil amendments can also change soil pH (Beaulieu, 2010). Soil amendments restore soil health and structure allowing establishment of vegetation, recreate ecological function of soils, decrease bioavailability of toxic pollutants, decrease leachability and mobility of contaminants, decrease erosion and improve soil drainage, and reduce costs compared to traditional remediation techniques (U.S. EPA, 2007).

Commonly used amendments may include municipal bio-solids, animal manures and litters, sugar beet lime, wood ash, coal combustion products such as fly ash, log yard waste, neutralizing lime products, composted bio-solids, and a variety of composted

agricultural by-products, as well as traditional agricultural fertilizers (Wallace and Terry, 1998). Soil amendments may therefore be broadly categorized into organic and inorganic. The addition of amendments restores soil quality by balancing pH, adding organic matter, increasing water holding capacity, re-establishing microbial communities, and alleviating compaction. As such, the use of soil amendments enables site remediation, re-vegetation and revitalization, and reuse (U.S. EPA, 2007).

The first and most essential components of any soil amendment strategy are an accurate assessment of existing site, soil conditions and knowledge of the range of target soil conditions appropriate for the re-vegetation species of interest. Post-revitalization land use also is an important consideration in choosing soil amendments and remedial strategies. Additionally, it is essential that potential soil amendments be carefully characterized for all important physical, chemical and microbiological properties. Higher application rates of soil amendments are required when rebuilding soil rather than simply enhancing damaged soil (U.S. EPA, 2007).

Biochar as a kind of organic matter has been used as soil amendment to improve soil structures and fertility qualities (Glaser *et al*., 2002; Atkinson *et al*., 2010).

2.3 BIOCHAR

The UK Biochar Research Centre defines biochar as the porous carbonaceous solid produced by the thermochemical conversion of organic materials in an oxygen-depleted atmosphere and which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement (Downie *et al.*,

2009). This definition is deliberately flexible and refers to both the production of biochar and its application.

Biochar is a fine-grained, highly porous charcoal substance that is distinguished from other charcoals in its intended use as a soil amendment. Biochar is charcoal that has been produced under conditions that optimize certain characteristics deemed useful in agriculture, such as high surface area per unit of volume and low amounts of residual resins. The particular heat treatment of organic biomass used to produce biochar contributes to its large surface area and its characteristic ability to persist in soils with very little biological decay (Lehmann and Rondon, 2006). Traditional charcoal is an example of biochar. However, the difference between charcoal and biochar lies primarily in the end use. Charcoal is a fuel, and biochar has a non-fuel use that makes carbon sequestration feasible. Otherwise there is no difference between charcoal carbon and biochar carbon (Tenenbaum, 2009).

Unlike fertilizers, biochar has an extremely long life in soils. Due to its molecular structure, biochar is chemically and biologically in a more stable form than the original carbon form it comes from, making it more difficult to break down. This means that in some cases it can remain stable in soil for hundreds to thousands of years.

Biochar is under investigation as an approach to carbon sequestration to produce negative carbon dioxide emissions. Biochar thus has the potential to help mitigate climate change, via carbon sequestration (Lean, 2008). Independently, biochar may act as a surface sorbent which is similar in some aspects to activated carbon (Lean, 2008), can improve soil fertility and raise crop production, be effective in adsorbing organic pollutants from

waste water, may improve soil tilth, fertility, and water retention, reduce soil erosion, vulnerability to degradation, and to some extent reduce the need for fertilizer inputs (Reddy *et al.,* 2011).

2.3.1 Background of Biochar

The use of biochar is an age old practice. The greatest suggestion that biochar may be beneficial to soil fertility comes from studies of the Amazonian Dark Earth (ADE) soils known as *terra preta* and *terra mulata.* ADEs are prized for their high nutrient levels and high fertility (Lehmann *et al.,* 2003). The high cation exchange capacity (CEC) of ADEs compared to adjacent soils is due to its black carbon content (Liang *et al.,* 2006). ADEs are a unique type of soils developed through intense anthropogenic activities such as biomass-burning and high-intensity nutrient depositions on pre-Columbian Amerindian settlements that transformed the original soils into Fimic Anthrosols throughout the Brazilian Amazon Basin. Pre-Columbian Amazonians are believed to have used biochar to enhance soil productivity. They produced it by smouldering agricultural waste – that is covering burning biomass with soil (Solomon *et al.,* 2007) in pits or trenches (Lehmann, 2007). European settlers called it *terra preta de Indio* (Glaser *et al.,* 2002). The term "biochar" was coined by Peter Read in 2009 to describe charcoal used as a soil improvement.

2.3.2 Production of Biochar

Biochar can be produced from a variety of biomass feedstocks, but is generally designated as biochar only if it produces a useable co-product for soil improvement. Biochars are not created equal. The efficiency and effectiveness of the process of its

creation and use can vary and the specific biomass sources used can affect the characterization and usability of the biochar (Reddy *et al.,* 2011).

Biochar is created by heating organic material under conditions of limited or no oxygen (Lehmann, 2007) – a process termed pyrolysis. Pyrolysis is one of many technologies to produce energy from biomass (Bridgwater, 2003). Pyrolysis is the direct thermal decomposition of biomass in the absence of oxygen to obtain an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from the pyrolysis is dependent on process conditions, and can be optimized to produce either energy or biochar (Gaunt and Lehmann, 2008). What distinguishes pyrolysis from alternative ways of converting biomass to energy is that pyrolysis produces a carbon-rich, solid by-product, biochar. Under complete or partial exclusion of oxygen, biomass is heated to moderate temperatures, between about 400 and 500°C (giving the process the name "low-temperature pyrolysis"), using a variety of different reactor configurations. At these temperatures, biomass undergoes exothermic processes and releases a multitude of gaseous components in addition to heat (Czernik and Bridgwater, 2004). In contrast to the organic C-rich biochar, burning biomass in a fire creates ash, which mainly contains minerals such as calcium (Ca) or magnesium (Mg) and inorganic carbonates. Also, in most fires, a small portion of the vegetation is only partially burned in areas of limited oxygen supply, with a portion remaining as char (Kuhlbusch and Crutzen, 1995).

Temperatures of 400–500°C (752–932 °F) produce more char, while temperatures above 700 °C (1,292 °F) favour the yield of liquid and gas fuel components (Winsley, 2007). Both slow and fast pyrolysis can be used. High-temperature pyrolysis (typically above 700°C), which is more commonly called gasification, is therefore less appropriate in this

context, as it yields much lower amounts of biochar, or none at all. Slow pyrolysis which produces substantially more char (~50%) is favourable.

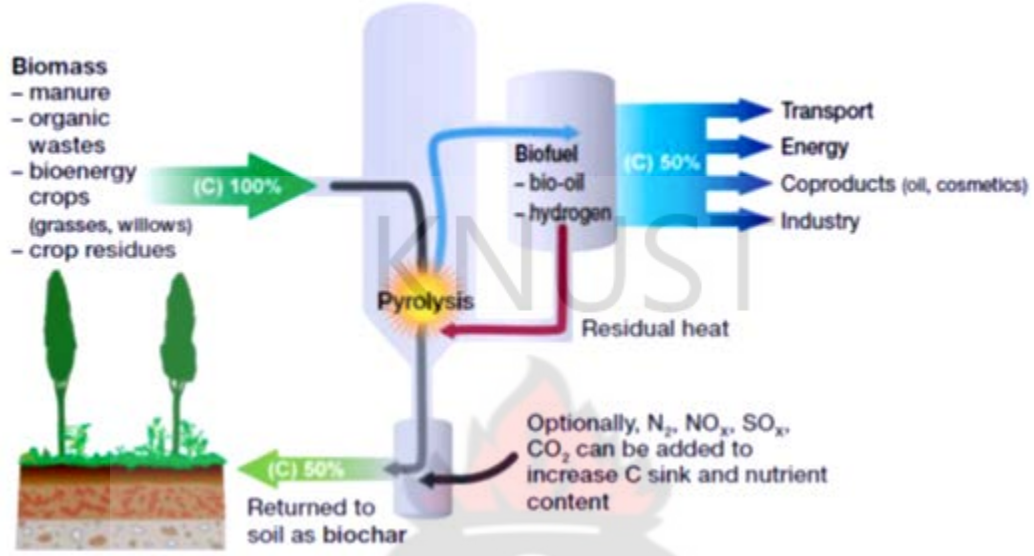

Plate 2.2: Concept of low-temperature pyrolysis bio-energy with biochar sequestration. Typically, about 50% of the pyrolyzed biomass is converted into biochar and can be returned to soil.

The products of the pyrolysis process vary by the raw material used, burning time, and temperature, but in principle, volatile hydrocarbons and most of the oxygen and hydrogen in the biomass are burned or driven off, leaving carbon-enriched black solids with a structure that resists chemical and microbial degradation (Tenenbaum, 2009). There are many ways to achieve pyrolysis. The type of organic matter (or feedstock) that is used and the conditions under which a biochar is produced greatly affect its relative quality as a soil amendment (McClellan *et al.*, 2007, McLaughlin *et al.*, 2009). Production of biochar generally releases more energy than it consumes, depending on the moisture content of the feedstock (Lehmann, 2007). Pyrolysis equipment now being developed at

several public and private institutions typically operates at 350-700°C (Tenenbaum, 2009).

2.3.3 Importance and Constraints of Biochar

Researchers who have tested the impact of biochar on soil fertility say that much of the benefit may derive from biochar's vast surface area and complex pore structure, which is hospitable to the bacteria and fungi that plants need to absorb nutrients from the soil (Tenenbaum, 2009). Charcoal-mediated enhancement of soil caused a 280-400% increase in plant uptake of nitrogen (Sombroek *et al.*, 2003). While raw organic materials supply nutrients to plants and soil microorganisms, biochar serves as a catalyst that enhances plant uptake of nutrients and water. Compared to other soil amendments, the high surface area and porosity of biochar enable it to adsorb or retain nutrients and water and also provide a habitat for beneficial microorganisms to flourish (Glaser *et al.*, 2002, Lehmann and Rondon 2006, Warnock *et al.*, 2007).

According to the IBI (2012), biochar and bioenergy co-production from urban, agricultural and forestry biomass residues can help combat global climate change by a number of different pathways that include direct sequestration of biochar in stable soil carbon pools, displacement of carbon-positive fossil fuel energy, increase in global Net Primary Production (NPP) from increased soil fertility and the reduction of nitrous oxide emissions.

There are additional pathways to reduced emissions that may result when biochar is added to soil. These include savings in energy and emissions from fertilizer production as

the need for fertilizer is reduced and potential reductions in methane emissions when biomass is charred rather than allowed to decompose (Amonette *et al.,* 2007).

The IBI (2012) states that as a soil enhancer, biochar makes soil more fertile, retains nutrients and cation exchange capacity, decreases soil acidity, decreases uptake of soil toxins, improves soil structure, improves nutrient use efficiency, improves water-holding capacity, decreases the releases of non-CO_2 greenhouse gases (CH_4, N_2O), and reduces the need for some chemical and fertilizer inputs.

However, even though some of these functions may lead directly or indirectly to increased production in some soils, the benefit of biochar is not universal. In fact, some biochars may have adverse effects on plant growth, and not all soils respond to biochar additions in the same way (Sohi *et al.,* 2009).

Studies that have reported positive effects with regard to crop production often involved highly degraded and nutrient-poor soils, whereas application of biochar to fertile and healthy soils does not always yield a positive change (Sohi *et al.,* 2009). However, depending on the sources, biochar may supply certain amounts of phosphorus and potassium to crops but will supply little nitrogen. On the other hand, biochar promotes growth of beneficial microbes and helps retain phosphorus and potassium in soil, improving crop utilization efficiency of the nutrients. Nevertheless, biochar fertilization may initially require more nitrogen from external sources since decomposition of biochar carbon will consume available nitrogen in soil. With the decrease in phosphorus fertilization and increase in nutrient retention, biochar should have positive effects on reducing nutrient runoff losses. Since biochar fertilization enhances soil aeration and

beneficial microbial activity, it will also inhibit soil borne pathogens but not above ground pests (Guo, 2008).

The amount of biochar that can be added to soils before it ceases to function as a beneficial soil amendment and becomes detrimental will be the limiting factor in the use of biochar as a soil additive (Glaser, 2007).

2.3.4 Biochar Application and Stability in Soils

Biochar may influence soil aggregates and its stability due to the interactions with soil organic matter, microorganisms and minerals (Piccolo *et al*., 1997; Verheijen *et al*., 2010). The slow oxidation properties of biochar determine the long term effect on soil aggregation (Verheijen *et al*., 2010).

The prevailing scientific understanding of biochar degradation in soil is that some portions of it are quite readily decomposable (termed “labile”), while the core structure of the material is highly resistant to degradation (termed “stable”). Analyses of biochar will indicate the relative amounts of labile and stable materials in each biochar material (Major, 2010). The degradable portion of biochar (composed of condensates, bio-oils, et cetera) is usually small and its size can be managed in the production process. Once this portion degrades in the years following application, the leftover will remain in soil for very long periods of time. There is variation in the exact composition of biochars, but basically a charred material will always be more recalcitrant (resistant to degradation) than its uncharred counterpart (Major, 2010). The effects of biochar on soil properties are influenced by many factors, such as the feedstock, procedure process, and the soil basic characteristic (Liu *et al.,* 2012).

Biochar has been applied at different rates to sandy soil ranging from 45 Mg ha^{-1} to 1000 Mg ha^{-1} (Novak *et al.,* 2009). Application rates significantly affect the properties of soils, and generally higher application rates have more pronounced effects (Chan *et al.,* 2009).

The rate at which biochar decomposes varies significantly and depends primarily on the feedstock, the method of pyrolysis (temperature and length of time) used to make the biochar, and the environment where the biochar char is incorporated. This makes it difficult to create standard decomposition rates for each type of biochar because there are so many permutations of production and use (Weisberg *et al.,* 2010). Since the characterization and therefore rates of decomposition vary, De Gryze (2010) recommended that field measurements of the quantity of biochar that remains after original application.

2.4 CHARCOAL

Charcoal is a light black residue consisting of carbon, and any remaining ash, obtained by removing water and other volatile constituents from animal and vegetation substances. Charcoal is usually produced by slow pyrolysis. It is usually an impure form of carbon as it contains ash (Anon, 2010). Charcoal may be activated to increase its effectiveness as a filter. Charcoal has the ability to turn unproductive soil into very rich soil. Its use as an adsorbent, like most of its other applications, has a very long history (Patrick, 1994). There is a long tradition in Japan of using charcoal as a soil amendment. Nishio (1996) stated that "the idea that the application of charcoal stimulates indigenous arbuscular mycorrhiza fungi in soil and thus promotes plant growth is relatively well-known in Japan, although the actual application of charcoal is limited due to its high cost". The

relationship between mycorrhizal fungi and charcoal may be important in realizing the potential of charcoal to improve fertility.

It is important not to confuse charcoal with other forms of impure non-crystalline carbon such as coke and soot. Although coke is produced by solid-phase pyrolysis (usually of bituminous coal), it is distinguished from charcoal in that a fluid phase is formed during carbonization. In the case of soot, this is formed in the gas phase by incomplete combustion rather than by solid-phase pyrolysis and it has a microstructure quite distinct from either coke or charcoal (Harris, 1999).

2.4.1 Background of Charcoal

Historically, production of wood charcoal in districts where there is an abundance of wood dates back to a very ancient period. The origins of charcoal production are intimately bound up with the beginnings of metallurgy approximately 5000 years ago. Attempts to smelt metals using wood fires could never have been entirely successful, since it would have been impossible to achieve sufficiently high temperatures. When plain wood is burned there is a large quantity of water driven off, plus assorted volatiles, and this limits the temperature of the fire. Burning charcoal, on the other hand, produces a much higher fire temperature (well over 1000^{o}C), with little smoke: ideal conditions for metal smelting and working (Harris, 1999).

2.4.2 Production of Charcoal

Charcoal is produced from wood by a complex process called carbonization. Carbonization occurs at temperatures between 450 to 600°C in absence of air. Under these conditions organic vapours and gases are lost and part of the organic substances

polymerizes, all of which increase the carbon content of the product. After the process is finished, charcoal is the final product that remains. One of the factors affecting quality as well as the yield is temperature. At relatively low temperatures around 300°C a high yield of charcoal is obtained. This charcoal has a high content of volatile material, which is undesirable because it produces noxious fumes during use. Temperatures around 600°C give lower yields but the charcoal has a low content of volatiles making it a preferred fuel. Charcoal can be made from both hardwood and softwood. However, hardwood is usually preferred because the charcoal has higher energy content and is easier to handle (Seidel, 2008).

2.4.3 Importance and Constraints of Charcoal

The use of charcoal as an adsorbent, like most of its other applications, has a very long history (Partrick, 1994). Egyptian papyri from around 1500 BC describe the use of charcoal to adsorb malodorous vapours from putrefying wounds, and there is an Old Testament reference (Numbers 19:9) to the ritual purification of water using the charred remains of a heifer. The first scientific study of the adsorptive properties of charcoal was made by the Swedish scientist Carl Wilhelm Scheele in the late 18th century. He described how the vapours adsorbed by charcoal could be expelled by heating, and taken up again during cooling. During the 19th century, work on the adsorptive properties of charcoal continued at a fairly low level. There were still relatively few applications for charcoal as an adsorbent, apart from specialised areas like sugar refining, and little incentive for research. Today, activated charcoal is used on an enormous scale in both vapour-phase and liquid-phase purification processes (Harris, 1999).

Wong, 2009 indicated that some key importance of charcoal in the horticultural field and they include the following:

- Porosity – Improve Drainage: Charcoal is a porous form of organic matter primarily composed of carbon. It is used as a soil conditioner to improve soil drainage. This is especially true for those pots without drainage holes since the charcoal will provide a place for excess water to settle. Research has shown that growing mediums with charcoal are able to buffer the effects of sporadic watering, and help prevent the plants from damping off. When compared with other moisture-retaining potting soil ingredients, charcoal has its advantages. Charcoal is in bigger chunks than perlite, yet light in weight. In addition, it does not break down as quick as bark, nor does it rot. Charcoal may help attain proper porosity levels in soil mixes.

- Organic: Charcoal is organic, a characteristic which some gardeners place high in value.

- Hold and Deliver Nutrients in the Soil: Charcoal can reduce the leaching of fertilizer in free draining soils as the charcoal's porous carbon structure enables the nutrients to be held for slower release to the plants. The inclusion of charcoal in open seedbeds showed that it facilitates the uptake of nutrients. Researches have shown that calcium uptake almost doubles, with significant increases in potassium, magnesium and phosphorus, the pH increases slightly and there is an obvious increase in organic matter.

Bacle (2008) also stated that not only does charcoal absorb excess humidity, but also some toxic elements which may be present in the soil. He also highlighted that charcoal acts as an antioxidant preventing root rot.

2.4.4 Charcoal Application and Stability in Soils

Charcoal serves to stabilize the organic matter in the soil, increase cation exchange capacity, and increase water retention due to its porous structure and high surface area (Ricigliano, 2011). Charcoal is carbon-rich and gives it the ability to persist in the soil indefinitely by not being susceptible to biological decay (Vuthisa, 2011). Bacle (2008) stated that by the shape and adsorbent properties of charcoal it will help stabilize soil humidity and texture thereby increasing soil physical quality. On a small scale, applying charcoal as an alternative to composts and manures as a source of carbon seems to be a promising way to maximize carbon content in soils due to its stability, which is exemplified in Terra Preta soils. Slash and char seems to be an efficient method of tapping into the carbon cycle in order to conserve it in the soil (Ricigliano, 2011).

The addition of charcoal is beneficial to the soil, but it also has the ability to bind up N and does not provide many essential nutrients. Therefore, it is important to also add a nutrient source along with charcoal amendments due to charcoal's high C:N ratio (Tenenbaum, 2009).

In theory, the charcoal amendments would only need to be applied once due to its stability for hundreds to thousands of years, which would sequester enough carbon to compensate for the production emissions (Lehmann, 2007).

2.5 FEEDSTOCK

A feedstock is a raw material (input) fed into a process for conversion into something different (output). Despite many different materials having been proposed as biomass feedstock (including wood, crop residues and manures), the suitability of each feedstock for such an application is dependent on a number of chemical, physical, environmental, as well as economic and logistical factors (Verheijen *et al*., 2010).

2.5.1 Feedstock for Charcoal

Charcoal is mostly produced from wood wastes such as sawdust, woodchips, slabs, twigs, small branches, stumps, roots, bamboo waste, sunflower husk, rice hull, peanut peel, wine dreg, molasses, dry stalks, hay, cane trash, corncob, coconut shell, coffee shell, crops straw and sewage sludge. Wood industries, sugar industries, oil industries, et cetera who supply these waste materials for charcoal production have an excellent opportunity as raw material suppliers (Brown and Holmgren, 2009).

2.5.2 Feedstock for Biochar

Biochar is not a single material, and its properties vary according to how it is made and from what it is made (Major, 2010). Biochar can and should be made from biomass waste materials (IBI, 2012). Biomass is a biological material from living or recently living organisms, most often referring to plant or plant-derived materials. As a renewable energy source, biomass can either be used directly or indirectly once or converted to another type of energy product such as biofuel (Biomass Energy Centre, 2012). Historically, humans have harnessed biomass derived energy products since the time when people began burning wood to make fire (Volk *et al.,* 2000). Wood remains the

largest biomass energy source today (Scheck, 2012) and examples include forest residues (such as dead trees, branches and tree stumps), yard clippings, wood chips and even municipal solid waste. Industrial biomass can be grown from numerous types of plants, including miscanthus, switchgrass, sorghum, willow, corn, sugarcane, bamboo and a variety of tree species ranging from eucalyptus to oil palm (Scheck, 2012). Making biochar from biomass waste materials should create no competition for land with any other land use option — such as food production or leaving the land in its pristine state (IBI, 2012).

Biomass waste materials appropriate for biochar production include crop residues (both field residues and processing residues such as nut shells, fruit pits, and bagasse), as well as yard, food and forestry wastes, and animal manures (IBI, 2012). Other feedstock available as biomass for biochar production include rice husk, rice straw, palm fibre, wood chippings, coconut fibre, maize stover, corn cobs, wood shavings, sawdust, stumps from felled trees, bamboo and tree branches. The quality of biochar is dependent on feedstock and the conversion process used (Anon, 2012).

One factor determining how much biochar may be produced is the existence of competing demands for biomass feedstock. Once environmental costs of carbon-based greenhouse gas emissions have been suitably internalised, we can expect market forces and the price mechanism to be the dominant factor in apportioning use of biomass resources between competing demands (Woolf, 2008). However, “when the alternative uses of biomass are likewise aimed at carbon reduction, the trade-offs become more complex”. Perhaps the most important example of this dilemma arises from the trade-off

between using biomass for energy generation and using it to produce biochar (Woolf, 2008).

When biochar is added to soil, renewable energy source – the energy that could be released by the combustion of the char – is forgone. Thus, even though it may be possible with some feedstocks to obtain some energy co-production along with biochar, this will always be less than the amount of energy that might be obtained by complete combustion of the original biomass. Therefore, the question arises as to whether it is more efficient in terms of avoided carbon dioxide emissions to use biomass as a source of energy to displace fossil fuels or whether it would be better to sequester a fraction of the carbon in the biomass as biochar and meet energy demand from other sources (including fossil fuels) (Woolf, 2008).

2.5.3 Sawdust as feedstock for Biochar Production

Wikipedia defines sawdust as a by-product of cutting, grinding, drilling, sanding, or otherwise pulverizing wood with a saw or other tool. It is composed of fine particles of wood. Sawdust has a variety of practical uses, including serving as mulch, as an alternative to clay cat litter, or as a fuel. Sawdust is often used to mulch or amend soils for horticultural crops. When incorporated into the soil, sawdust improves soil structure, increases the nutrient holding capacity of sandy soils and improves water drainage. As mulch, it reduces soil moisture loss, reduces or prevents weed growth and are decorative in landscapes (Barney and Colt, 1991).

Many localities collect yard waste (lawn, garden, shrub/tree trimmings) and make it available for local reuse. Similarly, large amounts of wood waste (bark chips, sawdust,

whole tree chips) may be available from wood processing facilities or from right-of-way maintenance activities. Collectively, these materials tend to vary greatly in composition, size, and relative decomposition/stability, but can serve as significant and beneficial organic matter amendments or mulching materials. In recent years, wood products have been increasingly utilized as fuel in industrial boilers and, therefore, are not as readily available (U.S. EPA, 2007). Sawdust is largely generated in Ghana due to the large number of timber processing facilities in the country. The burning of piles of sawdust releases carbon into the atmosphere which contributes to climate change. Hence the use of sawdust as a feedstock for biochar is more constructive rather than leaving it to decompose or burnt into ash.

2.6 CARBON SEQUESTRATION

It has been suggested by Sombroek *et al*. (2003) and Lehmann (2007) that biochar may be produced from material that would otherwise have degraded to release carbon dioxide into the atmosphere. Wood has a carbon content of about 50%, whereas biochar has a carbon content of about 70–80%, which can be permanently sequestered in soil. Over and above this, biochar may have the potential to increase atmospheric carbon dioxide uptake in the form of glomalin, a major component of humus produced by plant mycorrhizal fungi (Winsley, 2007). Biochar can be a simple yet powerful tool to combat climate change. Plants remove CO_2 from the atmosphere through photosynthesis, and then store the carbon in their tissues. CO_2 is released back into the atmosphere after plant tissues decay or are burned or consumed and the CO_2 is then mineralized. If plant materials are transformed into charcoal, however, the carbon is permanently fixed in a solid form – evidence from Amazonia, where Terra Preta remains black and productive after several

thousand years, suggests that biochar is highly stable. On average, half the biochar carbon is recalcitrant and would persistently remain in soil (Tenenbaum, 2009). Even though some carbon in biochar may well decay over the shorter term, biochar is a highly stable and long-term form of carbon sequestration overall, because charcoal is inert and resistant to biochemical breakdown (Winsley, 2007).

As organic materials decay, greenhouse gases, such as carbon dioxide and methane (which is 21 times more potent as a greenhouse gas than CO_2), are released into the atmosphere. By charring the organic material, much of the carbon becomes "fixed" into a more stable form, and when the resulting biochar is applied to soils, the carbon is effectively sequestered (Liang *et al.*, 2008). It is estimated that use of this method to "tie up" carbon has the potential to reduce current global carbon emissions by as much as 10 per cent (Woolf *et al.*, 2010).

There are two main ways that biochar can influence the global carbon cycle. The first is that, if biochar is produced from material that would otherwise have oxidised in the short to medium term, and the resultant carbon-rich char can be placed in an environment in which it is protected from oxidation, then it may provide a means to sequester carbon that would otherwise have entered the atmosphere as a greenhouse gas. The second is that gaseous and liquid products of pyrolysis may be used as a fuel that can offset the use of fossil fuels (Woolf, 2008).

To assess the carbon sequestration potential of adding biochar to soil, four factors need to be considered (Woolf, 2008). These include the longevity of char in the soil, the avoided

rate of greenhouse gas emission, how much biochar can be added to soils, and how much biochar can be produced by economically and environmentally acceptable means.

2.7 CARBON AND NITROGEN CYCLE

Carbon and nitrogen are circulated between the atmosphere, soil, and water. Carbon dioxide is fixed by plants and nitrogen by bacteria. The soil carbon pool is made up of different types of carbon with different turnover times. Labile carbon, as occurs in the microbial biomass, has a turnover time of about 1–5 years, humic carbon may turn over in decades, and inert organic matter such as charcoal may decay over thousands of years. Humic substances contain both carbon and nitrogen, so that soils acting as net sinks for carbon are also acting as sinks for nitrogen. Soils losing carbon are also losing nitrogen, including nitrous oxide and other forms (Winsley, 2007). Humus improves soil structure, moisture retention, and microbial activity. As soils approach nitrogen saturation, and plants are unable to take it up, the risk of nitrates and nitrates leaching into waterways increases. Lifting the C:N ratio in soils has the effect of increasing nitrogen retention and therefore reducing nitrous oxide emissions and nitrate leaching.

Adding biochar to soil may prevent or limit the anaerobic production of nitrous oxide. Biochar can reduce nitrogen fertiliser requirements and nitrous oxide emissions (Baum and Weitner, 2006). The carbon in biochar does not directly provide nutrients to plants. However, it improves soil structure and water retention, enhances nutrient availability, lowers acidity, and reduces the toxicity of aluminium to plant roots and soil microbiota. Biochar may help reduce the bioavailability of heavy metals and endocrine disruptors in some production systems and may therefore have potential in bioremediation.

2.8 LAWN ESTABLISHMENT

According to Norman (1971), commonly grown tropical grass species used in Ghana for lawn establishments include *Zoysia japonica* (Japanese Lawn Grass), *Paspalum conjugatum* (Paspalum), *Axonopus compressus* (Carpet Grass), *Chrysopogon aciculatus* (Love Grass), *Cynodon dactylon* (Bahama Grass) and *Stenotaphrum secundatum* (St. Augustine's Grass).

2.8.1 *Stenotaphrum secundatum*

Stenotaphrum secundatum is commonly known as St. Augustine grass. It is widely adapted to the warm, humid (subtropical) regions of the world. It is believed to be native to the coastal regions of both the Gulf of Mexico and the Mediterranean. It can grow satisfactorily in a wide variety of soils (Trenholm *et al.*, 2011).

It is a hardy perennial, creeping extensively by means of branched rhizomes and many-noded stolons. Exceedingly variable in size, the culms rise above the ground for 6-40 cm or more, much branched from numerous nodes, the branches trailing, producing flowering stems or fin-shaped tufts of leaves. The leaf-sheaths are strongly compressed and keeled and the leaves are nearly always glabrous except near the ligule, blades up to 12 mm wide, folded at first, then expanded, usually rounded or obtuse; ligule a fringe of short hairs. St. Augustine grass is more robust and taller than buffalo grass, which is used for lawns. *S. secundatum var. variegatum* is used as a decorative indoor plant.

St. Augustine grass grows on a wide range of soils. It spreads quickly by means of stolons and does not produce seed. It is rather slow to cover the ground, but eventually

provides a dense sward which crowds out weeds. It is an excellent grass type for erosion control.

Plate 2.3 St. Augustine's Grass

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter outlines a brief description of the study area and the methods employed in the evaluation of the adsorption of allelochemicals from soils using biochar and charcoal.

3.1 STUDY AREA

The field experiment was carried out at the Department of Horticulture, Kwame Nkrumah University of Science and Technology (KNUST) from the 18th of March to the 9th of June, 2013. The soil type is sandy loam with a pH range of 6.65 – 7.21. The Department has open areas as well as shady areas to improve on humidity. Wind effect is controlled because of the windbreaks planted at the frontage of the Department.

3.2 MATERIALS FOR THE STUDY

Areas of 3.8m x 10m were cleared beneath *Tectona grandis* (Teak), *Eucalyptus grandis* (Eucalyptus) and *Bambusa sp* (Bamboo) trees using a hoe, cutlass and rake. A rake and a garden fork were used to clear leaf fall around the plots twice a week.

A measuring tape was used to measure the plot sizes and pegs and ropes were used to mark out the plots. A garden fork was used to mix the amendments into the soil before planting and was also used during the first three weeks after planting to stir the soil. The Rapitest kit was used to measure light intensity at the study area and a 15 litre watering can was used for watering.

A $30cm^2$ quadrant was also used to measure the percentage coverage of grass. The amendments applied to the soil were biochar, charcoal as well as a control (where no amendment was applied to the existing soil under the trees).

3.3 EXPERIMENTAL DESIGN

Randomized Complete Block Design (RCBD) layout with six (6) treatments and three (3) replicates were employed in the experiment.

3.3.1 Plot Sizes

The plot sizes for the *Tectona grandis* (Teak) and *Eucalyptus grandis* (Eucalyptus) trees were 0.3m x 2m. The plots were in a radial form around the trees. All the plots were laid 2m away from the trees.

The plot sizes for the *Bambusa sp* (Bamboo) were 0.4m x 2m and the plots were in front of the bamboo stand. Distance between the treatments was 0.2m. The first replicate was laid 2m away from the bamboo stand, the second replicate was laid 6m away from the stand and the third replicate was laid between 3m and 5m away from the stand.

3.3.2 Data Analysis

All data gathered in the research were recorded and classified in the Microsoft Office Excel 2010. Data obtained were statistically analyzed using Statistix version 9. One-way analysis of variance (ANOVA) was used to determine significant differences between the treatments. The treatments means were separated using the Tukey's Multiple Comparison Test at 5% ($P \leq 0.05$).

3.4 SOIL AMENDMENTS

3.4.1 Biochar

The feedstock which was used in the production of biochar was sawdust. It was collected from the Wood Village at Sokoban in Kumasi, Ashanti Region of Ghana. Sawdust of *Tectona grandis* (Teak), *Khaya senegalensis* (Mahogany), *Entandrophragma cylindricum* (Sapele), and *Celtis mildbraedii* (Esafufuo) was collected and charred with the Biochar Reactor (Plate 3.1) – a furnace for charring at a Biochar Reactor at Chirepatre, in Kumasi (Ashanti Region).

Plate 3.1 Biochar Reactor

The charring process involved the following:

1. The Biochar Reactor is swept and firewood is loaded into the combustion chamber of the reactor.
2. A metal mesh and metal mats were laid in the main chamber of the reactor.
3. The reactor was then filled with the feedstock to be charred.

4. Fire was set into the reactor through the combustion chamber.
5. Due to the fact that the charring process is a slow pyrolysis process, oxygen should not be allowed into the reactor. All openings of the reactor were as such kept closed for a period of about 72 hours as charring went on. The biochar was produced at 500°C pyrolysis temperature.
6. After the feedstock had been properly charred water was poured into the reactor to prevent the charred material from burning into ash.
7. The charred material was afterwards collected from the reactor and air dried for at least 24 hours.
8. The charred material was then repacked into sacks and ready for use.

On the whole the sawdust of *Tectona grandis* (Teak), *Khaya senegalensis* (Mahogany), *Entandrophragma cylindricum* (Sapele) took about 72 hours to char. The sawdust of *Celtis mildbraedii* (Esafufuo) however took about 84 hours to char.

Chemical analysis was carried out on each of the biochar samples to determine the pH, total nitrogen, potassium and available phosphorous levels.

3.4.2 Charcoal

Charcoal for the study was bought from Techiman in the Brong Ahafo Region of Ghana. The charcoal was made from *Tectona grandis* (teak) which the producers consider lightwood charcoal because it burns faster. Other wood types which are considered lightwood for charcoal include *Mangifera indica* (Mango), *Cassia sp,* Ofram and Pear trees.

Chemical analysis was carried out on the charcoal to determine the pH, total nitrogen, potassium and available phosphorous levels.

3.5 RATE OF APPLICATION OF TREATMENTS

The treatments were applied to the soil at a depth of 3cm at a ratio of 1:1. This is because the roots of the grass (St. Augustine's grass) usually grow in the first 2 – 3cm of the topsoil where ample moisture and nutrients exist.

3.6 TESTS FOR ALLELOPATHY IN THE TREE SPECIES

The leaves and roots of the three selected allelopathic landscape trees, namely *Eucalyptus grandis* (Eucalyptus), *Tectona grandis* (Teak) and *Bambusa sp* (Bamboo) were collected, oven-dried at a temperature of 40^{o}C for about 30 hours and milled into a powdered form. The bark of Teak and Eucalyptus were also oven-dried and milled into powder at the same temperature and number of hours.

Phytochemical screening was carried out at the Department of Pharmacognosy, KNUST. The dried and powdered leaves, bark and roots of the three landscape trees: *Eucalyptus grandis* (Eucalyptus), *Tectona grandis* (Teak) and *Bambusa sp* (Bamboo) were analyzed at the laboratory to test for the presence of any or all of the following allelochemicals: flavonoids, tannins, glycosides, triterpenoids, saponins, ferulic acids and alkaloids. The presence of any of these chemicals in large quantities suggests that the tree is allelopathic. Based on the results from the laboratory analysis soils from beneath the trees were used as a medium to grow grass under the trees.

3.7 SOILS ANALYSES

Soils beneath Eucalyptus, Teak and Bamboo were collected 1m away from the trunk of the trees and analyzed to find out if the allelochemicals from the leaves and roots were present in the soil.

Again, soils beneath the trees were analyzed to find out the initial soil nutrients present in the soil. Total nitrogen, available phosphorous, soil potassium, soil organic carbon, soil organic matter, pH and water-holding capacity of the soils were analyzed.

The soil analyses were carried out at the Department of Crops and Soil Sciences, KNUST.

3.8 PARAMETERS STUDIED

The following parameters were studied:

3.8.1 Rate of growth of grass

The growth parameters that were measured were leaf count and the length of grass.

A 30cm rule was used to measure the length of grass once every week. The number of leaves on each stolon was also counted once every week.

3.8.2 Percentage coverage of grass

The percentage coverage of grass was recorded every two weeks after planting. A $30cm^2$ quadrant was used for measuring.

3.8.3 Soil nutrient analysis

Soil nutrient analysis was carried out three times during the period of the study. An initial analysis was carried out before planting, a second analysis was carried during the experiment and a final analysis at the end of the experiment.

3.8.4 Presence of weeds

The number of weeds on each plot were counted and recorded weekly.

3.8.5 Soil pH

Soils were collected from each of the plots and were analyzed in the lab to determine the pH.

3.8.6 Soil water-holding capacity

Soils were collected from each of the plots and were analyzed to find out which of the treatments could improve the water-holding capacity of the soil. This test was carried out three times during the research.

3.9 COLLECTION OF DATA

3.9.1 Primary Source of Data

Primary source of data was obtained from the parameters studied and the various laboratory analyses carried out on the soil, tree parts, and the treatments. The treatments were coded as follows: Teak biochar – T_{TB}, Esa biochar – T_{EB}, Sapele biochar – T_{SB}, Mahogany biochar – T_{MB}, Charcoal – T_{CH} and Control – T_{CT}.

3.9.2 Secondary Source of Data

Secondary source of data was gathered from relevant literature at the KNUST main library and from the internet. This literature review served as a guide for the analysis of the data gathered.

3.10 GRASS TYPE FOR THE STUDY

Stenotaphrum secundatum or St. Augustine grass was the grass type used for the study. It was obtained from the Department of Horticulture, KNUST.

CHAPTER FOUR

4.0 RESULTS

4.1 PHYTOCHEMICAL SCREENING

Phytochemical screening was carried out on the powdered leaves and roots of the landscape trees suspected to be allelopathic – namely, *Tectona grandis* (Teak), *Eucalyptus grandis* (Eucalyptus) and *Bambusa sp* (Bamboo) – before the research was started. Analysis was also carried out on the soil samples collected beneath the trees to find out if any allelochemicals have been released into the soils. Table 4.1 shows the results of the initial phytochemical screening.

Table 4.1 Results of initial phytochemical screening

TEST: ALKALOIDS – MAYER'S (DRAGENDORFF'S REAGENT)	
Sample	Concentration
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++
TEST: TANNINS (1% LEAD ACETATE)	
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++
TEST: TANNINS (1% FERRIC CHLORIDE)	
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++

TEST: GLYCOSIDES (GENERAL TESTS)	
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++
TEST: SAPONINS	
Teak leaves	+
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	+
Bamboo roots	++
TEST: FLAVONOIDS	
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++
TEST: TRITERPENOIDS	
Teak leaves	++
Eucalyptus leaves	++
Bamboo leaves	++
Teak roots	++
Eucalyptus roots	++
Bamboo roots	++

Inference: + - Allelochemicals are present but in low concentrations for the samples.

++ - Allelochemicals are present in high concentrations for the samples.

The results of the initial phytochemical screening show that the following allelochemicals – alkaloids, tannins, glycosides, saponins, flavonoids and triterpenoids - were present in the leaves and roots of the trees.

These allelochemicals were however not found in the soil samples collected beneath the trees. Two phytochemical screenings were therefore carried out during the research and also at the end of the research to find out if the allelochemicals were released into the soil after planting. Tables 4.2, 4.3 and 4.4 present the results of the analysis.

Table 4.2 Phytochemical screening for soil samples collected beneath the bamboo stand after 4WAP and 12WAP *S. secundatum*

TEST: ALKALOIDS – MAYER'S (DRAGENDORFF'S REAGENT)			
Sample	Concentration at 0WAP	Concentration at 4WAP	Concentration at 12WAP
T_{TB}	-	++	-
T_{EB}	-	+	-
T_{SB}	-	++	-
T_{MB}	-	+	+
T_{CH}	-	++	+
T_{CT}	-	++	++
TEST: TANNINS (1% LEAD ACETATE)			
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	++	+
T_{MB}	-	++	-
T_{CH}	-	+	+
T_{CT}	-	++	+
TEST: TANNINS (1% FERRIC CHLORIDE)			
T_{TB}	-	++	-
T_{EB}	-	++	-
T_{SB}	-	++	+
T_{MB}	-	+	-
T_{CH}	-	+	+
T_{CT}	-	+	+
TEST: GLYCOSIDES (GENERAL TESTS)			
T_{TB}	-	+	-
T_{EB}	-	++	+
T_{SB}	-	+	-
T_{MB}	-	++	+
T_{CH}	-	++	+
T_{CT}	-	++	+
TEST: GLYCOSIDES (CYNOGENIC GLYCOSIDES)			
T_{TB}	-	+	-
T_{EB}	-	+	-
T_{SB}	-	+	+
T_{MB}	-	+	+
T_{CH}	-	+	-
T_{CT}	-	+	-

TEST: SAPONINS			
T_{TB}	-	++	-
T_{EB}	-	++	+
T_{SB}	-	++	+
T_{MB}	-	++	+
T_{CH}	-	++	+
T_{CT}	-	++	+
TEST: FLAVONOIDS			
T_{TB}	-	-	-
T_{EB}	-	-	-
T_{SB}	-	-	-
T_{MB}	-	-	-
T_{CH}	-	-	-
T_{CT}	-	-	-
TEST: TRITERPENOIDS			
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	+	-
T_{MB}	-	+	-
T_{CH}	-	++	++
T_{CT}	-	++	++

Inference

- ++ : Allelochemicals are present in high concentrations in the sample.
- + : Allelochemicals are present in low concentrations in the sample.
- - : Allelochemicals are absent in the sample.

The results indicated in Table 4.2 shows that alkaloids, tannins, glycosides, saponins, and triterpenoids were released into the soil after planting (4WAP). At 12WAP the concentrations of most of the allelochemicals were minimal in the soil. Flavonoids were tested for but due to the unstable nature of the compound it was not detected in any of the samples. However, teak was able to reduce most of the allelochemicals since tannins (extracted by lead acetate) and triterpenoids were the only allelochemicals present at 12WAP. T_{CH} and T_{CT} had most of the allelochemicals still present. T_{CH} had the highest concentration of triterpenoids.

Table 4.3: Phytochemical screening for soil samples collected beneath the eucalyptus tree 4WAP and 12WAP *S. secundatum*

TEST: ALKALOIDS – MAYER'S (DRAGENDORFF'S REAGENT)			
Sample	Concentration at 0WAP	Concentration at 4WAP	Concentration at 12WAP
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	+	-
T_{MB}	-	++	+
T_{CH}	-	++	+
T_{CT}	-	++	++
TEST: TANNINS (1% LEAD ACETATE)			
T_{TB}	-	++	+
T_{EB}	-	++	+
T_{SB}	-	++	+
T_{MB}	-	++	+
T_{CH}	-	+	+
T_{CT}	-	++	+
TEST: TANNINS (1% FERRIC CHLORIDE)			
T_{TB}	-	+	+
T_{EB}	-	+	+
T_{SB}	-	++	+
T_{MB}	-	+	-
T_{CH}	-	+	+
T_{CT}	-	++	+
TEST: GLYCOSIDES (GENERAL TESTS)			
T_{TB}	-	++	+
T_{EB}	-	++	+
T_{SB}	-	+	-
T_{MB}	-	++	+
T_{CH}	-	++	+
T_{CT}	-	+	-
TEST: GLYCOSIDES (CYNOGENIC GLYCOSIDES)			
T_{TB}	-	+	-
T_{EB}	-	++	-
T_{SB}	-	++	+
T_{MB}	-	++	+
T_{CH}	-	+	-
T_{CT}	-	++	+

TEST: SAPONINS			
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	++	++
T_{MB}	-	++	+
T_{CH}	-	+	+
T_{CT}	-	++	+
TEST: FLAVONOIDS			
T_{TB}	-	-	-
T_{EB}	-	-	-
T_{SB}	-	-	-
T_{MB}	-	-	-
T_{CH}	-	-	-
T_{CT}	-	-	-
TEST: TRITERPENOIDS			
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	+	-
T_{MB}	-	++	+
T_{CH}	-	++	+
T_{CT}	-	++	++

Inference

- ++ : Allelochemicals are present in high concentrations in the sample.
- + : Allelochemicals are present in low concentrations in the sample.
- - : Allelochemicals are absent in the sample.

The results indicated that all the allelochemicals (except flavonoids) were present in the soil samples at 4WAP. T_{SB} had the highest concentration of saponins and tannins in most of the samples at 12WAP. Again flavonoids were absent due to the unstable nature of the compound. In the soil beneath the eucalyptus none of the treatments seemed to have been able to remove most of the allelochemicals since four or more allelochemicals were found in all the treatments (Table 4.3).

Table 4.4 Phytochemical screening for soil samples collected beneath the teak tree 4WAP and 12WAP *S. secundatum*

TEST: ALKALOIDS – MAYER'S (DRAGENDORFF'S REAGENT)			
Sample	Concentration at 0WAP	Concentration at 4WAP	Concentration at 12WAP
T_{TB}	-	++	+
T_{EB}	-	++	+
T_{SB}	-	+	+
T_{MB}	-	+	+
T_{CH}	-	+	+
T_{CT}	-	++	++
TEST: TANNINS (1% LEAD ACETATE)			
T_{TB}	-	+	+
T_{EB}	-	+	+
T_{SB}	-	++	+
T_{MB}	-	+	+
T_{CH}	-	+	+
T_{CT}	-	+	+
TEST: TANNINS (1% FERRIC CHLORIDE)			
T_{TB}	-	++	+
T_{EB}	-	+	+
T_{SB}	-	+	+
T_{MB}	-	+	+
T_{CH}	-	++	+
T_{CT}	-	++	+
TEST: GLYCOSIDES (GENERAL TESTS)			
T_{TB}	-	+	+
T_{EB}	-	+	-
T_{SB}	-	++	+
T_{MB}	-	+	-
T_{CH}	-	+	-
T_{CT}	-	++	+
TEST: GLYCOSIDES (CYNOGENIC GLYCOSIDES)			
T_{TB}	-	++	+
T_{EB}	-	+	-
T_{SB}	-	++	+
T_{MB}	-	++	+
T_{CH}	-	+	-
T_{CT}	-	+	-

TEST: SAPONINS			
T_{TB}	-	+	+
T_{EB}	-	+	+
T_{SB}	-	+	+
T_{MB}	-	+	+
T_{CH}	-	+	+
T_{CT}	-	+	+
TEST: FLAVONOIDS			
T_{TB}	-	-	-
T_{EB}	-	-	-
T_{SB}	-	-	-
T_{MB}	-	-	-
T_{CH}	-	-	-
T_{CT}	-	-	-
TEST: TRITERPENOIDS			
T_{TB}	-	+	-
T_{EB}	-	++	+
T_{SB}	-	+	+
T_{MB}	-	++	+
T_{CH}	-	+	+
T_{CT}	-	++	+

Inference

- ++ : Allelochemicals are present in high concentrations in the sample.
- + : Allelochemicals are present in low concentrations in the sample.
- - : Allelochemicals are absent in the sample.

At 4WAP, most of the allelochemicals were released into the soil. The final results however indicated that T_{EB} as well as T_{CH} were able to reduce the effect of most of the allelochemicals. T_{TB} and T_{SB} did not remove much of the allelochemicals (five allelochemicals were present in both of them) as shown in Table 4.4.

4.2 BIOCHAR AND CHARCOAL ANALYSIS BEFORE APPLICATION

Analyses were carried out on the treatments (biochar and charcoal) before application to the soils. The initial levels of nutrients in the treatments are based on the type of feedstock that was used and the method of production (Table 4.5).

Table 4.5 Results of biochar and charcoal analysis

SAMPLE ID	Total N%	AVAIL P(mg/kg)	K (cmol/kg)	pH
T_{EB}	0.535	0.17	1.63	9.2
T_{MB}	0.375	0.15	1.17	6.9
T_{SB}	0.340	0.085	1.73	7.5
T_{TB}	0.145	0.195	1.62	6.7
T_{CH}	0.080	0.382	1.69	6.4

4.3 SOIL PHYSICOCHEMICAL PROPERTIES BEFORE AND AFTER TREATMENT APPLICATIONS

4.3.1 Soil physicochemical properties beneath bamboo stand before and after treatment applications

a. Soil physicochemical properties beneath bamboo stand at 0WAP

Initial soil analysis carried out indicated that SOC (by Walkley and Black method; Nelson and Sommers 1982), total N (by Kjeldahl method, 1984) and available P (by Bray and Kurtz, 1945) were all moderate whereas soil K (by Black, 1986) was low. The pH was slightly alkaline and the SOM was also lower than the acceptable threshold value of 3.4% (Table 4.6).

Table 4.6 Soil physicochemical properties beneath bamboo stand 0WAP

Physicochemical Properties					
SOC (%)	**Total N (%)**	**Available P (mg/kg)**	**Soil K (cmol/kg)**	**Soil pH**	**Soil Water-Holding capacity**
1.52	0.15	10.47	0.16	7.2	7.02

b. Soil physicochemical properties beneath bamboo stand 8WAP

There were significant differences in SOC 8WAP between all treatments with T_{TB} performing best with a means of 1.78. Significant differences at P≤0.05 were noted in available P with T_{TB} performing best with a means of 22.03. T_{CH} decreased the available P from moderate to low recording a means of 6.48. There were significant differences at P≤0.05 in soil K with T_{EB} performing best 8WAP. pH was reduced in all the amended plots and significant differences were recorded. There were significant differences in the water-holding capacity 8WAP and only T_{CH} was able to increase the water-holding capacity 8WAP.

No significant differences were recorded in the total N and SOM. T_{EB} however performed best with a means of 0.16 in increasing total N and T_{SB} performed best in increasing the SOM (Table 4.7).

Table 4.7 Soil physicochemical properties beneath bamboo stand 8WAP

Treatments	**Physicochemical Properties**				
	SOC (%)	**Available P (mg/kg)**	**Soil K (cmol/kg)**	**Soil pH**	**Soil water-holding capacity (%)**
T_{TB}	1.78a	22.03a	0.09b	6.5ab	5.59abc
T_{EB}	1.76ab	10.48e	0.20a	6.4ab	6.76ab
T_{SB}	1.62bc	18.27c	0.17ab	6.6ab	5.43abc
T_{MB}	1.58cd	21.07b	0.10b	6.7a	4.97bc
T_{CH}	1.46d	6.48f	0.12ab	6.3b	7.45a
T_{CT}	1.74ab	16.46d	0.16ab	6.5ab	4.36c
CV (%)	**3.18**	**1.06**	**23.09**	**2.44**	**13.55**
HSD	**0.15**	**0.47**	**0.09**	**0.45**	**2.21**

c. Soil physicochemical properties beneath bamboo stand 12WAP

After 12 weeks of planting, there were no significant differences between the treatments for SOC but T_{CT} performed best with a means of 1.68 and T_{MB} performed least with a means of 1.48. There were also no significant differences for total N however T_{EB} performed better with a means of 0.16. Again, there were no significant differences between the treatments for soil K but T_{CH} and T_{EB} both performed best with means of 0.15 and T_{CT} performed least with a means of 0.10. Soil water-holding capacity also did not show any significant differences 12WAP however T_{CH} increased the water-holding capacity of the soil.

There were significant differences in the available P between all the treatments. There were significant differences in the treatments for SOM and T_{CT} performed best with a means of 2.89 and T_{MB} and T_{CH} both performing least with a means of 2.55. Significant differences were recorded for the treatment means 12WAP for soil pH (Table 4.8).

Table 4.8 Soil physicochemical properties beneath bamboo stand 12WAP

Treatments	**Physicochemical Properties**		
	Available P (mg/kg)	**SOM (%)**	**Soil pH**
T_{TB}	18.27a	2.85a	6.8ab
T_{EB}	8.84e	2.82a	7.0a
T_{SB}	9.65d	2.85a	6.5ab
T_{MB}	10.47c	2.55b	6.8ab
T_{CH}	5.70f	2.55b	6.7ab
T_{CT}	12.13b	2.89a	6.4b
CV (%)	**1.89**	**2.81**	**2.8**
HSD	**0.58**	**0.22**	**0.5**

4.3.2 Soil physicochemical properties beneath eucalyptus tree before and after treatment applications

a. Soil physicochemical properties beneath eucalyptus tree 0WAP

Initial analysis indicated that total N and soil K were both moderate (Table 4.9). SOC, SOM and available P were low. The pH was slightly alkaline.

Table 4.9 Soil physicochemical properties beneath eucalyptus tree 0WAP

Physicochemical Properties					
SOC (%)	**Total N (%)**	**Available P (mg/kg)**	**Soil K (cmol/kg)**	**Soil pH**	**Soil Water-Holding capacity**
1.22	0.104	6.48	0.22	7.2	5.74

b. Soil physicochemical properties beneath eucalyptus tree 8WAP

There were no significant differences between the treatments for SOC however T_{CH} performed best with a means of 1.84. There were also no significant differences between the treatments for total N but T_{EB} performed best with a means of 0.18. There were no significant differences between the treatment means for soil pH.

There were significant differences between the treatments for available P and soil K with T_{EB} performing best in both cases. Significant differences were also recorded between the treatment means for SOM with T_{CH} performing best. There were significant differences between the treatment means for water-holding capacity with T_{SB} performing tremendously well 8WAP with a means of 14.38 (Table 4.10).

Table 4.10 Soil physicochemical properties beneath eucalyptus tree 8WAP

Treatments	Physicochemical Properties			
	Available P (mg/kg)	**Soil K (cmol/kg)**	**SOM (%)**	**Soil water-holding capacity (%)**
T_{TB}	9.65b	0.17ab	3.00ab	13.67b
T_{EB}	12.13a	0.23a	3.00ab	12.96c
T_{SB}	8.84b	0.10b	3.00ab	14.38a
T_{MB}	6.48cd	0.09b	3.07ab	8.92e
T_{CH}	7.26c	0.18ab	3.17a	11.89d
T_{CT}	5.70d	0.19ab	2.76b	7.12f
CV (%)	**5.95**	**22.45**	**3.81**	**1.50**
HSD	**1.40**	**0.10**	**0.32**	**0.49**

c. Soil physicochemical properties beneath eucalyptus tree 12WAP

There were significant differences between the treatment means for SOC 12WAP. There were significant differences between the treatment means for available P with T_{TB} performing best with a treatment means of 12.97.

Significant differences were noted between the treatment means for soil K, SOM, pH and water-holding capacity 12WAP.

There was however no significant differences between the treatments for total N nonetheless T_{TB} performed better with a mean of 0.15 (Table 4.11).

Table 4.11 Soil physicochemical properties beneath eucalyptus tree 12WAP

Treatments	Physicochemical Properties					
	SOC	**Available P (mg/kg)**	**Soil K (cmol/kg)**	**SOM (%)**	**Soil pH**	**Soil water-holding capacity (%)**
T_{TB}	1.76a	12.97a	0.20b	3.03a	6.4ab	13.41a
T_{EB}	1.72ab	6.48c	0.18b	2.96a	6.6a	10.54c
T_{SB}	1.54abc	4.94e	0.45a	2.65ab	6.0b	13.28a
T_{MB}	1.40bc	6.48c	0.11b	2.41bc	6.2ab	9.45e
T_{CH}	1.62abc	5.70d	0.15b	2.79a	6.0b	11.89b
T_{CT}	1.30c	9.65b	0.13b	2.24c	5.4c	9.99d
CV (%)	**7.57**	**2.07**	**19.55**	**5.04**	**2.4**	**1.08**
HSD	**0.33**	**0.45**	**0.11**	**0.38**	**0.4**	**0.35**

4.3.3 Soil physicochemical properties beneath teak tree before and after treatment applications

a. Soil physicochemical properties beneath teak tree 0WAP

The soil beneath the teak tree recorded very poor results for all the parameters analyzed (Table 4.12). SOC, total N, and soil K were low whereas available P and SOM were very low. Soil pH was slightly acidic before treatments were applied.

Table 4.12 Soil physicochemical properties beneath teak tree 0WAP

Physicochemical Properties					
SOC (%)	**Total N (%)**	**Available P (mg/kg)**	**Soil K (cmol/kg)**	**Soil pH**	**Soil Water-Holding capacity**
0.86	0.095	3.44	0.08	6.7	5.36

b. Soil physicochemical properties beneath teak tree 8WAP

There were no significant differences between the treatment means for SOC and total N however T_{SB} performed best in both cases.

There were significant differences between the treatment means for available P with T_{EB} performing best with a means of 11.29. There were also significant differences between the treatment means for soil K and soil pH. T_{EB} performed best with a means of 0.22 and 6.66 respectively. Significant differences were recorded between the treatment means for SOM and water-holding capacity. T_{SB} performed best in both cases with a means of 2.31 and 11.22 respectively (Table 4.13).

Table 4.13 Soil physicochemical properties beneath teak tree 8WAP

Treatments	Physicochemical Properties				
	Available P (mg/kg)	**Soil K (cmol/kg)**	**SOM (%)**	**Soil pH**	**Soil water-holding capacity (%)**
T_{TB}	8.84b	0.18ab	2.03ab	6.5a	8.76d
T_{EB}	11.29a	0.22a	1.97b	6.7a	8.32e
T_{SB}	5.70c	0.16ab	2.31a	6.4ab	11.22a
T_{MB}	4.94d	0.10b	2.21ab	6.4a	9.58c
T_{CH}	8.84b	0.14ab	2.14ab	6.0b	9.94b
T_{CT}	4.94d	0.10b	1.55c	6.3ab	5.54f
CV (%	**2.09**	**26.08**	**5.52**	**2.1**	**1.15**
HSD	**0.44**	**0.11**	**0.32**	**0.4**	**0.29**

c. Soil physicochemical properties beneath teak tree 12WAP

There were no significant differences between the treatment means for total N however T_{SB} performed best with a means of 0.10. Soil K also recorded no significant differences between the treatment means however T_{CH} performed best with a means of 0.12.

There were significant differences between the amended plots and the T_{CT} plots for SOC. T_{SB} performed best with a means of 1.22 whilst T_{CT} performed least with a means of 0.40. There were also significant differences between the treatment means for the available P. There were significant differences between the treatment means for SOM and water-holding capacity. In both cases T_{SB} performed best. There were also significant differences between the treatment means for soil pH with T_{EB} performing best with a means of 6.37 (Table 4.14).

Table 4.14 Soil physicochemical properties beneath teak tree 12WAP

Treatments	Physicochemical Properties				
	SOC	**Available P (mg/kg)**	**SOM (%)**	**Soil pH**	**Soil water-holding capacity (%)**
T_{TB}	0.96a	8.84a	1.65b	6.4ab	8.79d
T_{EB}	1.02a	8.84a	1.75b	6.4a	6.93e
T_{SB}	1.22a	6.48b	2.10a	5.9bc	11.91a
T_{MB}	0.98a	2.70e	1.69b	5.9bc	9.51c
T_{CH}	1.10a	5.70c	1.90ab	5.8c	11.31b
T_{CT}	0.40b	3.44d	0.69c	5.2d	5.23f
CV (%)	**10.96**	**2.58**	**6.78**	**1.6**	**1.12**
HSD	**0.29**	**0.44**	**0.31**	**0.3**	**0.28**

4.4 SOIL TEXTURE ANALYSIS

4.4.1 Soil texture before planting

The soils beneath the three selected trees were analyzed to ascertain their texture before the start of the experiment. Soils beneath the bamboo and eucalyptus trees were loamy sand whilst that underneath the teak was sand (Table 4.15).

Table 4.15 Soil texture before planting

SAMPLE	SAND %	SILT%	CLAY%	TEXTURE CLASS
Soil beneath the bamboo stand	89.78	0.22	10.00	Loamy sand
Soil beneath the eucalyptus tree	89.76	0.32	9.92	Loamy sand
Soil beneath the teak tree	92.82	1.18	6.00	Sand

The soil texture for the soils beneath the three landscape trees used in the experiment were analyzed and classified into loamy sand (for soil beneath the bamboo and eucalyptus) and sand (for soil beneath the teak tree).

4.4.2 Soil texture after treatment application and planting

a. Soil texture 8WAP

For the bamboo stand, the T_{MB}, T_{EB} as well as the T_{CH} changed the soil texture from loamy sand to sandy loam. However, that of the T_{TB}, T_{SB} and the T_{CT} remained unchanged (loamy sand).

For the soils beneath the eucalyptus tree only the T_{EB} and T_{CH} changed the soil texture to sandy loam. The other treatments maintained the soil texture.

All treatments for the soil beneath the teak tree changed the soil texture. T_{EB} changed the soil texture from sand to sandy loam the other treatments changed the texture from sand to loamy sand (Table 4.16).

Table 4.16 Soil texture 8WAP

SAMPLE	SAND %	SILT %	CLAY %	TEXTURE CLASS
Bamboo stand				
T_{TB}	82.88	6.48	10.64	Loamy sand
T_{EB}	77.24	10.56	12.20	Sandy loam
T_{SB}	83.00	8.36	8.64	Loamy sand
T_{MB}	79.04	10.48	10.48	Sandy loam
T_{CH}	75.44	10.44	14.12	Sandy loam
T_{CT}	82.88	6.48	10.64	Loamy sand
Eucalyptus tree				
T_{TB}	82.96	6.40	10.64	Loamy sand
T_{EB}	75.20	14.32	10.48	Sandy loam
T_{SB}	84.96	6.48	8.56	Loamy sand
T_{MB}	83.04	8.48	8.48	Loamy sand
T_{CH}	77.24	14.64	8.12	Sandy loam
T_{CT}	84.76	2.60	12.64	Loamy sand
Teak tree				
T_{TB}	86.88	6.44	6.68	Loamy sand
T_{EB}	75.16	18.36	6.48	Sandy loam
T_{SB}	81.00	12.36	6.64	Loamy sand
T_{MB}	81.04	14.32	14.64	Loamy sand
T_{CH}	79.32	12.56	8.12	Loamy sand
T_{CT}	86.72	6.64	6.64	Loamy sand

b. Soil texture 12WAP

By the twelfth week, the soil beneath the bamboo stand had been changed to loamy sand by all treatments except T_{EB} that maintained the soil texture as sandy loam. The T_{TB} only changed the soil texture from loamy sand to sandy loam in the soil beneath the eucalyptus tree. The other treatments either changed the soil texture from sandy loam (T_{EB} and T_{CH}) to loamy sand or maintained the texture as loamy sand (T_{SB}, T_{MB} and T_{CT}).

The soils beneath the teak tree however were maintained as loamy sand in all the treatments. The T_{EB} also changed the soil texture to loamy sand (Table 4.17).

Table 4.17 Soil texture 12WAP

SAMPLE	SAND %	SILT %	CLAY %	TEXTURE CLASS
Bamboo stand				
T_{TB}	80.88	9.92	9.20	Loamy sand
T_{EB}	76.84	12.12	11.04	Sandy loam
T_{SB}	82.04	10.64	7.32	Loamy sand
T_{MB}	80.28	10.52	9.20	Loamy sand
T_{CH}	82.84	12.40	4.76	Loamy sand
T_{CT}	83.80	8.60	7.60	Loamy sand
Eucalyptus tree				
T_{TB}	78.92	11.84	9.24	Sandy loam
T_{EB}	79.06	13.74	7.20	Loamy sand
T_{SB}	83.96	10.64	5.40	Loamy sand
T_{MB}	81.08	13.72	5.20	Loamy sand
T_{CH}	79.84	13.28	6.88	Loamy sand
T_{CT}	82.84	7.56	9.60	Loamy sand
Teak tree				
T_{TB}	81.84	12.60	5.56	Loamy sand
T_{EB}	83.28	13.52	3.20	Loamy sand
T_{SB}	83.92	10.84	5.25	Loamy sand
T_{MB}	84.08	12.72	3.20	Loamy sand
T_{CH}	80.84	14.20	4.96	Loamy sand
T_{CT}	84.84	9.48	5.68	Loamy sand

4.5 RATE OF GROWTH OF GRASS

4.5.1 Rate of growth of grass beneath bamboo stand

There were no significant differences between the treatments applied to the soil underneath the bamboo stand 4WAP. The rate of growth of grass was virtually the same in all the treatments. T_{MB} however, performed best with a mean of 6.4 followed by T_{SB} (5.7), T_{CH} (5.6), T_{EB} (5.3), T_{TB} (5.1) and the T_{CT} (2.9) (Plates 4.1 and 4.2).

Plate 4.1 T_{SB} (left), T_{MB} (middle) and T_{TB} (right) plots beneath bamboo stand 4WAP

Plate 4.2 T_{EB} (left), T_{CH} (middle) and T_{CT} (right) plots beneath bamboo stand 4WAP

Again there were no significant differences between the treatments 8WAP. This means the grass performance was almost the same in all the amended soils. Nevertheless, T_{EB} performed better with a mean of 16.0 as compared to the other treatments (Plate 4.3).

Plate 4.3 T_{TB} (left) and T_{SB} (right) plots beneath the bamboo stand 8WAP

By the end of the twelfth week (12WAP), T_{EB} appeared to be performing better than all the other treatments with a mean of 29.1. T_{SB} and T_{CH} both had means of 27.3. T_{MB} and T_{TB} also had means of 27.0 each and T_{CT} scored least with a mean of 18.3. Again there were no significant differences between the treatments (Plates 4.4 and 4.5).

Plate 4.4 T_{SB} (left) and T_{TB} (right) plots beneath bamboo stand 12WAP

Plate 4.5 T_{CT} plot beneath bamboo stand 12WAP

4.5.2 Rate of growth of grass beneath the eucalyptus tree

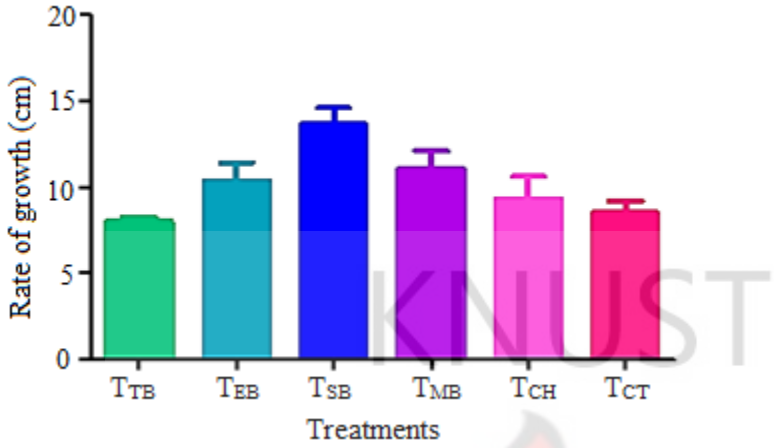

Figure 4.1 Rate of growth of grass beneath eucalyptus tree 4WAP

There were significant differences between the T_{SB} and the T_{TB} as well as the T_{SB} and the T_{CT}. The T_{SB} performed best with a means of 13.7 whilst T_{TB} performed least with a mean of 8.67 (Plates 4.6 and 4.7).

Plate 4.6 (From left) T_{MB}, T_{EB} and T_{TB} plots beneath eucalyptus tree 4WAP

Plate 4.7 (From right) T_{CT}, T_{SB} and T_{CH} plots beneath eucalyptus tree 4WAP

At 8WAP there were no significant differences between the treatments but T_{SB} again performed best with a mean of 45.9. This was followed by T_{CH}, T_{EB}, T_{TB}, T_{MB} and T_{CT} at mean of 36.3, 33.8, 32.5, 31.6, and 29.7 respectively (Plates 4.8 and 4.9).

Plate 4.8 T_{MB} (left) and T_{EB} (right) plots beneath eucalyptus 8WAP

Plate 4.9 T_{SB} (left) and T_{CT} (right) plots beneath eucalyptus tree 8WAP

At the end of week 12, there were no significant differences between the treatments. Nonetheless T_{SB} supported grass growth best with a means of 103.2. This was followed by the T_{TB} (80.5), T_{EB} (75.3), T_{CH} (67.9), T_{MB} (67.5) and the T_{CT} at 55.8 (Plates 4.10 and 4.11).

Plate 4.10 (From left) T_{MB}, T_{EB}, T_{TB} and T_{CH} plots beneath eucalyptus tree 12WAP

Plate 4.11 T_{EB} (left) and T_{SB} (right) plots beneath eucalyptus tree 12WAP

4.5.3 Rate of growth of grass beneath the teak tree

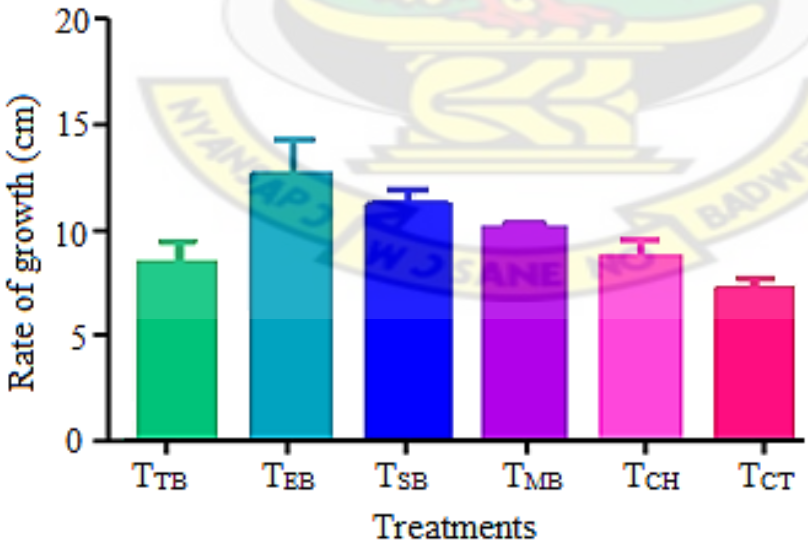

Figure 4.2 Rate of growth of grass beneath the teak tree 4WAP

The response of the St. Augustine grass to T_{EB} and T_{CT} was quite different with T_{EB} performing best with a means 14.5. All the other treatments did not show much significant differences (Plate 4.12).

Plate 4.12 (From right) T_{CH}, T_{MB}, T_{CT}, and T_{EB} plots beneath teak tree 4WAP

There were no significant differences between all the treatments at 8WAP although T_{EB} continued to perform better than all the other treatments (Plate 4.13).

Plate 4.13 (From left) T_{EB}, T_{TB}, T_{CT} and T_{CH} plots beneath teak tree 8WAP

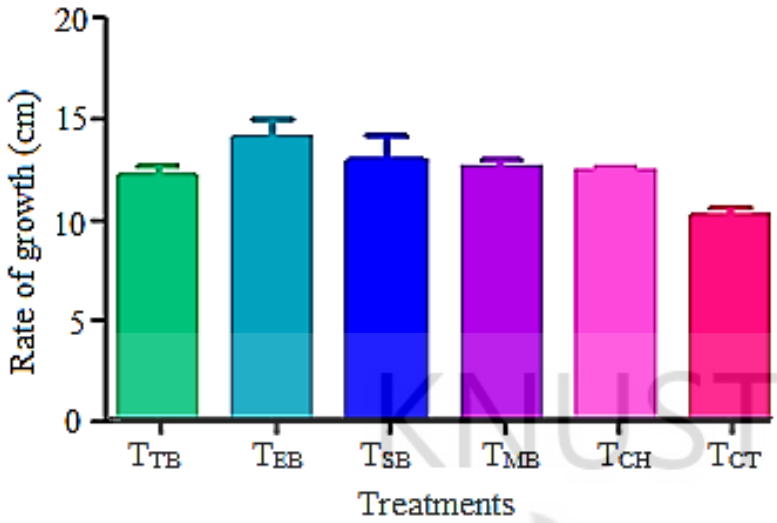

Figure 4.3 Rate of growth of grass beneath teak tree 12WAP

At 12WAP, there were significant differences between the T_{EB} and the T_{CT}. The T_{EB} continued to perform better with a means of 37.1 whilst T_{CT} recorded the least with a mean of 26.4 (Plate 4.14).

Plate 4.14 (From left) T_{TB}, T_{SB} and T_{EB} plots beneath teak tree 12WAP

4.6 PERCENTAGE COVERAGE OF GRASS

4.6.1 Percentage coverage of grass under bamboo stand

There were no significant differences between the treatments with respect to the percentage coverage of grass. There was a slow rate of spread from the second week through to the sixth week for all the treatments. However from the eighth week through to the twelfth week the rate of spread of the grass rose steadily in all the treatments but T_{CT}. The rate of spread for the T_{CT} started declining from the eighth week through to the twelfth week (Plate 4.15).

Plate 4.15 T_{CT} plot (left) as compared to T_{EB} plot (right) at 12WAP

4.6.2 Percentage coverage of grass under eucalyptus tree

Table 4.18 Percentage coverage of grass under eucalyptus tree

Treatments	Weeks					
	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12
T_{TB}	18%	40%	56%	71%	82%	85%
T_{EB}	15%	33%	48%	59%	74%	82%
T_{SB}	18%	37%	60%	74%	82%	89%
T_{MB}	11%	29%	37%	48%	59%	67%
T_{CH}	11%	26%	37%	44%	63%	63%
T_{CT}	11%	18%	29%	33%	48%	52%

Significant differences were observed for the rate of spread between the treatments (Table 4.18). The rate of spread from week two to week six was generally low. However, the rate of spread of the grass increased rapidly from the eighth week through to the twelfth week with T_{SB} performing best (Plate 4.16).

Plate 4.16 T_{SB} and T_{EB} plots showing 100% coverage at 12WAP

4.6.3. Percentage coverage of grass under teak tree

There were no significant differences for the treatments under the teak tree. The rate of spread of the grass was generally slow for all the treatments. However, the T_{SB} gave the highest rate of spread for the period (Plate 4.17).

Plate 4.17 T_{TB}, T_{SB} and T_{EB} plots showing about 60% coverage at 12WAP

4.7 WEED COUNT

4.7.1 Weed count under bamboo stand

There was no significant difference between the treatment means for the weed count. The T_{SB} was able to suppress the weeds better than the other treatments.

4.7.2 Weed count under eucalyptus tree

There were no significant differences between the treatments under the eucalyptus tree. However, the T_{MB} was able to control weed growth better than the other treatments. T_{CH} was not able to control the weed growth as it had the highest means.

4.7.3 Weed count under the teak tree

There were no significant differences between the treatment means however T_{SB} was able to suppress weed growth better than all other treatments.

CHAPTER FIVE

5.0 DISCUSSION

5.1 DYNAMICS OF ALLELOCHEMICALS IN SELECTED PLANTS AND IN SOIL

Initial phytochemical screening carried out on the leaves and roots of the three tree species suspected to be allelopathic revealed that the leaves and roots contained allelochemicals. The allelochemicals present were flavonoids, saponins, triterpenoids, glycosides, alkaloids, and tannins. These allelochemicals are secondary metabolites which are found in many plants. The allelochemicals detected (Table 4.1) are classified as secondary metabolites (Medentsev and Akimenko, 1998) and these include both simple molecules such as alcohols, sugars and organic acids; and complex compounds such as polyketides, flavonoids, terpenoids, non-ribosomal peptide compounds, phenols, tannins, alkaloids, polyacetylenes, fatty acids and steroids. However, these secondary metabolites are classified as allelochemicals based on their concentrations (Bhowmik and Inderjiit, 2003). Due to the high concentrations of allelochemicals that were found in the leaves and roots of the tree species, they were classified as allelopathic. Initial phytochemical screening carried out on the leaves and roots of bamboo, eucalyptus and teak trees confirmed that they were allelopathic as indicated by Baker (1966), Al-Mousawi and Al-Naib, (1976), Jayakumar *et al*, (1987), Lisanework and Michelson (1993), Macias *et al.* (2000) and Krishna *et al.* (2003). Their works concluded that these tree species inhibited the growth of any other plant species around them and hence the tree species were classified as allelopathic.

The presence of allelochemicals in the leaves and roots however gave no indications of their release into the surrounding soils. Coder (1999a) reported that once an allelochemical is outside its producer (conveyer) the chemical is easily modified, torn-apart, reassembled and or used by other organisms. Hence it could be suggested that the allelochemicals may have been released into the soil but because there was no undergrowth competing with the trees the allelochemicals may rather have been modified or used up by soil microorganisms. Many organisms respond quickly to allelopathic attack by breaking-up the chemicals or transforming them into non-damaging forms (Coder, 1999a).

Upon planting St. Augustine's species further analysis was carried out to find out if the allelochemicals were released into the soil after planting was done. The analysis tested positive for most of the allelochemicals (alkaloids, saponins, triterpenoids, glycosides and tannins) showing that they were released into the soil after the grasses were planted beneath the trees. This attests to what Coder (1999b) stated that allelochemicals are produced when a plant is under stress. N, phosphorus, water, and temperature extremes can all accelerate allelopathic chemical production. As stress between an allelopathic plant and a neighbouring plant species becomes great, allelopathy increases in importance.

By the twelfth week, flavonoids tested negative probably because of their unstable nature since they are known to have a half-life of 3 – 12 hours (Anon, 2010). This clearly indicates that the flavonoids may have been released into the soil but due to the short half-life it was broken down before the soil was analyzed.

Nonetheless, the application of biochar and charcoal to the soil was able to ameliorate the effects of the allelochemicals and allowed the grasses that were planted beneath the trees to thrive well. Verheijen *et al.* (2010) reported that, incorporation of black carbon (biochar) and charcoal into soil is expected to enhance overall sorption capacity of soils in a mechanistically different (and stronger) way than amorphous organic matter. The incorporation of biochar and charcoal therefore reduced the concentrations of the allelochemicals considerably in the soil to a favourable concentration and this allowed the grasses to thrive beneath the trees.

5.2 BIOCHAR AND CHARCOAL ANALYSIS

In the analysis that was carried out on the biochar and charcoal before the treatments were applied to the soil. The different levels of nutrients of biochar and charcoal were noticed to be dependent on the type of feedstock that was used in the production and the growing conditions of the feedstock (if the feedstock is organic in nature). As stated by Verheijen *et al.* (2010), even within a biomass feedstock type (example wood, grain husks, nut shells, manure and crop residues), different composition may arise from distinct growing environmental conditions (soil type, temperature and moisture content) and those relating to the time of harvest. Again, the method of biochar production as well as the temperature at which pyrolysis occurred also affects the nutrient composition and structure of the biochar produced.

The initial pH values of the treatments were in the range of 6.43 – 9.21. As was also recorded in the work of Chan and Xu (2009) where biochar pH values were reviewed

from a wide variety of feedstocks and a mean of pH of 8.1 was found in a total pH range of 6.2 – 9.6.

5.3 SOIL ORGANIC CARBON (SOC)

According to the results obtained, T_{TB} and T_{CH} performed better in increasing the SOC content in the soil beneath the bamboo. This may be as a result of high content of carbon in the biochar and charcoal that was applied to the soil before planting.

For the soil beneath the eucalyptus tree, the teak biochar performed better with a mean of 1.76 at the end of the research. The charcoal also performed considerably well (with a mean of 1.62) by the end of the research.

Even though all the treatments including the T_{CT} decreased the soil carbon by the twelfth week of the research T_{SB} again performed better in increasing the soil carbon content beneath the teak tree. This was followed by T_{CH} (Table 4.14).

Most the treatments in the plots beneath the three trees increased the SOC by the eighth week of the research. Shenbagavalli and Mahimairaja (2012) reported similar results after biochar application to soil. It was reported that the application of different rates of biochar had significant effect on SOC content. Biochar increased the SOC content from 5.1gkg^{-1} to a range of 6.9 – 18.1gkg^{-1}. Zackrisson *et al.* (1996); Pietikainen *et al.* (2000); DeLuca and Aplet (2008) reported that charcoal adds to stable SOC pools, enhances soil productivity, and positively influences soil biological properties.

Fontaine *et al.* (2004) reported that biochar has a priming effect when it is applied to soil. The priming effect is defined as “the acceleration of soil carbon decomposition by fresh

carbon input to soil" and is generally considered to be short-term changes in the turnover of soil micro-organisms (Kuzyakov *et al.,* 2000). The priming effect is thought to be a function of changes in microbial community composition upon fresh carbon input into soil (Fontaine *et al.,* 2004). This means that addition of a 'new' source of carbon (such as biochar or charcoal) into the soil system can potentially lead to a priming effect whereby SOC is reduced. This could be the reason why the SOC was reducing by the twelfth week by all the treatments. Several mechanisms may be involved in the priming effects. These include changes in soil pH, changes in water-filled pore space, changes in habitat structure, or changes in nutrient availability (Fontaine *et al.,* 2004). In the T_{CT} however, the reduction may be due to the release of the allelochemicals into the soil after planting was done because the percentage reduction was drastic.

5.4 SOIL NUTRIENTS, TEXTURE AND WATER-HOLDING CAPACITY

Many recent studies have been carried out to show the effect that biochar and charcoal have on soil physical, biological and chemical properties. These properties altogether affect plant growth and its response in the soil. Vuthisa (2011) stated that biochar retains nutrients because of cation exchange capacity (CEC). The CEC conserves nutrients added to the soil and improves the ability of the soil to capture and retain nutrients from other sources available at other times. When this organic matter decomposes, biochar captures some of the nutrients released. Downie *et al.* (2009) reported that the incorporation of biochar into soil can alter soil physical properties such as texture and structure with implications for soil aeration, water-holding capacity, plant growth and soil workability. Glaser *et al.* (2002) also reported that charcoal residues and charred biomass has been found to serve as ameliorate and improve the fertility of tropical soils by direct nutrient

addition and retention. According to Ogundele *et al.* (2011) available phosphorus, exchangeable bases, total N, organic carbon and base saturation was higher in soils of charcoal production sites than the adjacent lands.

5.4.1 Percentage N in the soil

Soil analysis 12WAP showed a decrease in N in all the treatments beneath the bamboo stand except for the T_{EB} which increased the N content. T_{EB} had the highest level of N before it was applied to the soil and this could account for the slight increase in the N content by the eighth week. By the twelfth week, there was a further decrease in the N content in some of the treatments (T_{EB}, T_{MB} and T_{CT}), whereas T_{SB}, T_{TB} and T_{CH} maintained the N content in the soil.

In the soils beneath the eucalyptus tree the situation was different. By the eighth week all the treatments increased the N content of the soil, with the T_{EB} recording the highest increase (0.104 to 0.18). Again, this could be attributed to the high N content in the T_{EB} before it was applied to the soil. By the twelfth week, all the treatments including the T_{EB} decreased the N content of the soil.

For the soils beneath the teak tree, all the soils increased the N content in the soil by the eighth week. By the twelfth week, all the treatments had decreased the N content in the soil.

The decrease in N content is in agreement with findings by Shenbagavalli and Mahimairaja (2012) where the addition of biochar to soil resulted in marked changes in the N (NH^{4+}, N^{-} and NO^{3-}) content of the soil. The reduction might be due to adsorption of NH^{4+} onto biochar particles. Lehmann *et al.* (2006) have also indicated that biochar

can adsorb both NH^{4+} and NH^{3-} from the soil solution thus reducing solution inorganic N at least temporarily, but perhaps concentrating it for microbial use. The reduction could be due to high C/N ratio of biochar and greater potential for N immobilization. Schneour (1966) and Liang *et al.* (2006) also suggested that it is possible that some amount of decomposition might have occurred when fresh biochar is added to soil and this could induce net immobilization of inorganic N already present in the soil solution thus leading to a reduction in the N content in the soil. Gundale and DeLuca (2006) reported that biochar addition to soil caused reduction in ammonification compared to the control due to adsorption and reduce the potential for NH^{3-} volatilization.

5.4.2 Available P in the soil

In the soils beneath the bamboo stand, available P in the soil was increased in all treatments except T_{CH} which decreased the available P by the eighth week of the research. T_{TB} had the highest P content and this could be attributed to the high available P in the biochar before application to the soil. By the twelfth week, all the treatments decreased the available P in the soil. Nonetheless, T_{TB} had the highest available P content.

The results for the soils beneath the eucalyptus tree indicated that by the eighth week, T_{CT} decreased the available P content and the other treatments increased the available P content. The decrease in the available P for the control plots could be attributed to the fact that after planting allelochemicals were released into the soil and these allelochemicals may have competed with the grass for the available nutrients in the soil hence the decrease in the available P. T_{TB} had the highest available P before application

to the soil and this was reflected in the available P content in the soil 8WAP. However by the twelfth week all the treatments had decreased the available P content except in the T_{TB} where there was an increase in the available P.

For the soils beneath the teak tree, all treatments increased the available P in the soil with T_{EB} recording the highest available P content in the soil. By the end of the research however all the treatments decreased the available P in the soil. Again, T_{CH} decreased the available P in the soil throughout the research.

The observed increase in available P by the eighth week due to application of biochar could be due to the presence of high P in the feedstock used in the biochar production. This affirms findings by Nigussie *et al.* (2012) that P was made available in the soil due to the presence of high P in the feedstock (maize stocks). However the decrease in available P in the T_{CH} plots does not agree with findings made by Ogundele *et al,* (2011) and Blanca *et al*. (2008). Their research reported increase in available P in the soils at charcoal production sites as compared to adjacent soils. Simone *et al.* (2008) also reported that increasing charcoal quantities in the soil increased soil P. This contradicts findings of this study where charcoal applied to the soil decreased the available P in the soils beneath all three allelopathic trees.

5.4.3 Soil potassium (K)

The results indicated that T_{EB}, T_{SB} and T_{CH} increased the soil K in the soil beneath the bamboo stand. This could be attributed to the high content of K in the biochar and charcoal before it was applied to the soil.

In the soils beneath the eucalyptus tree, T_{SB} increased the soil K and this may be due to the high K content in the biochar before it was applied to the soil.

The soils beneath the teak tree also revealed similar results where T_{EB}, T_{SB} and T_{CH} increased the soil K due to the high K content in the treatments before they were applied to the soil.

The increase in the soil K due to the high content of K in the biochar and charcoal before application to the soil affirms findings by Nigussie *et al.* (2012) and Lehmann *et al.* (2003) where soil K was increased due to the high content of K in biochar prior to its use as soil amendment. They concluded that high concentrations of biochar are likely to increase the soil K considerably and this can be beneficial in K deficient soils. Similarly, Ogundele *et al.* (2011) reported that low K content was found in the soil due to the low content of K in the trees that were used as feedstock for the charcoal which was used as a soil amendment.

5.4.4 Soil organic matter (SOM)

In the soils beneath the bamboo stand, all the treatments (except T_{CH}) increased the SOM 8WAP. By the twelfth week, T_{SB} and T_{CH} increased the SOM whilst the other treatments decreased the SOM. T_{SB} performed best in increasing the SOM.

Similar results were recorded in the soils beneath the eucalyptus tree. All the treatments increased the SOM after 8 weeks of planting with T_{CH} and T_{SB} performing best. Even though all the treatments reduced the SOM by the twelfth week, T_{SB} recorded the least percentage reduction.

In the soils beneath the teak tree, all the treatments increased the SOM by the eighth week with T_{SB} recording the highest percentage increase. Even though the treatments decreased the SOM by the twelfth week, T_{SB} again recorded the least percentage reduction.

The results for the initial biochar analysis indicated that T_{EB} had the highest organic matter. This however did not reflect in the soil to increase the SOM beneath all three trees. As reported by Verheijen *et al.* (2010) biochar can both increase and decrease the accessibility of SOM to microorganisms and enzymes. The unresponsive performance of T_{EB} in the soil could be attributed to the fact that it may have decreased the accessibility of SOM to microorganisms after its application. T_{SB} however performed better in the soils beneath the three trees in spite of its initial low organic matter content.

It could be noted from the results that even though T_{SB} performed better there was a slight decrease in the level of SOM. The decline in SOM has been defined by Jones (2007) as a negative imbalance between the build-up of SOM and rates of decomposition leading to an overall decline in SOM contents and/or quality, causing a deterioration or loss of one or more soil functions.

5.4.5 Soil pH

The initial pH of the soil before the research was reduced by all the treatments in the soils beneath the bamboo stand. By the twelfth week however it was increased by all the treatments to a range of 6.38 – 7.00. A reason for the increase in soil pH due to application of biochar could be because of high surface area and porous nature of biochar that increases the CEC of the soil (Nigussie *et al.*, 2012). Nigussie and Kissi (2011) also

reported that charcoal is likely to increase soil pH due to its porous nature which increases the CEC of the soil.

Similar results were recorded in the soils beneath the eucalyptus and teak trees where the initial pH was reduced in the soil by the end of the research.

The pH of the soils beneath the three trees was in a range of 5.21 – 7.00. The results show that all the soils beneath the trees were alkaline before the application of biochar. Cheng *et al.* (2008) carried out studies to demonstrate a reduction in pH due to biochar addition in alkaline soils. However, the reduction in the soil pH was to an acceptable range in which most plants thrive. Leonard (2012) reported that the optimum pH for most plants is 5.5 – 7.0. Cheng *et al.* (2008) reported that the reduction in soil pH might be due to release of protons (H^+) from the exchange sites of biochar (exchangeable acidity 49mmol kg^{-1}), and due to the proliferation of acid producing soil microorganisms. It is also likely that the production of organic acid during the decomposition of organic matter present in soil and biochar might have also contributed for the reduction in soil pH values.

5.4.6 Soil texture

T_{EB}, changed the soil texture beneath all the three trees from loamy sand (under bamboo stand and eucalyptus tree) and sandy (under teak tree) to sandy loam. All the other treatments however changed the soil texture beneath the teak tree from sand to loamy sand making it favourable for the grasses to do well in the soil. Sandy soils do not have sufficient organic matter to bind the sand grains into larger aggregates. In this case, the soil will have many large pore spaces and very few small pores. The plant roots will have plenty of air but water will drain freely through the soil with very little storage.

Soil texture influences other properties of the soil such as the water-holding capacity and nutrient retention and utilization.

5.4.7 Soil water-holding capacity

As discussed earlier, soil water-holding capacity is largely affected by soil particle size (texture) combined with structural characteristics and SOM content. However, other properties such as the ability of the soil to retain nutrients also affect its water-holding capacity.

The results show that T_{CH} and T_{EB} performed better in increasing the water-holding capacity of the soil beneath the bamboo stand. Even though the T_{EB} changed the soil texture from loamy sand to sandy loam it seemed to hold much water for the soil beneath the bamboo stand. This may be due to the fact that T_{EB} was able to hold much nutrients (N and K) and improve the pH of the soil. T_{CH} performed tremendously well in holding much water.

T_{SB} however performed best in the soils beneath the eucalyptus and the teak tree. T_{CH} also performed considerably well in water retention. T_{SB} performed best probably because of its ability to hold much nutrients in the soil. From the results, T_{SB} was able to improve the SOM, increase soil K and available P in the soil as well as improve upon the soil texture beneath both the eucalyptus and the teak tree.

Glaser *et al.* (2002) reported that water retention capacity was 18% higher in soils amended with charcoal as compared to adjacent soils where there was no amendment. Piccolo *et al.* (1997); Piccolo and Mbagwu, (1990) also reported that the presence of

small pores in the charcoal residues and charred biomass increases soil water-holding capacity of the soil.

Many authors (Dempster *et al.,* 2012, Kammann *et al.,* 2011, Karhu *et al.,* 2011 and Asai *et al.,* 2009) have reported on the remarkable water-holding capacity of soils amended with biochar. The high surface area of biochar as reported by Glaser *et al.* (2002) can lead to increased water retention, although the effect seems to depend on the initial texture of the soil as well as the available nutrients in the soil for the plants. A draw-back however is the large volume of biochar that needs to be added to the soil before it leads to increased water retention.

5.5 RESPONSE OF GRASS IN THE SOIL

5.5.1 Rate of growth of grass

The application of the treatments to the soil reduced the concentration of the allelochemicals and improved the soil to enable the grass do well beneath the trees. This was reflected on the experimental plots where the treatments were applied as compared to the control plots.

There were no significant differences between the amended soils beneath the bamboo stand throughout the research. Nevertheless, T_{EB} performed best. T_{CH} also performed considerably well throughout the research.

There were significant differences between the amended soils at the start of the research through to the fourth week in the soils beneath the eucalyptus tree. However, there were no significant differences from the fifth week through to the end of the research. T_{SB}

performed best throughout the research. Even though T_{CH} supported growth of the grass it was not as effective as the biochar treatments.

Again significant differences were observed in the soils beneath the teak tree from the start of the research through to the end of the fourth week. However, no significant differences were observed from the fifth week through to the end of the research. T_{EB} performed best throughout the research. Again, even though T_{CH} was able to support growth of the grass it was not as effective as the biochar treatments.

Verheijen *et al.* (2010) stated that biochar application is expected to improve the overall adsorption capacity of soils. This explains why the biochar treatments performed best. The low performance of the T_{CH} could be attributed to the structural and chemical properties of the allelochemicals. Zhu and Pignatello (2005), Zhu *et al.* (2005) and Wang *et al.* (2006) reported that adsorption to charcoals is mainly influenced by the structural and chemical properties of the contaminant as well as pore size distribution, surface area and functionality of the charcoal (Chen *et al.*, 2007).

5.5.2 Percentage coverage of grass

The rate of spread of the grasses beneath all the trees was slow and steady from the start of the research through to the sixth week. This was because the only means of irrigation for the grasses was by watering. There were no significant differences in the soils beneath the bamboo stand and the teak tree. Even though T_{EB} had the highest rate of growth in the soils beneath these trees, the rate of spread was not proportional to its growth rate. T_{TB} had the highest rate of spread in the soil beneath the bamboo stand whilst T_{SB} had the highest rate of spread beneath the teak tree. There were however significant differences in

the soils beneath the eucalyptus tree. T_{SB} had the highest rate of spread (with 100% coverage by the end of the research).

The percentage coverage of grass began to improve with the onset of rains from the seventh week through to the twelfth week. Anon (2011) also reported that as rainfall increases, total plant production of organic matter increases and hence soil organic matter and activity increases. Rain water also makes nutrients and minerals available for plant growth.

5.6 WEED EMERGENCE

Weed emergence is inversely proportional to the Percentage coverage of grass. The interconnected nature of St. Augustine's grass which is characterized by vigorous and rapid creeping stolons suppresses weed growth as the grass begins to spread. As stated by Duble (2013), a healthy St. Augustine's grass lawn effectively crowds out most weeds.

There were no significant differences in all the treatments beneath all the trees. In the soils beneath the bamboo stand, T_{SB} as well as T_{TB} were able to suppress weed growth better as they had the highest spread. T_{SB} and T_{MB} also were able to suppress weed growth in the soils beneath the eucalyptus tree and T_{SB} suppressed weed growth best in the soil beneath the teak tree. It was however realized that T_{CH} had poor weed growth suppression ability. Weeds occur in every lawn. However, they seldom become problems in well-managed, vigorously growing lawns.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The soil amendments used for the study (biochar and charcoal) reduced the effects of the allelochemicals in the soil to an optimum concentration and therefore boosted the resistance of *Stenotaphrum secundatum* which were planted beneath the allelopathic trees. The amendments used can therefore help establish different plant combinations in the landscape which hitherto was not possible beneath allelopathic plants and can be useful management tools for landscape designers and amenity horticulturists.

The specific allelochemicals found in the allelopathic plants were alkaloids, tannins, saponins, flavonoids, triterpenoids and glycosides. These were found in high concentrations and hence *Tectona grandis* (Teak), *Eucalyptus grandis* (Eucalyptus) and *Bambusa spp* (Bamboo) were concluded to be allelopathic.

The different nutrient levels in the biochar and charcoal that are used as soil amendments depend on the following: the type of feedstock that is used, the growing conditions (or environmental conditions) of the feedstock, the time of harvest of feedstock (if the feedstock is organic in nature), the method of production of biochar and charcoal and the temperature at which production of the amendment occurred.

The different nutrient levels in the biochar and charcoal that are used as soil amendments depend on the following: the type of feedstock that is used, the growing conditions (or environmental conditions) of the feedstock, the time of harvest of feedstock (if the

feedstock is organic in nature), the method of production of biochar and charcoal and the temperature at which production of the amendment occurred.

Both amendments used were able to increase the available nutrients in the soil, improve upon the soil pH, increase soil carbon as well as improve upon the water-holding capacity of the soil. The treatments also improved upon soil microorganisms in the soil which led to improved soil texture for better plant performance. However, sapele biochar and esa biochar performed best in improving the soil's ability to support plant growth amidst the presence of allelochemicals in the soil.

Biochar and charcoal can increase the rate of spread of St. Augustine's grass tremendously during the rainy season. Without rains, the grasses will spread but will take a longer time as compared to when there are rains.

Sapele biochar and esa biochar had the highest rate of spread of St. Augustine's grass even with the presence of allelochemicals in the soil.

Most of the grasses beneath the teak tree found it very difficult to spread due to the large leaves of the teak tree. The leaves blocked any amount of sunlight from reaching the ground. This affected the rate of growth and rate of spread of the grass negatively. Charcoal has a poor ability in the suppression of weed growth.

6.2 RECOMMENDATIONS

It is recommended that:

1. Sapele biochar and esa biochar should be considered as soil amendment for lawn establishment where allelochemicals are present in the soil.
2. Some amount of sunlight should be allowed when planting St. Augustine's grass since absolute shade will result in longer stolons which will however not spread easily.
3. To improve upon soil physical, biological and chemical properties, feedstock with higher nutrient availability should be considered for biochar and charcoal production.
4. During the research, plants of the Araceae family (especially *Caladium* sp) were found growing a few meters (about 1m and beyond) away from the bamboo stand. Plants of the Asparagaceae family (*Sanseviera* sp) were also found growing about 1m away from the base of the teak tree. It is therefore recommended that further research should be carried out on other plant family types that may do well beneath these allelopathic plants. These plants could be incorporated into the landscape together with grasses where the soil is tested and proved to have allelochemicals present in them.
5. Further studies should be conducted on the long term effects that biochar and charcoal may have on the allelochemicals.
6. Other feedstock types for biochar production should be considered in further studies to find out which feedstock type can also improve the soil where allelochemicals have been found to be present in a short period of time.

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APPENDICES

APPENDIX ONE: ANOVA TABLES

ANOVA Table for Treatment Means for SOC beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TTB	1.7800	A
TEB	1.7600	AB
TCT	1.7400	AB
TSB	1.6200	BC
TMB	1.5800	CD
TCH	1.4600	D

Critical Value for Comparison 0.1493
There are 4 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for N beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TEB	0.1700	A
TCT	0.1400	A
TTB	0.1300	A
TMB	0.1200	A
TCH	0.1100	A
TSB	0.1100	A

Critical Value for Comparison 0.1446
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TTB	22.030	A
TMB	21.070	B
TSB	18.270	C
TCT	16.460	D
TEB	10.480	E
TCH	6.480	F

Critical Value for Comparison 0.4726
All 6 means are significantly different from one another.

ANOVA Table for Treatment Means for K beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TEB	0.2000	A
TSB	0.1700	AB
TCT	0.1600	AB
TCH	0.1200	AB
TMB	0.1000	B
TTB	0.1000	B

Critical Value for Comparison 0.0926
There are 2 groups (A and B) in which the means are not significantly

different from one another.

ANOVA Table for Treatment Means for SOM beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TTB	3.0700	A
TEB	3.0300	A
TCT	3.0000	A
TSB	2.7900	A
TMB	2.7200	A
TCH	2.5200	A

Critical Value for Comparison 0.6802
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for pH beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT

TRT	Mean	Homogeneous Groups
TMB	6.7400	A
TSB	6.5500	AB
TTB	6.5300	AB
TCT	6.4600	AB
TEB	6.4200	AB
TCH	6.2500	B

Critical Value for Comparison 0.4480
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT

TRT	Mean	Homogeneous Groups
TCH	7.4500	A
TEB	6.7600	AB
TTB	5.5900	ABC
TSB	5.4300	ABC
TMB	4.9700	BC
TCT	4.3600	C

Critical Value for Comparison 2.2095
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for SOC beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TCT	1.6800	A
TTB	1.6600	A
TSB	1.6600	A
TEB	1.6400	A
TCH	1.4800	A
TMB	1.4800	A

Critical Value for Comparison 0.2377
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for N beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TEB	0.1600	A
TTB	0.1300	A
TCH	0.1300	A
TCT	0.1200	A
TMB	0.1100	A
TSB	0.1100	A

Critical Value for Comparison 0.0859
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TTB	18.270	A
TCT	12.130	B
TMB	10.470	C
TSB	9.650	D
TEB	8.840	E
TCH	5.700	F

Critical Value for Comparison 0.5806
All 6 means are significantly different from one another.

ANOVA Table for Treatment Means for K beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TCH	0.1500	A
TEB	0.1500	A
TSB	0.1400	A
TMB	0.1100	A
TTB	0.1100	A
TCT	0.1000	A

Critical Value for Comparison 0.1198
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for SOM beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TCT	2.8900	A
TSB	2.8500	A
TTB	2.8500	A
TEB	2.8200	A
TCH	2.5500	B
TMB	2.5500	B

Critical Value for Comparison 0.2191
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for pH beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT

TRT	Mean	Homogeneous Groups
TEB	7.0000	A
TTB	6.7800	AB
TMB	6.7500	AB
TCH	6.6700	AB
TSB	6.4700	AB
TCT	6.3800	B

Critical Value for Comparison 0.5334
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT

TRT	Mean	Homogeneous Groups
TCH	11.570	A
TEB	10.990	A
TTB	10.240	A
TMB	10.020	A
TCT	9.500	A
TSB	8.970	A

Critical Value for Comparison 2.6041
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for SOC beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TCH	1.8400	A
TMB	1.7800	A
TTB	1.7400	A
TEB	1.7400	A
TSB	1.7400	A
TCT	1.6000	A

Critical Value for Comparison 0.5436
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for N beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TEB	0.1800	A
TSB	0.1600	A
TTB	0.1600	A
TCH	0.1400	A
TMB	0.1400	A
TCT	0.1300	A

Critical Value for Comparison 0.1093
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TEB	12.130	A
TTB	9.650	B
TSB	8.840	B
TCH	7.260	C
TMB	6.480	CD
TCT	5.700	D

Critical Value for Comparison 1.4045
There are 4 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for K beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TEB	0.2300	A
TCT	0.1900	AB
TCH	0.1800	AB
TTB	0.1700	AB
TSB	0.1000	B
TMB	0.0900	B

Critical Value for Comparison 0.1017
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for SOM beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TCH	3.1700	A
TMB	3.0700	AB
TEB	3.0100	AB
TSB	3.0000	AB
TTB	3.0000	AB
TCT	2.7600	B

Critical Value for Comparison 0.3237
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for pH beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT

TRT	Mean	Homogeneous Groups
TCH	6.6300	A
TTB	6.5600	A
TEB	6.5600	A
TMB	6.5500	A
TSB	6.5200	A
TCT	6.4600	A

Critical Value for Comparison 0.7870
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT

TRT	Mean	Homogeneous Groups
TSB	14.380	A
TTB	13.670	B
TEB	12.960	C
TCH	11.890	D
TMB	8.920	E
TCT	7.120	F

Critical Value for Comparison 0.4864
All 6 means are significantly different from one another.

ANOVA Table for Treatment Means for SOC beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TTB	1.7600	A
TEB	1.7200	AB
TCH	1.6200	ABC
TSB	1.5400	ABC
TMB	1.4000	BC
TCT	1.3000	C

Critical Value for Comparison 0.3336
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for N beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TTB	0.1500	A
TCH	0.1400	A
TEB	0.1400	A
TCT	0.1200	A
TSB	0.1200	A
TMB	0.1100	A

Critical Value for Comparison 0.0711
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TTB	12.970	A
TCT	9.650	B
TEB	6.480	C
TMB	6.480	C
TCH	5.700	D
TSB	4.940	E

Critical Value for Comparison 0.4520
There are 5 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for K beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TSB	0.4500	A
TTB	0.2000	B
TEB	0.1800	B
TCH	0.1500	B
TCT	0.1300	B
TMB	0.1100	B

Critical Value for Comparison 0.1125
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for SOM beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TEB	2.9400	A
TTB	2.9400	A
TCH	2.7900	A
TSB	2.6500	AB
TMB	2.4100	BC
TCT	2.2400	C

Critical Value for Comparison 0.3797

There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for pH beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT

TRT	Mean	Homogeneous Groups
TEB	6.6200	A
TTB	6.3700	AB
TMB	6.2400	AB
TSB	6.0400	B
TCH	6.0300	B
TCT	5.3700	C

Critical Value for Comparison 0.4223
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT

TRT	Mean	Homogeneous Groups
TTB	13.410	A
TSB	13.280	A
TCH	11.890	B
TEB	10.540	C
TCT	9.990	D
TMB	9.450	E

Critical Value for Comparison 0.3494
There are 5 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for SOC beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TSB	1.3400	A
TMB	1.2800	A
TCH	1.2400	A
TTB	1.1800	A
TEB	1.1400	A
TCT	0.9000	A

Critical Value for Comparison 0.4577
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for N beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TSB	0.1100	A
TCH	0.1000	A
TMB	0.1000	A
TTB	0.1000	A
TEB	0.0900	A
TCT	0.0700	A

Critical Value for Comparison 0.0968
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TEB	11.290	A
TCH	8.840	B
TTB	8.840	B
TSB	5.700	C
TMB	4.940	D
TCT	4.940	D

Critical Value for Comparison 0.4397
There are 4 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for K beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TEB	0.2200	A
TTB	0.1800	AB
TSB	0.1600	AB
TCH	0.1400	AB
TMB	0.1000	B
TCT	0.1000	B

Critical Value for Comparison 0.1107
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for SOM beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TSB	2.3100	A
TMB	2.2100	AB
TCH	2.1400	AB
TTB	2.0300	AB
TEB	1.9700	B
TCT	1.5500	C

Critical Value for Comparison 0.3178
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for pH beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT

TRT	Mean	Homogeneous Groups
TEB	6.6600	A
TTB	6.4800	A
TMB	6.4400	A
TSB	6.3900	AB
TCT	6.3300	AB
TCH	6.0400	B

Critical Value for Comparison 0.3789
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT

TRT	Mean	Homogeneous Groups
TSB	11.220	A
TCH	9.940	B
TMB	9.580	C
TTB	8.760	D
TEB	8.320	E
TCT	5.540	F

Critical Value for Comparison 0.2891
All 6 means are significantly different from one another.

ANOVA Table for Treatment Means for SOC beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOC for TRT

TRT	Mean	Homogeneous Groups
TSB	1.2200	A
TCH	1.1000	A
TEB	1.0200	A
TMB	0.9800	A
TTB	0.9600	A
TCT	0.4000	B

Critical Value for Comparison 0.2937
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for N beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of N for TRT

TRT	Mean	Homogeneous Groups
TSB	0.1000	A
TCH	0.0900	A
TEB	0.0900	A
TMB	0.0900	A
TTB	0.0900	A
TCT	0.0600	A

Critical Value for Comparison 0.0845
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for P beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of P for TRT

TRT	Mean	Homogeneous Groups
TEB	8.8400	A
TTB	8.8400	A
TSB	6.4800	B
TCH	5.7000	C
TCT	3.4400	D
TMB	2.7000	E

Critical Value for Comparison 0.4378
There are 5 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for K beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of K for TRT

TRT	Mean	Homogeneous Groups
TCH	0.1200	A
TEB	0.1200	A
TTB	0.1200	A
TMB	0.1000	A
TSB	0.1000	A
TCT	0.0800	A

Critical Value for Comparison 0.0845
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for SOM beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of SOM for TRT

TRT	Mean	Homogeneous Groups
TSB	2.1000	A
TCH	1.9000	AB
TEB	1.7500	B
TMB	1.6900	B
TTB	1.6500	B
TCT	0.6900	C

Critical Value for Comparison 0.3128
There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for pH beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of PH for TRT		
TRT	**Mean**	**Homogeneous Groups**
TEB	6.3700	A
TTB	6.1400	AB
TMB	5.9100	BC
TSB	5.9000	BC
TCH	5.7700	C
TCT	5.2100	D

Critical Value for Comparison 0.2603
There are 4 groups (A, B, etc.) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Water-Holding Capacity beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of WATER for TRT		
TRT	**Mean**	**Homogeneous Groups**
TSB	11.910	A
TCH	11.310	B
TMB	9.510	C
TTB	8.790	D
TEB	6.930	E
TCT	5.230	F

Critical Value for Comparison 0.2841
All 6 means are significantly different from one another.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Bamboo Stand 4WAP

Tukey HSD All-Pairwise Comparisons Test of BAMSTL01 for TRT		
TRT	Mean	Homogeneous Groups
TMB	6.4000	A
TSB	5.7000	A
TCH	5.6333	A
TEB	5.2667	A
TTB	5.1333	A
TCT	2.9000	A

Critical Value for Comparison 4.4018
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Bamboo Stand 8WAP

Tukey HSD All-Pairwise Comparisons Test of BAMSTL02 for TRT		
TRT	Mean	Homogeneous Groups
TMB	14.867	AB
TSB	14.633	AB
TCH	14.800	AB
TEB	15.967	A
TTB	14.533	AB
TCT	9.067	B

Critical Value for Comparison 6.6240
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Bamboo Stand 12WAP

Tukey HSD All-Pairwise Comparisons Test of BAMSTL03 for TRT		
TRT	Mean	Homogeneous Groups
TMB	26.967	A
TSB	27.300	A
TCH	27.300	A
TEB	29.133	A
TTB	27.000	A
TCT	18.300	A

Critical Value for Comparison 20.784
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Eucalyptus Tree 4WAP

Tukey HSD All-Pairwise Comparisons Test of EUSTL01 for TRT		
TRT	Mean	Homogeneous Groups
TMB	11.133	AB
TSB	13.667	A
TCH	9.333	AB
TEB	10.400	AB
TTB	8.033	B
TCT	8.533	B

Critical Value for Comparison 4.6045
There are 2 groups (A and B) in which the means are not significantly different from one another.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Eucalyptus Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of EUSTL02 for TRT		
TRT	Mean	Homogeneous Groups
TMB	31.567	A
TSB	45.867	A
TCH	36.267	A
TEB	33.767	A
TTB	32.467	A
TCT	29.667	A

Critical Value for Comparison 18.326
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Eucalyptus Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of EUSTL03 for TRT		
TRT	Mean	Homogeneous Groups
TMB	54.47	A
TSB	103.23	A
TCH	67.93	A
TEB	75.33	A
TTB	80.50	A
TCT	68.83	A

Critical Value for Comparison 55.473
There are no significant pairwise differences among the means.

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Teak Tree 4WAP

Tukey HSD All-Pairwise Comparisons Test of TEASTL01 for TRT		
TRT	Mean	Homogeneous Groups
TMB	11.600	AB
TSB	12.900	AB
TCH	10.000	AB
TEB	14.500	A
TTB	9.700	AB
TCT	8.300	B
Critical Value for Comparison 5.3291		
There are 2 groups (A and B) in which the means are not significantly different from one another.		

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Teak Tree 8WAP

Tukey HSD All-Pairwise Comparisons Test of TEASTL02 for TRT		
TRT	Mean	Homogeneous Groups
TMB	26.633	A
TSB	27.433	A
TCH	26.633	A
TEB	28.933	A
TTB	23.000	A
TCT	20.967	A
Critical Value for Comparison 9.6145		
There are no significant pairwise differences among the means.		

ANOVA Table for Treatment Means for Rate of Growth of Grass beneath Teak Tree 12WAP

Tukey HSD All-Pairwise Comparisons Test of TEASTL03 for TRT		
TRT	Mean	Homogeneous Groups
TMB	33.133	AB
TSB	34.067	AB
TCH	32.633	AB
TEB	37.133	A
TTB	31.967	AB
TCT	26.767	B
Critical Value for Comparison 9.2393		
There are no significant pairwise differences among the means.		

APPENDIX TWO: SOME PLANT SPECIES FOUND GROWING BENEATH THE BAMBOO STAND

Caladium sp

Caladium sp

Syngonium sp