University of Reading

Sustainable Integrated Fertiliser Management in Ghanaian Cocoa Production Systems

PhD in Environmental Science

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Abstract

For over forty years, research to improve the fertility of cocoa soils in Ghana has focused on getting the right combination and application rates of mineral fertilisers to increase yield without considering the long-term maintenance of soil health. A nationwide fertiliser formulation and rate is therefore recommended. Cocoa pod husks (CPHs) are currently discarded as a waste but could be major source of organic matter and soil nutrients. They contain 1000 mg N kg^{-1}, 3000 mg P kg^{-1}, and 48571 mg K kg^{-1}. This study aimed to assess the effects of land management practices on chemical and physical properties of the soils across the different cocoa growing regions of Ghana and to investigate the scope for using CPHs to increase the sustainability of cocoa plantations. Field observations indicated that about 80% of farmers apply fertiliser, fungicides and insecticides to increase yield. About 50% of farmers perceive CPHs to benefit soil fertility and therefore spread husks on their farms. To study and compare the effects of land management practices on chemical and physical properties of the soils, soil nutrient levels of plots managed by farmers with their business as usual practices were compared with plots managed by the Cocoa Research Institute of Ghana (CRIG) researchers strictly according to their recommended management practices. Results showed that there were no significant differences in soil nutrients between the farmer managed and researcher managed plots and soils on both sites were inherently acidic and low in nutrients, particularly N and K. In the laboratory, CPHs were co-composted with different rates of NPK mineral fertiliser (equivalent to 0%, 25%, 50% and 100% of the recommended rate of NPK 50-100-50 for a single seedling) within bench-scale bioreactors. There were no significant differences in available K between any treatments, suggesting that CPH does not require mineral K amendment during composting. Co-composting CPH with 25%, 50% or 100% N and P fertiliser additions will all produce a high-quality amendment for cocoa soils, but lower additions (i.e. 25%) of N and P are more efficient in terms of minimising nutrient losses during the composting process. CPH co-composted with NPK amendments were applied to cocoa seedlings and compared to CPH composts co-amended with NPK in terms of soil nutrient availability, plant nutrient uptake and seedling growth. Findings indicated that CPH, co-composted with mineral N and P, is a promising soil amendment for increasing the health and fertility of Ghanaian cocoa soils.

Dedication

To Freddie, my ever-loving *dependable husband*, and to my daughters Jojo and Jodi, my constant cheer leaders, my “*honey*” and “*sunshine*”. Thank you, guys, for believing in me and being my anchor.

Acknowledgement

You, O Lord, are my shield!
My glory and the One who lifts up my head.
I cried out to you, my Lord, with my voice,
And you heard me from your holy hill
Psalms 3: 3 & 4

I am eternally grateful to you, Jehovah, for bestowing Your grace and mercy on me throughout this journey. Thank you, Abba father.

I would like to thank my mum and dad for always being there for me and giving me their best. I acknowledge my siblings (Siblings for Life!), Charlotte, Prince and Derrick for their immense support. Your thoughtfulness, prayers and kind words of encouragement are deeply appreciated.

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Chapter 1. INTRODUCTION

1.1. **Background**

Cocoa production in Ghana is mainly concentrated in the forested areas of the country (Figure 1-1) where the climatic conditions are favourable for growing cocoa (Boateng et al., 2014). It is predominantly produced by small-scale farmers with average farm sizes of approximately 2-3 hectares per farmer (Asante-Poku and Angelucci, 2013). Tetteh Quashie who brought cocoa pods from Fernando Po to establish a farm at Mampong Akuapem in the Eastern Region in 1879 first introduced cocoa cultivation in Ghana (Essegbey and Ofori-Gyamfi, 2012; Leiter and Harding, 2004). Most farmers in the sub region cultivated oil palm then, but with the fall in the price of palm oil globally, most of them switched to cocoa (Kolavalli and Vigneri, 2011; Leiter and Harding, 2004). An increase in the number of commercial migrant farmers acquiring forestlands for cocoa production expedited the spread of cocoa cultivation through Ashanti and Brong-Ahafo regions to the Western Region (Boateng et al., 2014; Kolavalli and Vigneri, 2011). The Western Region currently produces over 50% of total annual harvest, followed by the Ashanti region (16%) and then Eastern and Brong Ahafo regions, which together produce about 19% (Acheampong et al., 2014; Asante-Poku and Angelucci, 2013).

Until the late 1960s, Ghana was the leading producer of cocoa in the world, but then faced a major decline in production, which nearly ended the sector in the early 1980s (Essegbey and Ofori-Gyamfi, 2012; Kolavalli and Vigneri, 2011; Leiter and Harding, 2004). This crisis initiated a series of economic reforms that included increases in farm gate prices, introduction of free pest and disease control programs, the introduction of packages of hybrid seeds, fertilizers, insecticides and fungicides, improved marketing facilities, and the repair of roads in cocoa growing areas (Wessel and Quist-Wessel, 2015). These interventions resulted in a gradual increase in production from the 1990s, largely between 2001 and 2003 (Kolavalli and Vigneri, 2011). Ghana is currently ranked second in terms of the quantity of cocoa beans exported, after Cote d'Ivoire. This export position has been sustained since 2005 and reached a record high of 1,004,000 MT in 2011 (Acheampong et al., 2014; Asante-Poku and Angelucci, 2013; Wessel and Quist-Wessel, 2015). In terms of quality, Ghana's cocoa is ranked number one as the world leader in producing premium quality cocoa (Amankwah-Amoah et al., 2018; Gockowski et al., 2011) because of its relatively high fat content and low levels of debris, resulting in high cocoa butter yields and low levels of bean defects. These characteristics, coupled with the farmers' careful fermentation and drying process produce a distinct cocoa liquor flavour (Gilbert, 2009; Kolavalli and Vigneri, 2011)

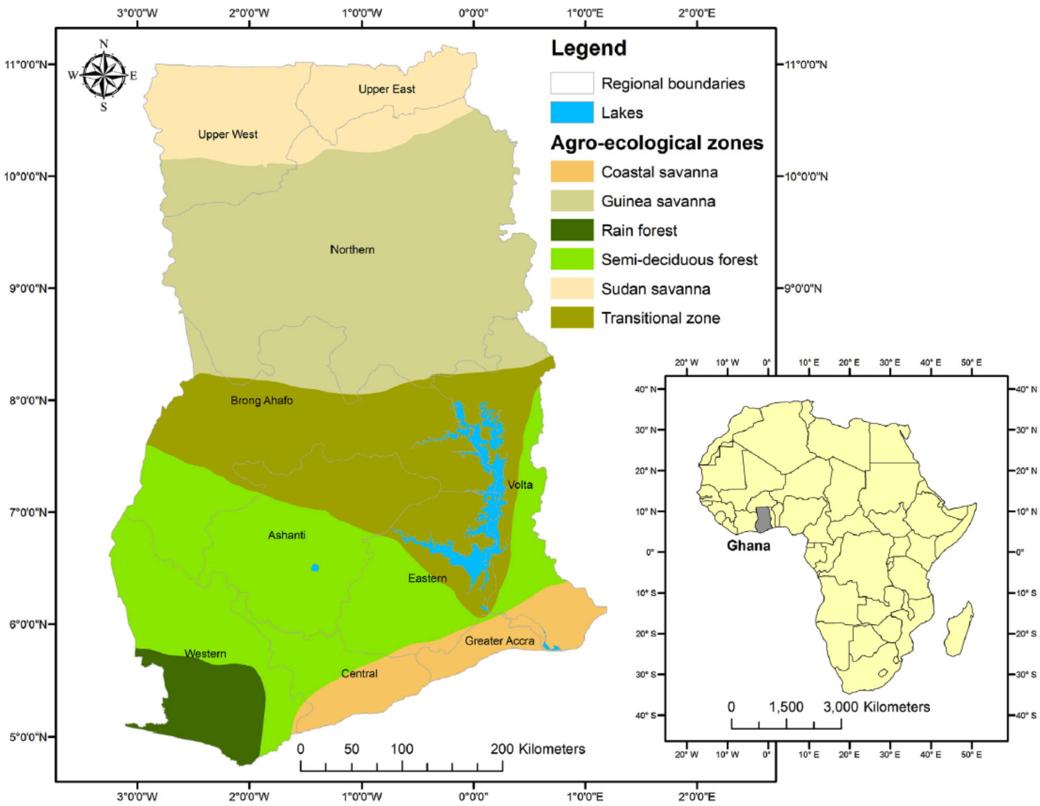

Figure 1-1: A map showing agroecological zones in Ghana (Rhebergen et al., 2016)

Increasing cocoa yields in Ghana is very critical to the nation's economic development as the commodity is the country's second biggest export and foreign exchange earner (Kolavalli and Vigneri 2011). It is the livelihood of about 700,000 smallholder farmers who are collectively the main producers of cocoa but are faced with production challenges that limit yield (Anthonio and Aikins 2009, Asante-Poku and Angelucci 2013, Acheampong, Dawoe et al. 2014). Because average farm sizes are small (about 2-3 hectares), most farmers receive low returns from cocoa due to the high cost of production (Asante-Poku and Angelucci 2013). Average annual yield is estimated at about 350 kg/ha (Barrientos, Asenso-Okyere et al. 2007, Gockowskia, Afari-Sefaab et al. 2013). This average yield is less than 20% of the reported yield potential of approximately 1,800 kg/ha (Aneani and Ofori-Frimpong 2013; Breisinger, Diao et al. 2008).

Lower yields have been associated with poor pest and disease control, a decline in soil fertility, inadequate use of inputs, overage cocoa trees, and challenging climatic conditions. These challenges have led to farmers adopting traditional cultivation practices which involve less inputs (Wessel and Quist-Wessel 2015) instead of the practices recommended by government owned Ghana Cocoa Board (COCOBOD) through its subsidiary Cocoa Research Institute of Ghana (CRIG). At the same time, COCOBOD has been under pressure to increase production to meet the rising world cocoa demand and also improve the living standards of producers (ICCO, 2007; World Cocoa Foundation, 2014; Snoeck, Koko et al. 2016). For almost two decades now, the COCOBOD has been providing support to farmers by supplying free fertilisers, insecticides and fungicides with the aim of achieving its target to increase total production by 100,000 tonnes annually (Breisinger, Diao et al. 2008). This investment seemed to have paid off in 2011 when production exceeded a record breaking 1,000,000 tonnes. However, this increase in productivity was achieved more due to an expansion of cropping area than due to an increase in yield (Teal, Zeitlin et al. 2006, Breisinger, Diao et al. 2008, Dawoe, Quashie-Sam et al. 2013). A much greater yield increase was expected, considering the huge investments over the years. Moreover, it is becoming politically and economically difficult for the government to sustain the financial support for the cocoa farmers.

Cocoa production in Ghana is heavily dependent on inorganic fertilizers since the soil nutrients are heavily depleted after years of cropping (van Vliet, Slingerland et al. 2015). Twenty years of research in Ghana, as well as several other trials elsewhere, demonstrated that intensive cropping with hybrid varieties in the absence of shade trees improves yield significantly if inorganic fertilisers are also applied (Ahenkorah, Halm et al. 1987, Acheampong, Dawoe et al. 2014, van Vliet, Slingerland et al. 2015). However, cocoa production with the hybrid varieties without regular fertilisation cannot be sustained beyond fifteen years, unlike the traditional varieties that are grown less intensively, under shade trees, where yields are sustainable with little fertilisation for at least 25 years (Obiri, Bright et al. 2007, Acheampong, Dawoe et al. 2014). The results of fertiliser trials undertaken at different locations vary widely in yield response to fertilisers (van Vliet, Slingerland et al. 2015), but fertiliser recommendations, based on these trials, are implemented homogenously across all growing areas. The same fertiliser (Asaase Wura (N:P:K 0:22:18 + 9CaO + 7S + 6 MgO) and Cocofeed (N:P:K 0:30:20) for mature cocoa plants is supplied to all farms across the entire cocoa growing region with the same recommended application rate (375 kg/ha) without prior soil testing (Afrifa, Ofori-Frimpong et al. 2009). These fertilisers does not contain nitrogen as it is reported that overhead shade trees provide sufficient nitrogen and any addition through fertiliser application affects yield as vegetative growth is promoted at the expense of fruit production (Snoeck and Dubos, 2018). To ensure the best use of these expensive fertilisers, it is important to find out if this "one fits all" approach is economically efficient and environmentally sustainable and if there are alternative fertilisation strategies that could be adopted.

1.2. **Research Aims**

This study aimed to assess the effects of land management practices on soil fertility across different cocoa growing regions and investigate the scope for using on-farm wastes to increase the sustainability of Ghanaian cocoa plantations.

1.3. **Research Objectives**

The main objectives of the study were to:

- Assess the effects of land management on the chemical and physical properties of cocoa soils from four major cocoa growing regions of Ghana.
- Identify whether recommended fertiliser regimes by COCOBOD improve the soil fertility in cocoa farms.
- Develop interventions that make the best possible use of on-farm wastes to maintain soil fertility and improve the sustainability of cocoa production.

Chapter 2. IMPROVING SOIL HEALTH IS KEY TO CLOSING THE YIELD GAP OF COCOA PRODUCTION IN GHANA - A REVIEW

2.1. **Overview of Cocoa Production in Ghana**

Cocoa is Ghana's major cash crop, providing employment to smallholder farmers that represent about 25-30% of Ghana's population (Acheampong et al., 2014; Anthonio and Aikins, 2009; Asante-Poku and Angelucci, 2013). Cocoa production in Ghana is mainly concentrated in the forested areas of the country (Figure 2-1) where the climatic conditions are favourable for growing cocoa (Boateng et al., 2014). Globally, there has been an increasing demand for cocoa since the early nineties and producing countries, including Ghana, have responded to this demand by putting measures in place to increase production (Kolavalli and Vigneri, 2018). The Government of Ghana, through the establishment of Ghana Cocoa Board (COCBOD) in 1947, is the main agency that manages the cocoa industry (Essegbey and Ofori-Gyamfi, 2012; Williams, 2009). Unlike in Côte d'Ivoire and other producing countries where government's involvement in the sector is minimal, COCOBOD has put structures in place, which consist of rehabilitation programs for old cocoa farms, spraying programs to control pests and diseases, and supply of subsidized fertilizers on credit, improvements in extension systems to encourage adoption of new technologies and improved varieties (Aneani and Ofori-Frimpong, 2013; Breisinger et al., 2008; Teal et al., 2006). Ghanaian farmers are well motivated by the high producer prices and input incentives given by COCOBOD which has resulted in increased cocoa production (Commodities and Development Report, 2017).

2.2. **Ghanaian Cocoa Yields and their Potential**

Crop yield potential is defined as the yield achieved when a crop is grown under favourable conditions with optimum supply of water and nutrients, and without the presence of pests, diseases and weeds (Evans and Fischer, 1999; Lobell et al., 2009). The yield gap is the difference between the actual yield the farmer attains and potential yield estimated (van Ittersum et al., 2013). Lobell et al. (2009) states that one must increase crop yield and/or cropping area in order to increase production but also noted that the likelihood of increasing area cropped is often greater than the likelihood of increasing yield. From Figure 2-2, it is clear that production increases in Côte d'Ivoire and Ghana who together produce two-thirds of the worlds cocoa (FAOSTAT, 2015) have been driven more by an increase in the area of land cultivated than an increase in yield per area cultivated between the mid 1990s and 2004 (Breisinger et al., 2008; Dawoe et al., 2013; Teal et al., 2006).

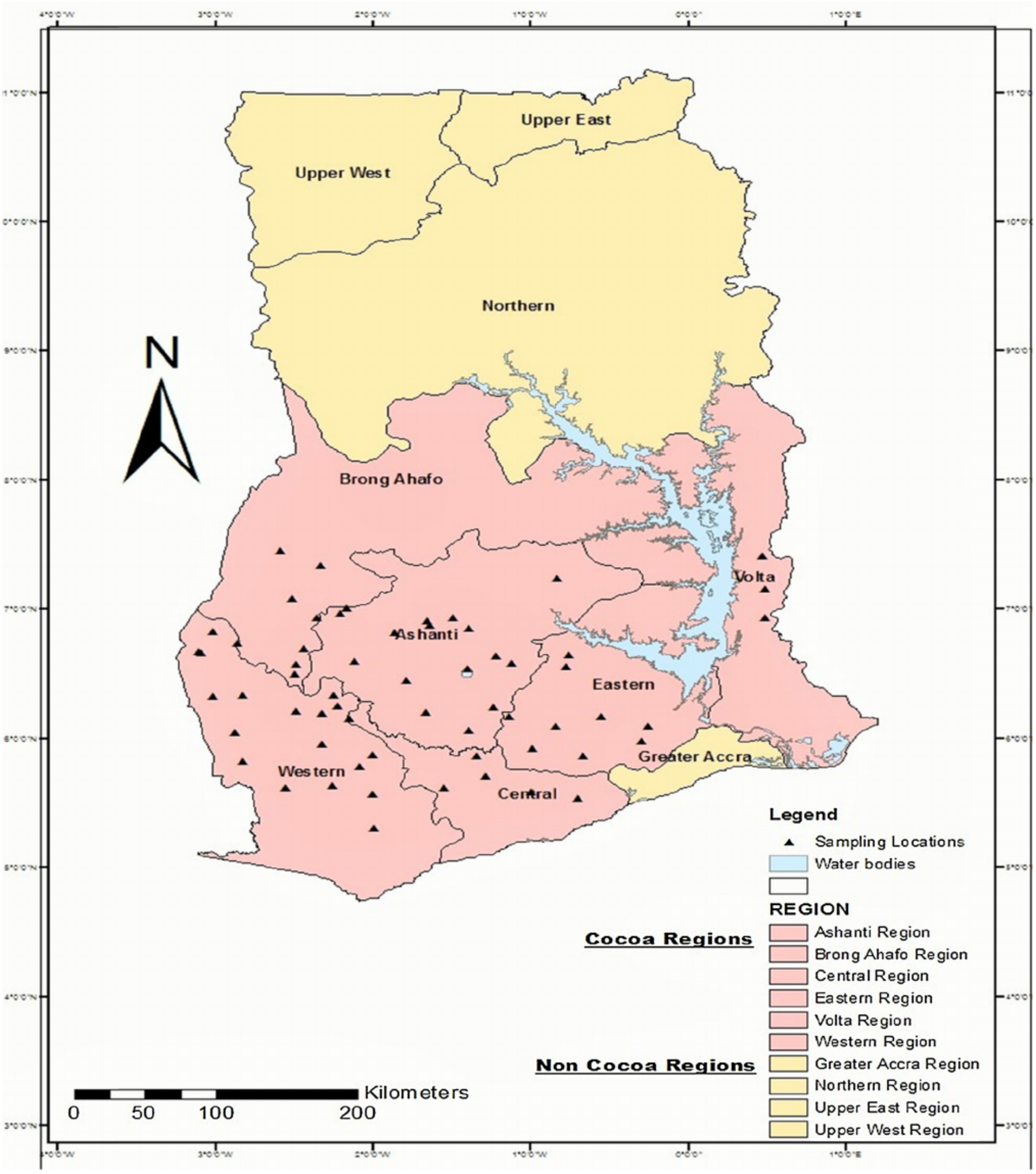

Figure 2-1: A map showing cocoa growing areas in Ghana (Dankyi et al., 2015)

In Ghana an increase in the area of land cultivated contributed to increase in production from 2002 to 2004, but the area declined from two million hectares in 2004 to 1.8 million hectares in 2006 (Figure 2-2) (MOFA 2006; Cocoa Board 2007 cited in Breisinger, Diao et al. 2008). This decrease may be due to farmers succumbing to the production constraints and alternatively growing less capital-intensive crops or selling their lands to illegal miners (known locally as "Galamsey") to use as capital for other more profitable ventures. Illegal small-scale mining has been identified as a factor contributing to the decline in cocoa productivity recently due to almost irremediable damages to farms and water bodies (Boateng et al., 2014). However, since

2009, the area of land used to grow cocoa in Ghana has remained fairly constant, as has the yield, resulting in stagnated production. Like Ghana and Côte d'Ivoire, increases in production observed in Nigeria and Cameroon (who are the fourth and fifth largest producers in Africa but share similar climatic conditions as Côte d'Ivoire and Ghana) are driven more by cropping area than yield.

Cocoa cultivation has gradually taken over about 14–15 million ha (1.5 million ha in Ghana) of tropical forests globally. This has been a global environmental concern pushing companies and consuming countries to commit to reducing deforestation associated with cocoa production by developing strategies to increase yields. Therefore, increasing cocoa production to meet growing demand, without expanding the area cropped, has become a global challenge (Vaast and Somarriba, 2014). Since forestland is limited and fast disappearing, further expansion is environmentally costly, socially unacceptable and inherently unsustainable. The prospect of sustainable cocoa production in Ghana depends on reviving production in the original cocoa regions such as the Ashanti and Eastern which, unlike the Western region, has soils classified as suitable for cocoa farming (Dawoe et al., 2013). The aim then is to identify strategies to improve yield to secure sustainable cocoa production.

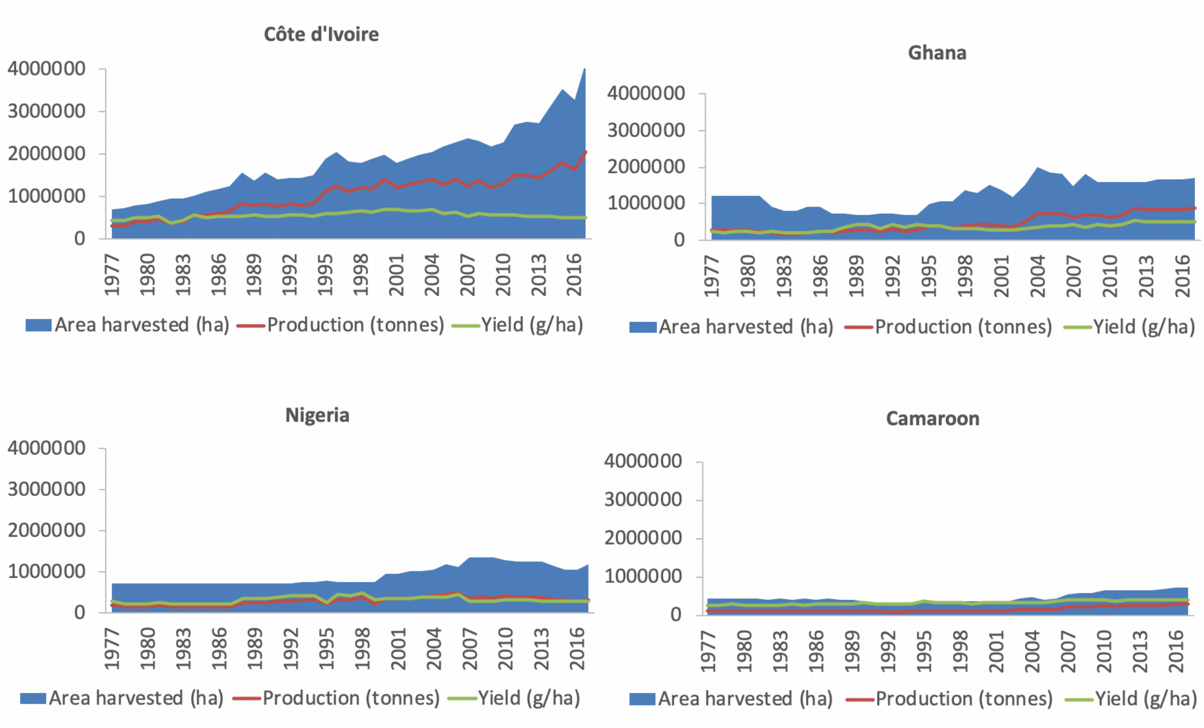

Figure 2-2: A combined chart showing trends in area harvested, production and yield in Africa's leading producing countries from 1977 to 2017. Data source: FAOSTAT (2015)

Ghana produces cocoa below its yield potential, which has been estimated to be 1,000-1,500 kg ha^{-1} (FAO 2005; MOFA 2007, cited in Breisinger, Diao et al. 2008). An experiment conducted by Aneani and Ofori-Frimpong (2013) identified a yield potential of 1,889 kg ha^{-1} and an existing yield gap of 1,553 kg ha^{-1}. Because national average yield in Ghana is estimated at 400 kg ha^{-1}, only about 18% of yield potential is realised. There is a need to understand the reasons for the yield gap to realise yield potential (Basso et al., 2013). Factors identified as determinants of cocoa yields in Ghana are soil fertility, pest and diseases, maintenance and agronomic practices, access to credit, and infrastructure (Acheampong et al., 2014). Research directed towards addressing these challenges, to bridge the huge yield gap identified in the areas being cultivated already, should be exploited to ensure sustainable cocoa production in Ghana.

2.3. **Cocoa cultivation and management systems**

Cocoa plantations in Ghana were traditionally established under carefully cleared canopy of typical primary or secondary forest or under that of established shade trees, close to the natural conditions under which the cocoa plants are adapted to survive (Acheampong et al., 2014; Duguma et al., 2001; Greenberg and Center, 1998). Traditional land preparation involves slash and burn, which returns nutrients from the forest biomass, in the form of ash, back to the soil (Dawoe, 2009). Cocoa grown on cleared virgin forestlands, or even secondary forest, yields higher than cocoa grown on previously cropped or deforested lands due to a phenomena known as the "Forest Rent" (Ruf and Schroth, 2004). This refers to the rich nutrients readily available to the cocoa crops when grown on cleared forestlands that reduces the requirement for farmers to purchase and apply fertilisers. Farmers therefore prefer to acquire virgin forestlands to start cocoa production rather than rehabilitating old unproductive farms, which require high inputs such as labour (especially for clearing old crops and controlling weeds) and fertiliser (Ruf and Schroth, 2004; Wessel and Quist-Wessel, 2015). This preference, however, is not ecologically sustainable since the "forest Rent" eventually becomes exhausted after 20-30 years (Ahenkorah et al., 1987; Dawoe, 2009) when productivity declines and production is maintained by clearing another area of virgin forest.

The traditional agroforest cocoa production system, utilising remnant forest or planted shade trees, has been promoted to compensate for the deforestation caused by cocoa expansion

(Acheampong et al., 2014; Gockowski and Sonwa, 2008; Gockowski, 2008; Greenberg and Center, 1998; Soto-Pinto et al., 2010; Tscharntke et al., 2011). Cocoa agroforestry is believed to conserve natural resources, enhance functional biodiversity, and improve soil fertility (Vaast and Somarriba, 2014), even though little has been done scientifically to quantify the ecological benefits (Acheampong et al., 2014; Ofori-Frimpong et al., 2007). A more diverse agroforest cocoa production system can provide greater economic security to farmers through the provision of forest products that are of commercial and domestic value (Anglaaere et al., 2011). However, the introduction of early yielding cocoa varieties that are suited to low or no canopy shade has facilitated the growing of cocoa trees in full sun or with fewer shade trees (Ofori-Frimpong et al., 2007; Wessel and Quist-Wessel, 2015). This recent development therefore results in a variety of practices along a spectrum that spans two extreme circumstances; (i) the traditional extensive production with low inputs and mostly agroforest or shaded plantations, and (ii) the more intensive production using new hybrid varieties with little or no shade trees. Farms can therefore be categorised according to the shade levels and species diversity of shade trees (Acheampong et al., 2014; Gockowski and Sonwa, 2008; Gockowski, 2008).

Higher yields have been observed under full sun cocoa production with fertiliser applications (Acheampong et al., 2014) than that under shaded systems. Generally, yield in full sun cocoa as compared to shaded plantations is greater due to higher crop density in the former than in the latter. A twenty-year study of hybrid cocoa, which varied shade and fertiliser levels, showed a significant increase in yield on full sun plots without fertiliser, and an even greater increase with fertiliser, compared to the shaded plots with and without fertiliser (Ahenkorah et al., 1987). These on-station trials formed the basis for farmers' decision to adopt the no-shade intensive cultivation system, combined with the use of fertiliser. This cultivation system has been well adopted (especially in the Western Region) but with insufficient (or without) use of fertiliser (Acheampong et al., 2014; Gockowski and Sonwa, 2008; Obiri et al., 2007). Consequently, the yield obtained did not meet the expected yield, based on the on-station trials. Other studies have observed the yield increase in unshaded cocoa farms to be short-lived, compared to the shaded farms. Yield in unshaded farms has been observed to decline after 10 to 15 years, after which farms become virtually unproductive from 18 to 29 years, whereas in the traditional shaded system yield only starts to decline after 25 years (Acheampong et al., 2014; Obiri et al., 2007). This observation is in agreement with Ahenkorah et al. (1987) who stipulated that intensive cultivation of cocoa in Ghana cannot sustain high yields after 15 years. Furthermore, the short-term benefits of full sun cocoa cultivation are largely due to the initially fertile forest soils (Acheampong et al., 2014); especially in the Western Region which is the youngest cocoa growing region, still benefiting from the "forest rent".

Shaded cocoa competes with shade trees for nutrients, water and sunlight, which may affect its yield during the first few years, after establishment. However, in the long term, the plant diversity in the shaded cocoa system can create an environment similar to that of a secondary forest and maintain important soil processes that improve soil quality (Cezar et al., 2015; Dawoe et al., 2013). Although both intensive and extensive cultivation systems could equally benefit from the "forest rent", it seems that the traditional agro-forested cocoa has the ability to self-regulate soil fertility, in the absence of fertiliser application, better than the full sun system. These ecosystem functions provided by the shade trees could explain why the shaded system has a longer production period. With good soil ecological functions and favourable rainfall, the production period of the shaded system may extend to about 70 years compared to 20 years without shade (Cezar et al., 2015; Obiri et al., 2007).

Traditional cocoa agroforestry systems with the right shade levels can be a more sustainable option for cocoa production in Ghana since smallholder farmers who can barely afford the fertiliser (a major requirement for productive full sun cultivation) produce the majority of the country's cocoa. Notwithstanding, the majority of farmers, unaware of this fact, are still driven by the short-term benefits of full sun cultivation. However, economic benefits of other forest products derived from the traditional shade system remains the motivation behind some farmers' decision not to shift to full sun cultivation. There are risks and costly production constraints induced by ecological stresses on the cocoa plants when grown without the shade. Cocoa plants can become more susceptible to mirid pests and weeds (before their canopies close up), and become exposed to sun scorching and drought, while soil fertility declines (Ahenkorah et al., 1987; Anglaaere et al., 2011; Obiri et al., 2007). These observations have led to a renewed interest (both national and international) in the establishment of sustainable shaded cocoa.

2.4. **Health of Cocoa Soils in Ghana**

The development of a soil at any given time is the outcome of several factors that interrelate to give it its distinguished characteristics. These characteristics determine its suitability for one land use or the other. The majority of Ghana's cocoa is grown in the Semi-deciduous forest agroecological zone on six soil classes recognised as suitable for cocoa production; Acrisols

(66%), Lixisols (18%) and Luvisols (7%) and about 7.5% on Nitisols, Ferralsols and Fluvisols (Snoeck et al., 2010b) (Table 2-1). Cocoa adjusts to a wide range of soil classes and types, but good yield depends on the soil's quality. Soil quality is defined as the ability of soil to support plant life without reducing environmental quality or risking human and animal health within its ecological and land-use boundaries (Doran and Safley, 1997). In the case of a cocoa plantation, it is the ability of the soil to sustain cocoa yield while maintaining environmental quality within the ecosystem. The terms "soil quality" and "soil health" are considered synonymous among soil scientists but recently "soil health" is preferred as it represents soils as a vibrant living system, which hosts diverse living organisms that facilitate its capacity to function and therefore needs to be managed to sustain plant life, whereas soil quality is thought of as the soil's suitability for a chosen land use as affected by management practices and climatic conditions (Doran and Safley, 1997; Doran and Zeiss, 2000; Stefanoski et al., 2016).

It has been argued that soil quality is difficult to measure without any indication of an ideal value as reference and it is better measured by comparing management practices to determine if a specific soil indicator is enhanced or diminished by the management practice (Juhos et al., 2016; Rousseau et al., 2012; Stefanoski et al., 2016). Others are of the view that a holistic approach involving the use of multiple indicators representing the soil's physical, chemical and biological characteristics (as well as their interactions) allows for a better assessment (Cherubin et al., 2017; Doran and Safley, 1997; Magdoff, 2001; Stefanoski et al., 2016). The use of these indicators has become indispensable in the evaluation of sustainable agriculture. However, to provide ample management information to farmers on the differences among the management systems without unreasonable expense, the use of a small number of indicators is useful (Lima et al., 2013; Stefanoski et al., 2016). The increasing recognition of the importance of soil quality has led to the development of myriads of soil quality indexes (SQI) and assessment frameworks based on the indicators and other relating factors such as ecology, climate and crop yield. In cocoa production systems, soil physical and chemical properties are commonly used as indicators of soil quality, whereas biological properties as indicators are gradually being explored, but seemingly not in Ghana. To determine the soil quality of cocoa soils in Ghana, an understanding of how soil properties, particularly the underexplored biological properties, vary in space and time, are impacted by land management, and relate to crop yield is required.

2.4.1. Physical and chemical properties as indicators of cocoa soil health

Most Ghanaian soils cropped to cocoa are formed from heavily weathered parent rocks (with kaolinitic clay minerals components) and thus have low pH, low cation exchange capacity and low organic matter content with nitrogen and phosphorus being the most limiting nutrients (Asiamah, 2008; Bationo et al., 2018; Jayne et al., 2015) (Table 2-1). The transition from forests to cocoa farms, especially the no shade systems, impacts soil physical and chemical properties significantly (Dawoe et al., 2013). The cocoa plant adapts very well to many soil types but soils cropped to cocoa should have sufficient available nutrients to meet the minimum nutrient requirements, have a soil depth of about 1.5m that allow good root development without any obstructions, and preferably a texture of approximately 30 % clay, 50 % sand, and 20 % silt (Snoeck et al. 2016, ICCO, 2013) Nutrient availability and absorption are primarily affected by soil water availability, acidity, aluminium toxicity, and the organic matter content of soils (Baligar and Fageria, 2005b; Snoeck et al., 2016). Cocoa is sensitive to both droughty (sandy) and waterlogged (clayey) soils, and since production in Ghana is purely rain-fed, good draining soils that withhold enough water to make nutrients available is essential. Water deficit can account for about 50% of the cocoa yield gap (Zuidema et al., 2005). High rates of Al saturation in cocoa soils negatively affect the growth of cocoa. Al reduces root and shoot growth and subsequently, nutrient uptake. Soil aluminium concentration is negatively associated with pH, the lower the pH, the higher the aluminium concentration. The Western Region of Ghana where the majority of Ghana's cocoa is grown has soils have low soil pH and this is not only limited the to the western region, but gradually becoming common in other parts of the country especially the lowlands (Buri et al., 2005; Ofori-Frimpong et al., 1999) due to the over-application of nitrogenous fertilisers.

Table 2-1: Reference soil groups and properties of cocoa soils in Ghana

RSG*	Physical properties	Chemical properties	Management
Acrisols	-High subsoil clay content -Top soil have low aggregate stability	Low CEC (< 24cmol kg^{-1} clay) BS<50% within 25-100cm Low pH low nutrients	Prevent erosion Preserve organic matter Regular fertilisation required Agroforestry recommended for low input farming
Lixisols	-High subsoil clay content -Top soil have low aggregate stability	Low CEC (< 24cmol kg^{-1} clay) BS<50% within 25-100cm Low pH Fairly leached Low nutrients	Prevent erosion Preserve organic matter Regular fertilisation and liming required

Luvisols	-High subsoil clay content	High CEC (>24cmol kg^{-1} clay) BS > 50% in top 50-100cm in all parts of the subsoil Fertile soils	
Nitisols	-Clayey subsurface horizon -Low activity clay, with many iron oxides -High aggregate stability -Deep well drained soil -Fair water holding capacity -High organic matter	P-fixation, Fertile soil, rich in Fe	Application of slow release P fertilizers
Ferralsols	Deeply weathered, red or yellow soils of the humid tropics dominated by kaolinite and iron and aluminium Oxides -Good soil depth and permeability -Stable microstructure	low pH and water holding capacity Poor chemical fertility, strong P-fixation	manuring, mulching and/or adequate (i.e. long enough) fallow periods or agroforestry practices Application of slow release P fertilizers
Fluvisols	-Developed in alluvial deposits -Poorly drained	Severe acidity and high levels of Al toxicity.	Water management required: dry period stimulates microbial activity and promotes mineralization of organic matter

* RSG -Reference Soil Groups

Sourced, compiled and modified from (Asiamah, 2008; Bationo et al., 2018; WRB, 2015)

2.4.1.1. *Soil nutrient status and diagnostic methods for assessing cocoa nutrient requirements*

There have been an many studies on the nutrient status of cocoa-growing soils and the use of mineral fertilisers in cocoa production (Afrifa et al., 2009; Ahenkorah et al., 1987; Snoeck et al., 2010b; Snoeck et al., 2016) and few on the use of organic fertilisers (Acheampong et al., 2015). These studies assessed the ability of fertilisers applied to different soils under different management practices to influence the establishment and yield of cocoa. The fertiliser application field trials undertaken by Ahenkorah et al (1987) looked at application of different rates of mineral fertiliser under different shade levels and concluded that yield sustainability is only possible with continuous application of fertiliser and that the best yields are achieved under full sun. This study however did not consider the spatial variations in the influence of soil properties on nutrient release and absorption, which could explain the differences in yield they observed on different plots. Most studies supported the requirement for mineral fertiliser application to maintain sustainability, but recent findings indicate that different soil types require site-specific fertiliser formulations instead of the blanket fertiliser recommended across all cocoa growing regions (Afrifa et al., 2009; Baah et al., 2011; Ofori-Frimpong et al., 1997; Snoeck et al., 2010b; Snoeck et al., 2016). In Ghana, a single fertiliser formulation (N:P:K 0:22:18 + 9CaO + 7S + 6 MgO) is recommended to cocoa farmers across all cocoa growing regions despite the fact that the cocoa growing regions vary in soil properties. Snoeck et al (2010) recognise the importance of examining the suitability of the recommended fertiliser over time in order to develop feasible strategies towards the recovery of soil fertility for sustainable cocoa production. They also stressed the need to monitor the quality of cocoa soils in all growing regions. This when done appropriately will indicate where and when to adjust the blanket fertilisers to ensure the right form and rate of fertilisers are applied to achieve desired results.

To attain the optimum use of fertilisers for optimum yield, it is important to know the crop's nutrient requirements, the soil nutrient status, ratios and availability and then the crop nutrient uptake (Hartemink, 2005; Snoeck, 2007; van Vliet et al., 2015). Fertiliser formulations and calculation of application rates in most cocoa producing countries have been based on fertiliser response trials (to determine the required nutrient thresholds), nutrient balance (between supply and export through harvest), soil nutrient status assessment and sometimes the nutrients contained in the crop (Snoeck et al., 2016; Van Vliet and Giller, 2017), and then soil diagnostic models. Currently, site specific fertiliser formulations are being recommended using the soil diagnostic tools to calculated fertiliser needs of cocoa. This tool was first developed by Jadin (1975) and then advanced by Jadin and Snoeck (1985) and much later by Snoeck (2006) based on numerous fertiliser trials which measured soil nutrient status, balances and ratios. (Snoeck et al., 2016). It compares actual and optimal soil nutrient levels and calculates the quantity of key nutrient needed to rectify any nutrient imbalance (Dossa et al., 2018b). This has been used over the years for diagnosing soil nutrient deficiencies and computing the amount of nutrients that will be required to balance the nutrient loss after harvesting has been used to determine the fertiliser requirements of cocoa (Afrifa et al., 2009; Dossa et al., 2018a; Dossa et al., 2018b; Koko et al., 2011; N'guessan et al., 2017; Snoeck et al., 2007; Snoeck et al., 2010b).

Snoeck et al (2010) developed a method that maps the nutrient requirements of cocoa to the soil nutrient status in all growing regions in Ghana by combining GIS technology with soil diagnostic modelling. Through this study it was discovered that the recommended fertiliser formula suits only 6% of the land cropped to cocoa. This discovery may imply that the major intervention promoted by COCOBOD to improve soil quality and boost production is not optimised in 94% of the area it is adopted. It was recommended in the study that at least 30 different location-specific fertiliser formulations are required. This recommendation was based on soil nutrient thresholds and ratios of some specific nutrients and details of the methods of assessing fertiliser requirements are thoroughly discussed in Snoeck et al (2016). Research to fully understand the interactions of location specific soil properties and their role in making nutrients available is needed.

2.4.2. **Biological indicators of quality and health of cocoa soils**

The use of biological indicators to measure soil quality is a relatively new concept that is based on the soils natural ability to support plant life through soil ecological functions and the provision of ecosystem services. Biological indicators are temporally dynamic and are sensitive to changes in soil management practices and climate, making them a particularly useful tool (Doran and Zeiss, 2000; Rousseau et al., 2012). Biological indicators of soil quality have gained research attention quite quickly even though little evidence has been provided to link the indicators to aboveground productivity. Just like their physical and chemical counterparts, no single biological parameter can be used in isolation to holistically represent soil quality or health. Factors frequently measured are soil microbial biomass and activity, nitrogen mineralisation, rate of litter decomposition and soil organic matter. Soil organic matter (SOM) represents a key indicator for soil quality (Brady et al., 2015). It is the main determinant of biological activity because it is the primary food source for soil organisms and has a major influence on the physical and chemical properties of soils (Robert 2001). However, SOM dynamics are still not well understood under perennial cropping systems like cocoa (Rousseau et al., 2012).

Biologically healthy soils contain diverse active organisms with constant supply of high quality organic residue to produce high levels of SOM that increases water holding capacity and cation exchange capacity (Magdoff, 2001). This SOM provides an important link between biological and physico-chemical indicators that needs to be considered for sustainable fertility management of cocoa soils. Land use change from forests to cocoa farms affects soil functional biodiversity and ecological processes such as the decomposition of organic residues and nutrient cycling (Bossio, Girvan et al. 2005, Goma-Tchimbakala, Moutsambote et al. 2008, Dawoe, Quashie-Sam et al. 2013). However, higher carbon storage capacity has been observed in cocoa agroforests than in unshaded cocoa (also higher than other agricultural land uses) in several studies (Dawoe, Quashie-Sam et al. 2013). The studies also reveal differentiation in carbon stocks between ecological zones, management practices and the age of the farm. Theoretically, plant diversity affects these soil biological properties, although research in support of this theory is contradictory (Bardgett, 2005). Research linking the ecological functionality of cocoa soils with the soil biota within Ghanaian cocoa production systems is lacking. However, a few studies have quantified changes in carbon and nutrient stocks with time under cocoa systems, either via chronosequences or the monitoring of long-term plots (Acheampong et al., 2014; Asare, 2006; Dawoe et al., 2009; Isaac et al., 2007; Ofori-Frimpong et al., 2007). Some studies have observed that the rate of litter decomposition in cocoa plantations decreases following forest conversion as litter quality changes (Dawoe et al., 2009; Ofori-Frimpong et al., 2007). Dawoe, et al (2009) expected similar decomposition rates in forest ecosystems and cocoa plantations since no significant differences existed in the C:N ratios of the litter, and so the differences observed in decomposition rate were attributed to changes in the structure and/or function of the soil biological community following conversion. However, the study did not focus on the soil organisms, the actors of decomposition. Soil fauna play a major role in converting cocoa litter into useable forms of nutrients for plants. In Bahia, Brazil, cocoa agroforestry systems have shown to have increased abundance and diversity of soil and litter fauna (da Silva Moço et al., 2009). However, experiments to understand how cocoa management systems in Ghana influence the abundance, diversity, and activity of soil fauna are lacking.

2.4.3. Relationship between shade, litter and soil quality

Research is currently being undertaken to devise shade management strategies designed to both increase productivity and optimise ecological benefits. While little evidence exists to quantify the ecological benefits of shade trees (Acheampong et al., 2014), the functional benefits to cocoa are known to include favourable microclimate, erosion control and soil quality improvement (Acheampong et al., 2014; Asare, 2016; Beer et al., 1998; Ofori-Frimpong et al., 2007; Udawatta et al., 2017) and these benefits are particularly important to farmers during long severe dry periods in Ghana. The quantitative effects of shade on cocoa yield has been established in most cocoa producing countries (Bisseleua et al., 2009; Mortimer et al., 2017; Rajab et al., 2016), including Ghana (Acheampong et al., 2015; Ahenkorah et al., 1987; Asare, 2016; Beer, 1987; Snoeck et al., 2016), and the consensus is that well managed agroforest plantations with the right level of shade has long term positive effects on yield, possibly because of enhanced delivery of ecosystem services in the shaded farms, compared to the monoculture plantation. The density of shade levels adopted by farmers in Ghana has been categorised by Ashley-Asare and Mason (2011) as low, medium or high, according to canopy cover (10%, 25% and 50%, respectively), tree density (28, 35 and 51 shade trees/ha) and diameter at breast height (34.3, 61.8 and 50.1 cm) (Acheampong et al., 2014). Beer et al. (1998) recommended an optimum shade cover range between 40% and 70%, and this recommendation still seems to be well accepted (Mortimer et al., 2017).

Shading cocoa crops has also been shown to increase crop nutrient uptake in the Western Region of Ghana (Isaac et al., 2007). Thus, the ability of cocoa agroforestry systems to survive with little or no fertilisation is attributed to enhanced nutrient cycling through the decomposition and mineralisation of nutrients entering the soil from litter fall. The litter is mainly made up of fallen leaves of cocoa and shade trees and, in lesser quantities, their fruits and any other plant parts that are pruned or fall on the soil surface. These plant litter inputs are the main sources of organic matter and this can be important, even more so than N_2 fixation by leguminous shade trees, because of the positive effects of SOM on both soil chemical and physical properties (Beer et al., 1998). Comparing the processes of nutrient recycling in cocoa production systems to native primary or secondary forest in terms of the rate of decomposition and amount of nutrients released depends on the litter quality, the diversity of active decomposers, and the microclimate of a particular cocoa ecosystems. Both litter quality and decomposer diversity decrease with decreasing shade (Blaser et al., 2017; da Silva Moço et al., 2009; Dawoe et al., 2013; Duguma et al., 2001; Fontes et al., 2014; Wartenberg et al., 2017). In Ghana, litter quality, which is indicated by the chemical composition and C:N ratio of the litter, is decreased when native forest is converted to shaded farms. This decline in litter quality correlates with a reduction in litter decomposition rate (Dawoe, Isaac et al. 2009). Ofori-Frimpong et al (2007) observed that litter fall of cocoa leaves on unshaded cocoa farms was higher than that of shaded ones, but the litter decomposition rate and the release of nutrients from the litters on shaded farms was faster than on unshaded farms. This could be because, even though high litterfall is observed in unshaded plantation due to stress on the cocoa trees, litter quality is enhanced in the shaded one due to tree diversity brought about by the different shade trees.

However, SOM content was found to be significantly higher in the forest soils than all the cocoa systems. This difference between the forest and the cocoa plantations was attributed to a decrease in tree diversity, supported by Ahenkorah et al (1974), who reported a SOM loss of 54000 kg/ha fifteen years after forest conversion (Ofori- Frimpong et al, 2007). It is also possible that this loss was due to an increase in soil erosion as a result of reduced interception of rainfall by shade/forest trees. Likewise, changes in soil quality along a chronosequence of cocoa agroforestry systems has been observed in few studies. The release of nutrients from litter in older cocoa plantations (35-55 years old) was reported to be enough to recover the nutrients extracted by the cocoa crop (Pérez-Flores, Pérez et al. 2017). Litter decomposition rate and CEC was significantly greater in a >25-year-old cocoa agroforestry system than in 1–4 year old plantation, and vesicular arbuscular mycorrhizal fungi spores were twice as abundant and more diverse in the older plantation (Snoeck et al., 2010a). These findings demonstrate that shade and litter are important drivers affecting soil quality and more studies are required to quantify their contribution to improving the physical, chemical and biological properties of cocoa soils in Ghana.

2.4.4. Soil management strategies for sustainable cocoa production in Ghana

Poor soil fertility in cocoa soils worldwide has been a major concern for all stakeholders. Research for sustainable production has called for a shift away from soil management strategies that exclusively provide inorganic fertiliser application rates and towards strategies aimed at improving soil structure and soil ecological functions while reducing negative environmental impacts. The gradual reduction in the rates of inorganic fertilisers used and the introduction of organic fertilisers is being researched in several cocoa producing countries (Fidelis and Rajashekhar Rao, 2017; Munongo et al., 2017; Sriharti and Dyah, 2018). Organic fertilisers increase SOM content; an important soil attribute that has a major influence on soil properties and ecological functions such as soil water conservation and nutrient cycling (Alvarenga et al., 2017; Coleman et al., 2017; Nigussie et al., 2015).

The use of both organic and inorganic fertilisers as an integrated nutrient management strategy is gaining research attention in cocoa production systems. However, information on the dynamics of the types of organic amendments, their application rates, and their effects on soil quality in cocoa cropping systems is very much limited. However, organic fertilisers offer an important opportunity to enhance the sustainability of cocoa production, particularly in Ghana where soils cultivated with cocoa have low SOM content, low nutrient availability, (particularly nitrogen and phosphorus) (Asiamah, 2008; Jayne et al., 2015) due to years of nutrient mining through harvesting. Knowledge regarding the benefits of organic fertilisers is mostly confined to the use of poultry manure and the ash from burnt cocoa pod husks, which is an option recommended to Ghanaian cocoa farmers (Opoku-Ameyaw et al., 2010).

Cocoa pod husks (CPH), a major source of organic matter on cocoa farms, contain 1000 mg N kg^{-1}, 3000 mg P kg^{-1}, and 48571 mg K kg^{-1} (Didier Snoeck, 2016; Hartemink, 2005). Their use as a soil amendment has revealed significant improvements in soil properties and plant growth (Agele and Agbona, 2008; Fidelis and Rajashekhar Rao, 2017; Moyin-Jesu, 2007; Munongo et al., 2017; Ofori-Frimpong et al., 2010; Sosu, 2014). Yet the potential to use CPH as an organic fertiliser in cocoa plantations has been underexplored, largely because it is believed that spreading husks may contribute to the spread of black pod disease (Phytophthora spp.) (Agele and Agbona, 2008; Opoku-Ameyaw et al., 2010) and so CPH are treated as farm waste that must be disposed of. As a result, research into alternative off-farm uses, such as feedstock for bioenergy (González-García, 2018; Ofori-Boateng and Lee, 2013; Saladini et al., 2016; Syamsiro et al., 2012), animal feed (Osei et al., 1991), traditional soap making (Owusu-Bennoah and Visker, 1994), chemical extracts for pharmaceutical and food processing (Vriesmann and de Oliveira Petkowicz, 2017), and as biosorbent and bioremediation agents (de Luna et al., 2017; Lawal et al., 2017; Olu-Owolabi et al., 2012) has attracted far more interest than research into potential of CPH as a soil organic amendment. The little research undertaken has focused more on the use of CPH composts as organic amendments on arable and horticultural fields than on cocoa plantations where it may be of greatest use to return the nutrients mined to grow the husks. Thus, there is an urgent need for fundamental research on the suitability of CPH-based soil amendments that combines nutrient management with integrated pest and disease management in Ghanaian cocoa plantations.

Composting, one of the most conventional and environmentally suitable means of valorising agricultural waste, has been suggested as a means for farmers in Ghana to recycle CPH into organic fertilisers (Opoku-Ameyaw et al., 2010; van Vliet et al., 2015). However, this has not been widely adopted, unlike in Indonesia, Papua New Guinea and Cameroon where an increase in on-farm composting of CPH has been sighted (Munongo et al., 2017). The application of CPH composts can reduce inorganic fertiliser use, thereby saving costs and improving soil quality and health.

Composting CPH without any co-amendments results in reduced N availability through immobilisation. Therefore, some studies have looked at the effects of various co-amendments to CPH based compost on soil nutrient fluxes. Co-composting CPH with other amendments such as poultry manure and nitrogen rich green leaves (such as Neem, Tithonia, or grass clippings) enhances the fertilising potential of CPH (Elisée and Emile, 2017; Kayode et al., 2015; Munongo et al., 2017). The combination of the CPH and the co-amendment provides benefits that are greater than the sum of the individual additions. Poultry manure performs better than the leaves since the former is richer in nutrients especially N, P and K. Nutrient release from compost is slower than inorganic fertilisers and therefore is not made immediately available to plants (Bernal et al., 2017a; van Vliet et al., 2015). In some situations (such as on a typical Ghanaian cocoa farm) sourcing these co-amendments is challenging as they are not widely available. Some studies have assessed the efficacy of CPH enriched with inorganic fertilisers. The growth of cocoa seedlings were enhanced when soil was amended with CPH composted with topsoil than when used together with NPK 15-15-15 (Ofori-Frimpong et al., 2010), but when CPH was composted with urea and then with triple superphosphate, the former supressed plant height while latter improved growth (Fidelis and Rajashekhar Rao, 2017). The emphasis for future research on organic amendments for cocoa plantations in Ghana should be on finding the right balance of nutrients that optimises nutrient release and plant availability. Therefore, the study of integrated organic (CPH) and inorganic fertility management in cocoa production systems is needed to find the optimum proportions that combine to increase the sustainability of cocoa production.

2.5. Summary

Ghanaian cocoa soils are acidic and have low CEC and nutrient availability and the major tool recommended by COCOBOD to increase soil fertility is the use of mineral fertiliser applied as a single formulation at a countrywide recommended rate that is suitable for only 6% of the cocoa growing areas. Soil quality of Ghanaian cocoa plantations is assessed by measuring physio-chemical properties, based on the assumption that supplying sufficient nutrients to balance the cocoa nutrient requirement alone will increase the quality of the soil. There is currently no consideration of soil biological indicators of health in Ghanaian cocoa cropping systems. It is evident that the supply of mineral fertiliser is most effective in soils with high organic matter content (Swift, 1997; Tittonnel and Giller, 2013; Snapp et al, 2014 cited in Jayne at al. 2015) and that shade trees on farms increase the supply and mineralisation rate of decomposable organic matter. SOM plays a vital role in soil water conservation and nutrient supply and SOM levels of at least 3% are optimal for cocoa growth (Snoeck et al., 2016; Somarriba et al., 2013). SOM cannot be discussed without the soil biological community to which it shares a special relationship. Soil organisms, particularly soil fauna, play a major role in organic matter decomposition and mineralisation to make nutrients available to plants. The adoption of properly managed cocoa agroforestry systems have the potential to increase the sustainability of cocoa production (Beer et al., 1998; Blaser et al., 2017; Gockowski and Sonwa, 2011) and in farms that are rarely fertilised, the potential of litter fall in these systems to supply nutrients to the cocoa crop should be exploited (Aleixo et al., 2017). Cocoa agroforestry systems also have potential for greater carbon sequestration and better provision of ecosystem services by soil organisms (Snoeck et al., 2010a). Site-specific fertiliser recommendations should be implemented that are appropriate to regional soil types and, if possible, integrated with organic amendments that recycle the nutrients in the CPH back into the soil. It is clear that CPH are important and underutilised resource that have a potential to improve soil health and therefore future research should focus on how CPH can be safely composted and returned to the soil to decrease the impact of nutrient mining in in Ghanaian cocoa production systems.

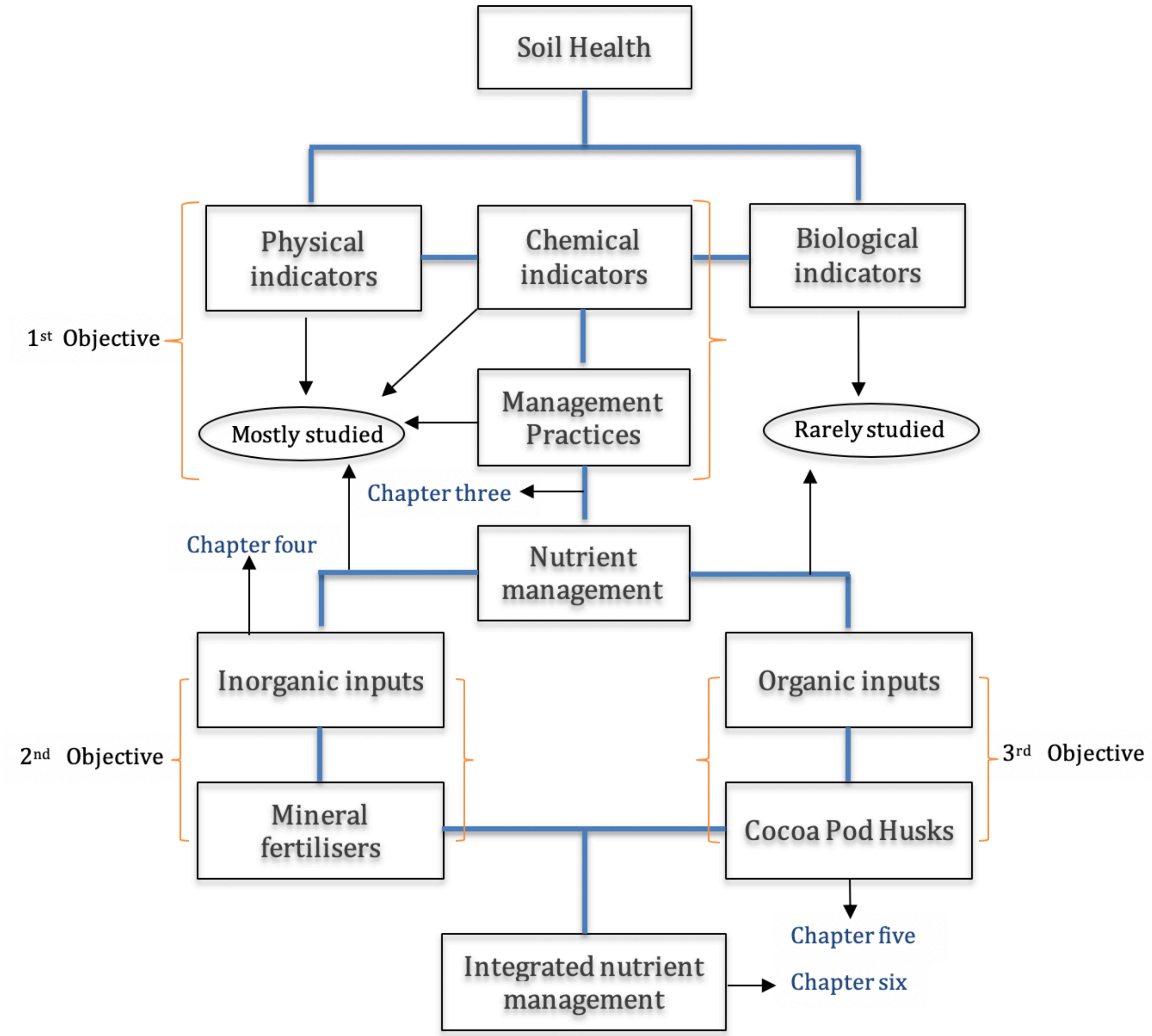

Figure 2-3: A framework indicating research approach, objectives (stated in section 1.3 of chapter 1) and identified knowledge gaps in soil nutrient management.

Chapter 3. PRELIMINARY STUDY ON SOIL MANAGEMENT PRACTICES ADOPTED BY FARMERS

3.1. **Introduction**

The purpose of this chapter is to give insight into how the PhD study developed. The findings of this preliminary study shifted the focus of the study from how management practices relate to fertility of cocoa soils to how farm waste could be recycled to improve soil fertility (findings are reported in chapters 4, 5 and 6). This study used sites of the Mapping Cocoa Productivity Project (MCPP); a collaborative research program that was ran by Cocoa Research Institute of Ghana (CRIG) and the University of Reading from 2012 to 2016 (Daymond et al., 2018). It looked at the impact of interventions such as the application of fertilizer, insecticide and fungicide on cocoa production in Ghana on 96 selected farms from four cocoa growing regions (Ashanti, Eastern, Brong Ahafo and Western regions). As part of this project, the farms were characterised through the collection of baseline data which included farmer profile, farm size, cocoa tree density, shade species present, and soil properties and agronomic practices in place. On 48 out of the 96 farms, detailed cropping data were collected as well as temperature and relative humidity data by means of on-farm data-loggers. At the time of selecting sites for this study, the project was in a phase where interventions were being implemented on 28 farms to compare the impact of 'best practice' with the farmer's normal practice on cocoa productivity. One half of each of the 28 farms was managed using recommended practices for sustainable cocoa production in Ghana, while the other half of the farm was managed by the farmer with his adopted management practices.

3.2. **Methodology**

24 sites (12 in the Ashanti Region and 12 in the Eastern Region) of the MCPP sites were selected and surveyed in this study. These two regions were selected for this study because each contained both shaded and unshaded management systems on similar soil types (Ferric Acrisols in the Ashanti Region and Ferric Lixisols in the Eastern Region). A trip was made to each of the 24 farms to compare MCPP data on shade levels and management practices to the present situation to know if there have been significant changes since the data was collected three years before. Information on age of the cocoa farm, land management practices and cropping history were also gathered. The information presented here is based on personal on-farm observations and interactions with expert agronomists who work closely with the farmers

on the MCPP research. Management practices were observed using standards as stipulated in a manual published by experts from the Cocoa Research Institute of Ghana (CRIG) (Opoku-Ameyaw et al., 2010).

3.3. **Results and Discussion**

3.3.1. **Use of inorganic fertilizer**

Observations on 24 farms in the Ashanti and Eastern regions revealed that 16 farmers use inorganic fertiliser, even though time of application varies depending on when the farmer can acquire the fertiliser. CRIG recommends that fertiliser should be applied by the start of the rainy season, which is April/May. It has however been stated that time of fertiliser application has no significant effect on yield (Baah et al., 2011). All farmers apply pesticides and fungicides and manually weed at least once a year.

3.3.2. **Return of pruning residues**

Crop residue is returned to cocoa soils in the form of pruning debris, litter fall and cocoa pod husks. CRIG recommends that mature cocoa trees be pruned at least once a year (basal shoots called chupons, excess and diseased branches, and weeds such as epiphytes and mistletoes should be removed). 8 farmers had correctly pruned their chupons. Most farmers are hesitant to remove the chupons as the fruits borne on them are considered part of their yield. However, the pruning improves air circulation and allows sunlight into the farm to help reduce the incidence and spread of diseases, especially black pod (Opoku-Ameyaw et al., 2010).

3.3.3. **Shade trees and litter fall**

Litter fall was observed to be a major source of soil organic matter on the farms. Litter is left on the soil surfaces and decompose naturally. Quality and quantity of cocoa litter has been associated with plant density and diversity. Studies have shown that litter production in unshaded cocoa farms are higher than in shaded ones, but that the rate of decomposition of litter and release of nutrients is faster on shaded farms than on unshaded ones (Dawoe et al., 2013; Ofori-Frimpong et al., 2007). This is because cocoa trees under shade are protected by the shade trees from the effects of draught in the dry season and so are able to preserve their leaves better than the unshaded cocoa trees. It is estimated that for every kg of litter, about 14g of N, 1.2g of P and 8.9g of K are returned to the soil (Hartemink, 2005). It is recommended that at least 40% shade be maintained on a mature cocoa farm and so there should be about 15-18 shade trees per hectare. Based on this, shade levels were categorised on the farms visited in this study as no shade (<5 trees/ha), light shade (6-12 trees/ha) shaded (13-20 trees/ha) and over shaded (> 21 trees/ha). Only 7 farms had the recommended shade level. 5 farms were overshaded, while the rest had little or no shade. Average yields (as reported in the MCPP) on farms categorised into each shade level were compared (Figure 3-1). The cocoa yields on farms with light shade were the lowest, while the shaded cocoa farms recorded slightly higher yields than no-shade and the over-shaded cocoa farms but were not statically significant.

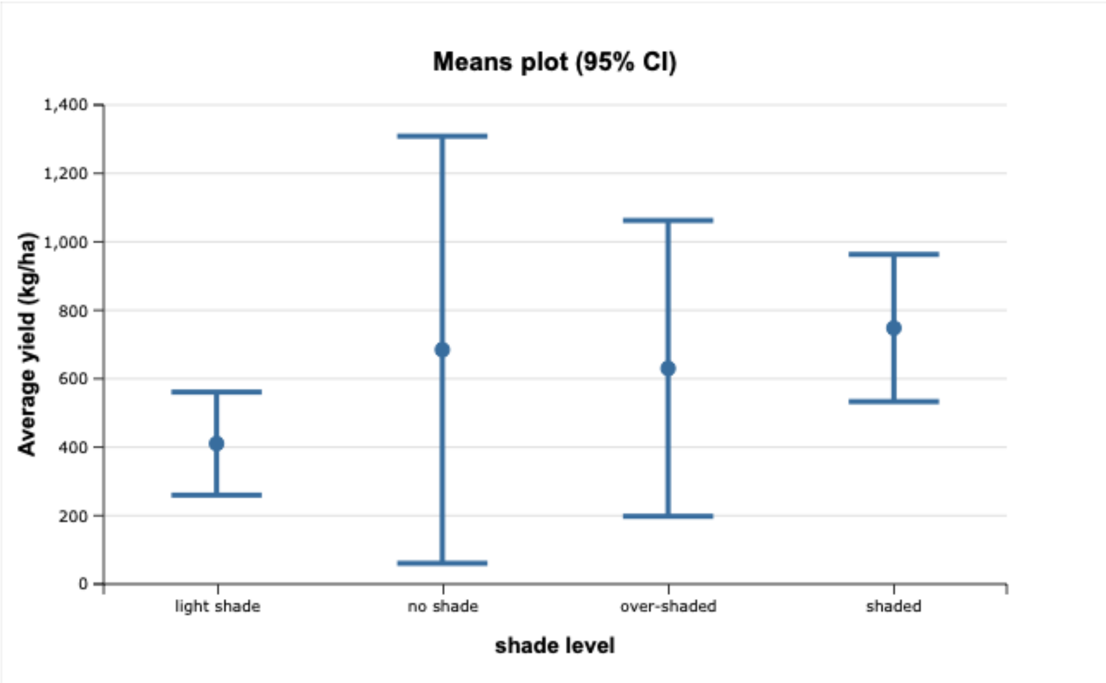

Figure 3-1: Means plot showing differences in average cocoa yields (2012/2013-2013/2014) on farms with different shade levels.

Farmers decision to have shade on their farms or not is determined by how they perceive the potential benefits of the shade trees which include protection of cocoa trees from excess sunlight, wind and impacts of heavy rains, and felling of economic shade trees as timber. (Acheampong et al., 2014; Vaast and Somarriba, 2014). The choice of shade trees is therefore influenced more by the economic value of the shade trees rather than their suitability as a recommended shade tree for cocoa.

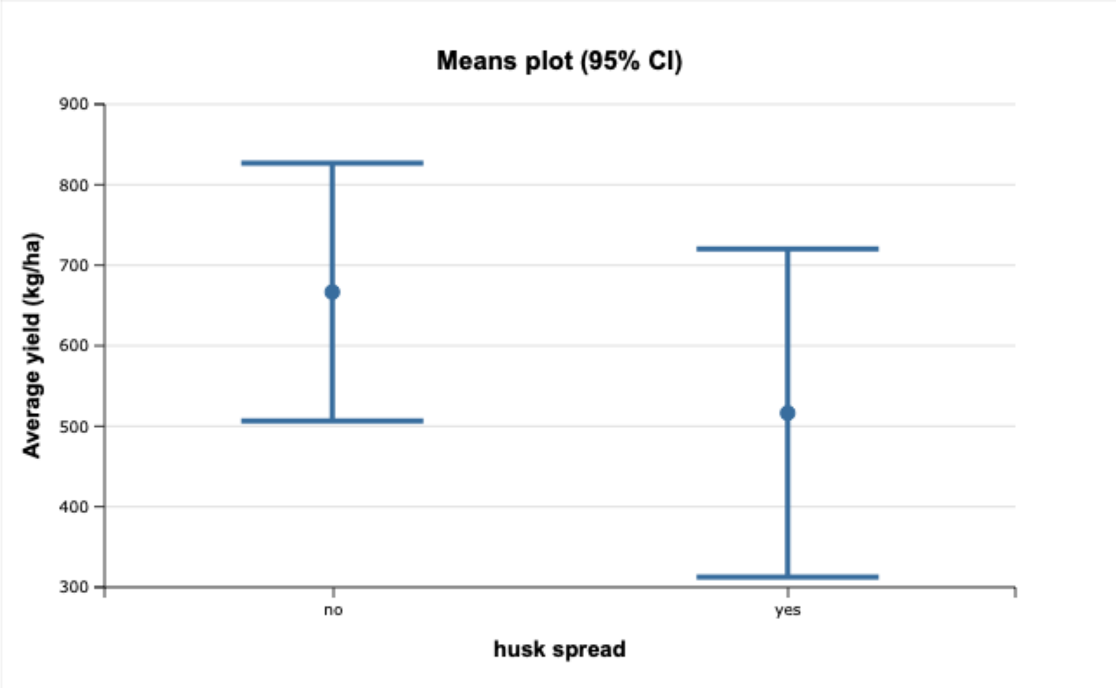

Figure 3-2: Means plot showing farms with Cocoa pod husks spread on them yielded lower than those without.

3.3.4. Cocoa pod husks

Cocoa pod husks (CPH) are the main crop residues that are left on the farm after harvest. The cocoa pods take the most nutrients (35 kg N, 6 kg P, and 60 kg per 1000 kg of dry beans) from the soils and the husk alone contains 15kg of N, 2kg of P and 50kg of K per every 1000kg of dry cocoa beans harvested (Didier Snoeck, 2016; Hartemink, 2005). Locations are selected by farmers for pod cracking on each farm and these positions are rotated annually around the farm to prevent pods from piling up. Farmers had noticed the dying of trees around huge piles and so adopted this rotation strategy. The heat from decomposition of the CPH are the probable cause of trees dying around the large piles of discarded CPH. Farmers believe that CPH adds nutrients to the soils because trees around the cracking locations tend to develop more fruits than those farther away, but also suspect that the piles make the fruits more prone to black pod disease. Most farmers therefore prefer not to retain the husks on the farm but cannot afford the labour cost of clearing the waste. 42% of farmers spread the CPH on the farm floor as mulch. Yield data collected by CRIG as part of the MCPP reflected that the possible nutrient addition of the husks through spreading did not result in an increase in yield (Figure 3-2). This finding could be because of an increased prevalence of black pod disease by the CPH. It could also be that some other yield determining factors are masking any impact.

3.4. **Conclusions**

There were a wide range of management practices adopted by farmers across the 24 farms visited in the Ashanti Region and Eastern Region of Ghana. Farmers depend solely on the government to supply free or subsidised fertiliser to them and expect free spraying against insect infestation and diseases. The level of shade on farms is inconsistent but seems to confer some benefit to crop yield. Some farmers prune trees and apply the prunings to the soil, while approximately half the farmers visited spread cocoa pod husks across the farm, without a clear benefit to the crop yield.

Chapter 4. EFFECTS OF LAND MANAGEMENT ON THE PHYSICAL AND CHEMICAL PROPERTIES OF GHANAIAN COCOA SOILS

4.1. Introduction

Cocoa is grown in Ghana across a wide range of soil types (mainly Acrisols, Lixisols, Luvisols, Ferralsols and Fluvisols, in order of decreasing coverage) and in several different regions (Ashanti, Brong-Ahafo, Central, Eastern, Western and Volta). Over a century of cropping cocoa has resulted in reduced fertility, which has affected yield. Increasing cocoa yields in Ghana is very critical to the nation's economic development as the commodity is the country's second biggest export and foreign exchange earner (Kolavalli and Vigneri, 2011). It is the livelihood of about 800,000 smallholder farmers who are collectively the main producers of cocoa, and yet face production challenges that limit yield (Acheampong et al., 2014; Anthonio and Aikins, 2009; Asante-Poku and Angelucci, 2013). These challenges include unfavourable climatic conditions, pest and disease, and poor soil fertility. The government of Ghana, realising these challenges, has since 2001 initiated programmes including the Cocoa High-Technology Programme (CHTP) and the National Cocoa Disease and Pest Control (CODAPEC). These programmes involve the supply of subsidised fertiliser to farmers and the spraying of farms against mirids and black pod disease, to increase cocoa productivity (Kumi and Daymond, 2015). These practices are recommended by the Cocoa Research Institute of Ghana (CRIG), based on research that has shown that yields are not sustainable without the judicious use of fertiliser (Afrifa et al., 2009; Snoeck et al., 2010b; Snoeck et al., 2016). Cocoa production in Ghana has therefore become heavily dependent on inorganic fertilizers (van Vliet et al., 2015). Even though the cost of fertiliser is subsidised, many farmers still cannot afford it (Aneani et al., 2012) and this has led to the adoption of traditional cultivation practices which require fewer inputs (Wessel and Quist-Wessel, 2015).

Research to date on cocoa soils in Ghana has focused on achieving the appropriate composition and application rates of mineral fertilisers to increase yield, whereas attempts to understand the overall soil health and promote long-term maintenance of soil fertility have been neglected. Optimum soil nutrient thresholds have been recommended for achieving optimum yields (Snoeck et al., 2016) and to achieve these thresholds, a single fertiliser formulation, (N:P:K 0:22:18 + 9CaO + 7S + 6 MgO) is recommended by CRIG for use in all cocoa growing regions at the same application rate (375 kg ha^{-1}), without prior soil testing (Afrifa et al., 2009; Jayne et al., 2015; Snoeck et al., 2010b), and irrespective of the different soil types across the growing regions. To ensure efficient use of these expensive fertilisers, it is important to determine whether this "one formula fits all" approach is efficient. This study aimed to assess the effects of soil management practices on soil chemical and physical properties across the different cocoa growing regions and to detect whether the fertiliser regimes recommended by CRIG actually improve the soil fertility.

4.2. Methodology

4.2.1. Study area

The study was conducted in Ashanti, Brong Ahafo, Eastern and Western regions of Ghana (Figure 4-1). The selected sites from these regions fall within the semi-deciduous forest agro-ecological zone of Ghana, which experiences an average rainfall between 1200 to 1600mm/yr and an annual average temperature between 25°C and 26°C (Opoku-Ameyaw et al., 2010). The soils in the study area are predominantly Ferric Acrisols, with some instances of Ferric Lixisols. Both soil groups are characterised by a subsoil enriched with highly weathered, low activity, clay (an argic horizon). They have a low cation exchange capacity (less than 24 $cmol_c\ kg^{-1}$) because they are dominated by 1:1 kaolinite clays. Acrisols have a base saturation of <50%, while Lixisols have a base saturation of >50% (FAO, 2014). These soils are typically well drained, deep and are texturally classed as sandy clay loam with pH between 5.1 and 6.5 (Adjei-Gyapong and Asiamah, 2002). The vegetation cover within the semi-deciduous forest agro-ecological zone of these regions is mainly cocoa, variegated mostly with naturally generated shade trees, and other food crops. The shade trees are principally semi-deciduous forest type that shed their leaves in the dry season.

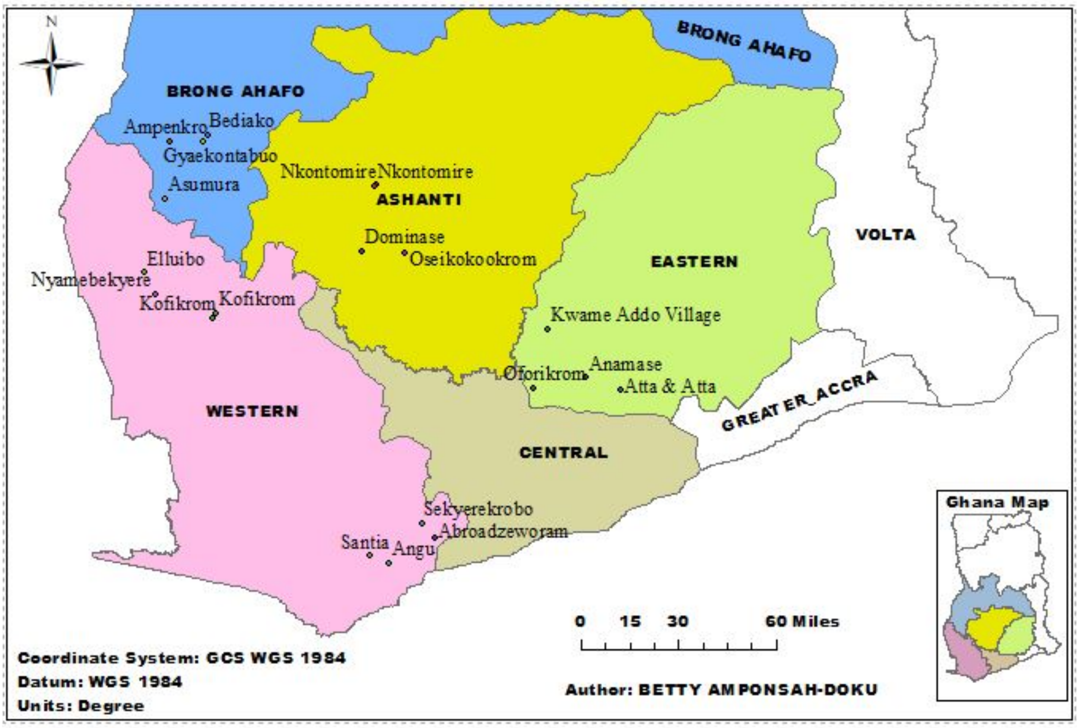

Figure 4-1: Map of study area showing the location of the selected farms across the four different cocoa growing regions of Ghana.

4.2.2. Sampling and data collection

Twenty farms were selected within the study area (Figure 4-1) across the four different cocoa growing regions of Ghana; Ashanti Region (4 farms), Eastern Region (4 farms), Brong Ahafo Region (4 farms) and Western Region, which was split into two; Western North (4 farms) and Western South (4 farms). The farms formed part of the project "Mapping Cocoa Productivity" (a collaboration between the Cocoa Research Institute of Ghana, University of Reading and Mondelez International) (Daymond et al., 2018). The 20 farms were selected for homogeneity since they were the plots receiving all four CRIG approved intervention packages (fertiliser, insecticide and fungicide treatments). Each farm was split into four plots using diagonal intersections. Two randomly assigned plots (each representing one replicate) were managed by CRIG using their approved intervention packages as an intervention treatment (T1) which were strictly applied according to the recommended rates and time of application (Table 4-1). The other two plots were managed by farmers with their own usual practices as a control treatment (T0). The control treatment here refers to the normal "business as usual" farmer practices and does not suggest that treatment was applied.

Sixty-four trees on each farm (16 per plot) were marked and used for data collection throughout the study. This research design enabled us to identify if the soil fertility on CRIG plots were different from that on the farmers plot. To test this, 5 soil samples were taken with auger from the top 20cm in each of the four plots, on each of the 20 farms, and bulked to form a composite. In total, 80 composite samples were air-dried, sieved through a 2 mm mesh, packaged and shipped to the University of Reading, UK in October 2016. The samples were analysed to assess their physical (texture) and chemical (pH, organic matter content, and available nutrients) properties to determine whether the interventions, particularly fertilisation, influenced these properties. Shade intensity and yield data collected by CRIG from 2015 to 2016 were provided to allow comparison of these parameters with the results of soil analyses. Shade levels were determined by means of hemispherical photography and image analysis. Yield was determined by regular assessment of pods per tree in different size classes.

Table 4-1: Chemical composition and rate of application of the intervention treatments carried out by the Cocoa Research Institute of Ghana (CRIG) in the Mapping Cocoa Productivity project

Treatment	Name	Active Ingredient/ Composition	Rate of application
Fertiliser	Cocofeed Plus	NPK 2-21-17+4S+10CaO+5MgO+0.1B+0.3Zn	375 kg $ha^{-1}yr^{-1}$
Insecticide	Confidor	Imidacloprid	30ml/11litre water/150ml/Ha
	Akatemaster	Bifenthrin	100ml/11litre water/500ml/Ha
Fungicide	Ridomil Gold 66 WP	6% metalaxyl-M and 60% copper (in form of cuprous oxide)	50g/15 litre water
	Fungikill 50 WP	35% copper (as hydroxide) + 15% metalaxyl	50g/15 litre water

4.2.3. Analytical methods

Soil texture was classified, based on particle size distribution (Mastersizer 3000 laser particle size analyser) and the use of a Soil Texture Triangle. pH was measured by a Jenway 3310 pH meter, calibrated with pH 4 and pH 7 buffers, in 1:5 soil-water solution. Organic matter (OM) was determined by means of loss on ignition after heating overnight in a Gallenkamp Muffle Furnace at 500°C. Total carbon and total nitrogen were analysed using a Thermo Scientific Flash combustion Elemental Analyser, calibrated with 1 mg and 3 mg samples of an aspartic acid standard. Available nutrients (P, K, Ca, Mg, Na, Mn, Cu, Fe, Zn, Al and As) were extracted from a 2 g sample of soil with 20 ml of Mehlich 3 solution, following Pierzynski (2000), and analysed by ICP-OES (Perkin Elmer Optima 7300 DV Inductively Coupled Plasma - Optical Emission Spectrometer). Cation exchange capacity (CEC) was calculated from the results as the sum of all cations (in milli-equivalents per 100g) extracted with the Mehlich 3 extract. Base saturation (BS) was calculated as the sum of the K, Ca, and Mg (in milli-equivalents per 100g), as a percentage of CEC.

4.2.4. **Data Analysis**

Data was statistically analysed using Minitab 17 statistical software. Two-way analysis of variance (ANOVA) was used to test for differences in soil properties (texture, pH, OM, CEC, BS, total N and C, and available nutrients) as affected by the management practices (CRIG or farmer) using region and fertiliser application (T0 vs T1) as factors at a 0.05 significance level. Multiple linear regression with stepwise selection was also used to ascertain whether the measured soil properties influenced the crop yield.

4.3. **Results**

4.3.1. **Characterisation of soil physical and chemical properties**

Differences in soil physical and chemical properties between CRIG-managed plots and farmer-managed plots in all four regions were not statistically significant ($p<0.05$). However, there were significant differences in most soil properties observed between regions, apart from soil organic matter (SOM), phosphorus and iron.

The pH of soil samples from all 4 regions were below pH 7 and therefore classified as acidic. Western-North recorded the lowest regional mean pH (4.96) whereas Brong Ahafo recorded the highest (5.87) (Table 4-2). Organic matter content ranged from 1.8% to 12.1% with most samples falling within 3.9% to 7.6%. Mean OM in CRIG intervention plots was generally higher than the farmer plots, although not statistically significantly ($p<0.05$). Soils in Ashanti Region had the highest mean OM content (6.77) with Western South being the lowest (4.72) (Table 4-2). The same observation was recorded for %C, %N and CEC (Table 4-2). Soils in Ashanti, Western North and Western South regions were classed as Silt Loam, while Brong-Ahafo and Eastern regions were classed as Sandy Loam based on their sand, silt and clay percentages (Figure 4-4).

Mean soil properties of both CRIG plots and farmer plots within each region in the study area were compared with the recommended thresholds according to Snoeck et al (2016) to assess their suitability for cocoa productivity. Mean pH, CEC and BS of both farmer and CRIG-managed plots in each region were slightly above the minimum threshold, except in Western North, where the mean pH and BS were below the minimum threshold. Soil samples in both CRIG- and farmer-managed plots within all regions had mean total organic carbon levels that were below the lower threshold value of 1.7%, except in the Ashanti Region where %C in CRIG-managed plots was slightly above the threshold (Figure 4-2).

Table 4-2: Concentration of available nutrients, total carbon, total nitrogen, pH, SOM, CEC, BS and particle size.

Nutrients	P	K	Ca	Mg	Na	Fe	Mn	Cu	Zn	Al	As
AR	9.48 ^{a}	94.18 ^{ab}	1355 ^{a}	197 ^{a}	14.16 ^{a}	151 ^{a}	141 ^{b}	2.2 ^{a}	2.13 ^{ab}	764 ^{ab}	0.11 ^{a}
BAR	12.11 ^{a}	129.4 ^{a}	1325 ^{a}	145 ^{a}	14.34 ^{a}	134 ^{a}	262 ^{a}	5.7 ^{b}	4.12 ^{ab}	707 ^{ab}	0.03 ^{b}
ER	9.34 ^{a}	45.2 ^{b}	822 ^{ab}	152 ^{a}	11.19 ^{a}	162 ^{a}	100 ^{b}	1.99 ^{b}	1.65 ^{ab}	675 ^{b}	0.01 ^{b}
WN	13.51 ^{a}	82.4 ^{b}	593 ^{b}	110 ^{a}	11.11 ^{a}	166 ^{a}	97 ^{b}	2.51 ^{b}	0.71 ^{b}	1014 ^{a}	0.01 ^{b}
WS	10.35 ^{a}	68.04 ^{b}	552 ^{b}	124 ^{a}	10.73 ^{a}	162 ^{a}	187 ^{ab}	2.96 ^{b}	3.34 ^{a}	574 ^{b}	0.01 ^{b}
Mean	10.96	83.84	930	146	12.31	155	157	3.07	2.39	747	0.03
SE. Mean.	0.81	14.01	174	15	0.80	5.68	30.86	0.68	0.61	73.6	0.02
Soil property	**C%**	**N %**	**pH**	**SOM**	**CEC**	**BS (Ca, Mg & K)**		**Sand**		**Silt**	**Clay**
AR	1.78 ^{a}	0.16 ^{a}	5.34 ^{ab}	6.77 ^{a}	18.3 ^{a}	39.7 ^{a}		31.3 ^{b}		60.5 ^{a}	1.93 ^{a}
BAR	1.32 ^{ab}	0.12 ^{ab}	5.87 ^{a}	5.29 ^{a}	17.5 ^{a}	41.4 ^{a}		52.5 ^{a}		40.2 ^{b}	1.05 ^{a}
ER	1.5 ^{ab}	0.13 ^{ab}	5.64 ^{ab}	5.83 ^{a}	14.0 ^{ab}	37.4 ^{ab}		56.0 ^{a}		42.8 ^{b}	1.21 ^{a}
WN	1.42 ^{ab}	0.12 ^{ab}	4.96 ^{b}	6.14 ^{a}	16.4 ^{ab}	24.2 ^{b}		40.7 ^{b}		57.5 ^{a}	1.79 ^{a}
WS	1.09 ^{b}	0.09 ^{b}	5.28 ^{ab}	4.72 ^{a}	11.7 ^{b}	31.0 ^{ab}		42.6 ^{ab}		49.4 ^{ab}	1.79 ^{a}
Mean	1.42	0.12	5.42	5.75	15.6	34.7		44.6		50.1	1.56
SE. Mean.	0.11	0.01	0.16	0.35	1.22	3.18		4.40		3.97	0.18

AR -Ashanti Region, BAR -Brong Ahafo Region, ER -Eastern Region, WN -Western North Region, WS -Western South Region. Mean values in the same column with the same superscript for the different regions are not significantly different at P<0.05 level according to Tukey's HSD test.

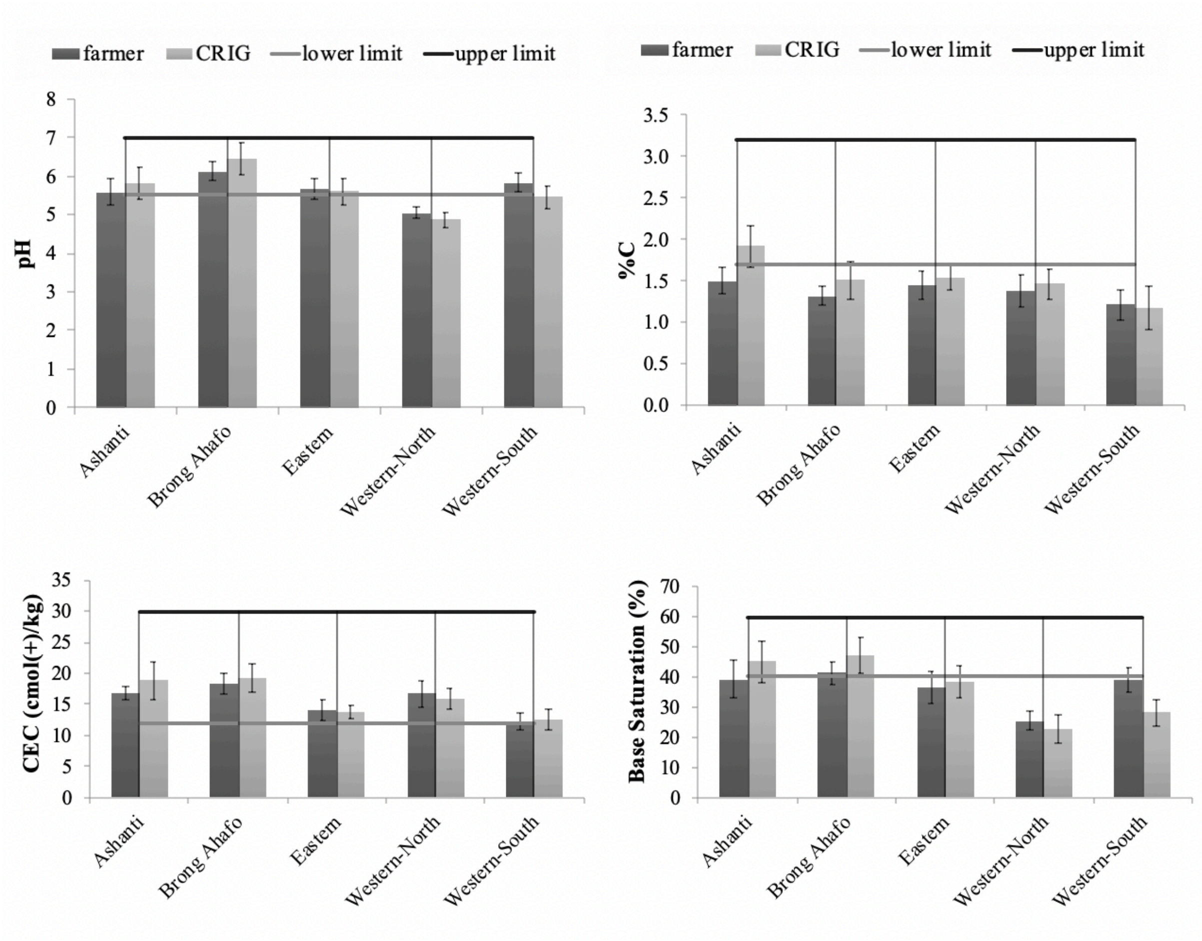

Figure 4-2: Chemical properties (pH, %C, CEC and Base saturation) of both research (CRIG) and farmer plots within each region compared to their upper and lower limits required for optimum cocoa productivity according to Snoeck et al, 2016. No statistically significant differences were found between treatments. Error bars are standard error of mean, n=4.

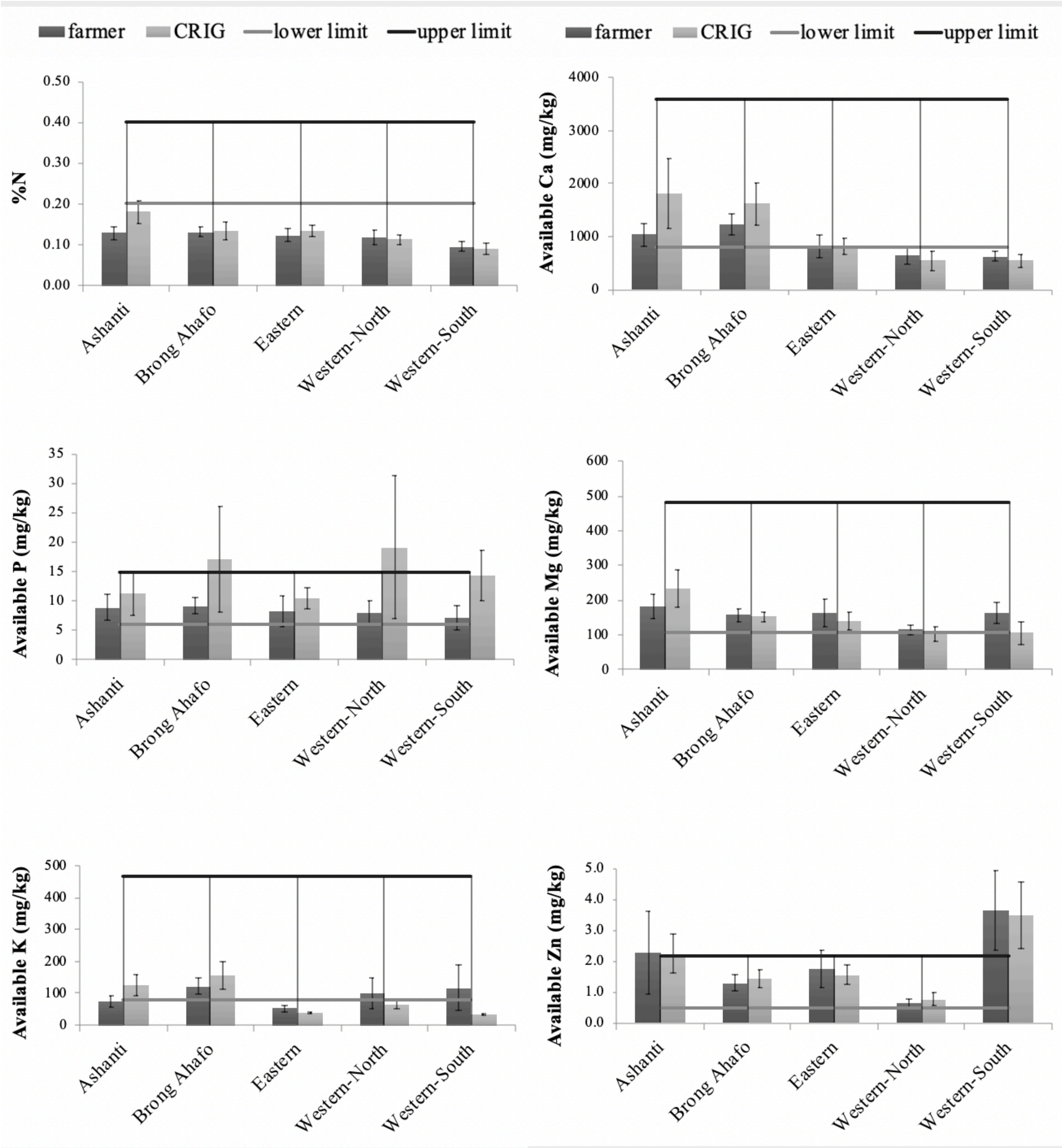

Figure 4-3: Major soil nutrient levels (total N, available P, K, Ca, Mg and Zn) of both research (CRIG) and farmer plots within each region compared to their upper and lower limits required for optimum cocoa productivity according to Snoeck et al, 2016. No significant differences existed between treatments, but each was low in total N and available K. Error bars are standard error of mean, n=4.

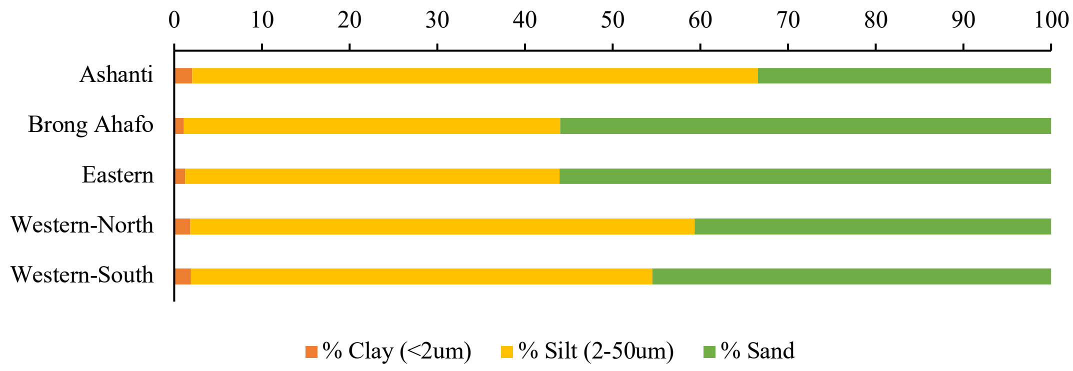

Figure 4-4: Particle size distribution of soil from each region.

4.3.2. Soil nutrient levels in CRIG and farmer plots

Mean total soil nutrient levels of both CRIG plots and farmer plots within each region in the study area were compared with the recommended nutrient thresholds according to Snoeck et al (2016) to assess their nutrient status for cocoa productivity. Soil samples in both CRIG and farmer plots within all regions had mean total N levels below the lower threshold of 0.2% (Figure 4-3), according to Snoeck et al (2016). Mean available K levels from all CRIG plots and farmer plots within the Eastern region were below the lower threshold, while levels within Brong Ahafo were between the upper and lower thresholds, but only slightly above the lower limit. Mean available K from CRIG-managed plots within Western North and Western North, as well as that from farmer plots within Ashanti, were also slightly above the lower limit (Figure 4-3). Mean available P levels from both CRIG and farmer-managed plots in all regions were mostly between the upper and lower threshold values, with only the mean values from CRIG-managed plots in Brong Ahafo and Western North being slightly above the upper limit.

Mean available Ca levels from both CRIG and famer-managed plots in Ashanti and Brong Ahafo regions were within the recommended threshold, with mean values from the CRIG-managed plots being higher, though not significantly so, than famer-managed plots. Ca availability in both CRIG and farm-managed plots in Eastern region were only slightly above the minimum threshold value, while those of Western North and Western South fell short of the lower threshold. Mean Mg levels were slightly above the minimum limit in all plots. Mean Zn levels were all above the lower threshold, with mean values in the Western South being twice the upper threshold. Typically, the mean available concentrations of Fe, Al, and Mn across the different regions were 3, 5-10 and 10-20 times above their respective upper threshold, while mean values of Cu were between the upper and lower thresholds in the Eastern region. Mean values in the other regions were slightly above the upper limit.

4.3.3. Relationships between soil properties and yield

Differences between CRIG intervention plot mean cocoa yields (pods per tree for the year 2016) and those of farmer managed plots within regions, as well as differences between regions, were not statistically significant ($p > 0.05$). This is despite yields being higher on CRIG plots in all regions, except Ashanti (Figure 4-5). High yield variability was observed within regions, particularly in Brong Ahafo which recorded both the highest (30 pods/tree/year) and the lowest yield (7 pods/tree/ year). These yields could not clearly be explained by the soil properties. There were weak significant correlations between yield and a number of the soil parameters (K, Ca, Cu, Mn and As, pH and CEC). K had a significant positive nonlinear relationship with yield with a very low R^2 value of 0.089 ($p < 0.05$), and the nutrient ratios N/P and N/K had a significant negative relationship with yield with relatively higher R^2 values of 0.149 and 0.16, respectively ($p < 0.01$), even though N and P individually showed no significant relationship with yield. The best multiple linear regression model for yield included the variables As, CEC, Mn, Cu and pH and had an R^2 value of 0.35 and $p<0.001$(Table 4-3) Cu, CEC and pH had a positive relationship with yield. CEC was positively affected by OM and pH ($R^2 = 0.73$, $p<0.0001$), but OM alone had no relationship with yield. K and nutrient ratios N/P and N/K could not be included in the model.

Table 4-3: Multiple linear regression models for predicting yield from chemical variables As, CEC, Mn, Cu and pH. Only significant parameter combinations in the multiple linear regression are reported in the table

Response variable	Fitted terms	F-Value	R^2	P-Value
Yield	As	9.51	0.14	<0.01
	As + CEC	11.09	0.27	<0.0001
	As + CEC + Mn	8.1	0.30	<0.0001
	As + CEC + Mn + Cu	7.01	0.33	<0.001
	As + CEC + Mn + Cu + pH	6.03	0.35	<0.001

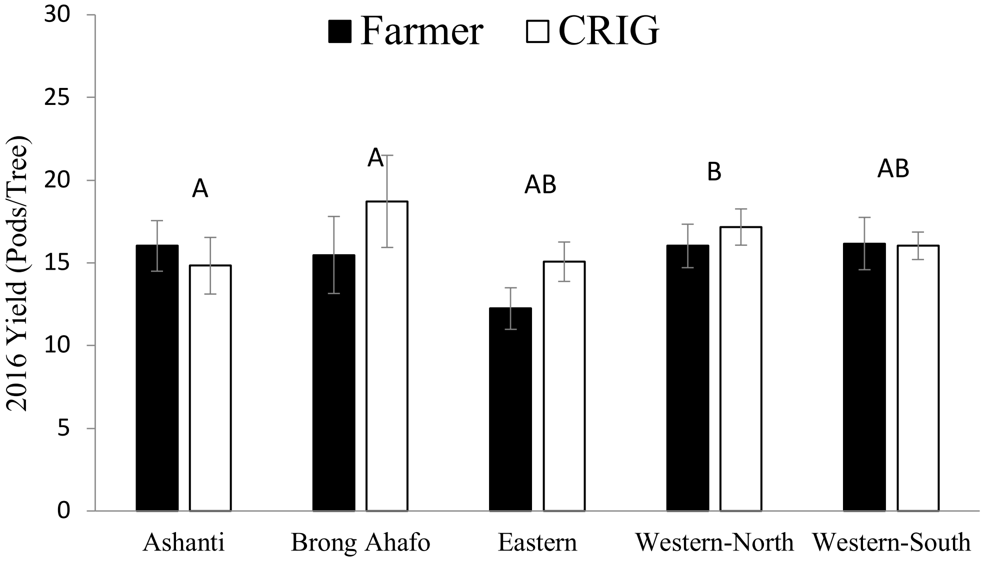

Figure 4-5: Crop yield (pods per tree in 2016) for both research (CRIG) and farmer plots within each region. Columns with different letters above indicate statistically significant differences between regions ($p<0.05$)

4.4. **Discussion**

4.4.1. **Soil management practices adopted by farmers affected soil properties similarly to CRIG recommended practices.**

The similar soil characteristics found between CRIG- and famer-managed plots may be that farmers adopted practices are not different from the land management interventions applied in the CRIG plots, particularly fertiliser use even though previous studies had shown that only about 33% of farmers have adopted fertiliser use, and even fewer are able to sustain it due to the high cost of fertiliser (Aneani et al., 2012; Danso-Abbeam and Baiyegunhi, 2017). Generally the results of the present study indicate that fertiliser application (applied over a period of 3 years), though known to improve yield significantly (Aneani and Ofori-Frimpong, 2013), does not necessarily improve the soil fertility. Total N was deficient and available K hovered at the minimum level known to be optimal for cocoa production (Snoeck et al 2016) even on CRIG-managed plots (Figure 4-3). Even though available P was within the recommended threshold on both plots, high variability (as indicated by the error bars) was observed within CRIG managed plots in each region compared to the farmer managed plots. It can be inferred therefore that P availability as affected by the judicious application of the recommended blanket fertiliser varies between plots in the same region. This supports the finding that soil types vary greatly even on the same farm (Dossa et al., 2018b; N'guessan et al., 2017; Snoeck et al., 2010b; Van Vliet and Giller, 2017).

The regional variation in soil properties may be attributed to the different soil types and environmental conditions (Buri et al., 2005): Western Regional soils are known be very acidic, as observed in this study for the Western-north farms, primarily due to high rainfall and highly weathered parent materials (Buri et al., 2005; Obiri-Nyarko, 2012; Ofori-Frimpong et al., 1999). Besides, it has been reported that the blanket fertiliser formulated for use in all growing regions is only suitable for 6% of the cocoa growing areas in Ghana (Snoeck et al., 2010b). The wide range of soil nutrient values observed between farms and regions illustrates the need to move away from blanket formulations and focus on site specific fertiliser formulations.

4.4.2. Cocoa soils are intrinsically low in nutrients and have poor chemical properties, even after fertiliser application.

Generally, the results of this study agree with other studies in stating that Ghanaian soils cropped to cocoa are generally low in nutrients; especially nitrogen, phosphorus and potassium (Asiamah, 2008; Bationo et al., 2018; Dossa et al., 2018a; Jayne et al., 2015; Snoeck et al., 2010b). Mean N in each region was below recommended thresholds and regional mean values for P, K, Ca and Mg were only slightly above the minimum threshold. It has been reported that enough N is added to cocoa soils through litter decomposition and that excess application of inorganic N stresses the crops, especially if the crop is under shade (Dawoe et al., 2009; Hartemink, 2005; Snoeck et al., 2010b). Therefore, the N content in the recommended fertiliser (NPK 2-21-17+4S+10CaO+5MgO+0.1B+0.3Zn) is present at a much lower level (2%) compared to P (21%) and K (17%). The low levels of N found across the study areas could be attributed to its susceptibility to leaching and volatilisation (van Vliet et al., 2015). The observation may also indicate that the nitrogen being cycled through litter decomposition is insufficient to support crop demand, particularly when the number of unshaded farms has increased since the introduction of hybrid cocoa varieties. On farms with less or no shade, litter decomposition rate and the release of nutrients is slow due to lack of diversity in the litter fall which attracts less diverse soil fauna (Moço et al., 2010; Ofori-Frimpong et al., 2007). Also, cocoa litter has high CN ratio of more than 30 (Tondoh et al., 2015) and so less nitrogen is available for decomposing microbial organisms.

From Figure 4-3, it appears that available P in the soil was consistently higher in the CRIG-managed plots than at the farmer-managed plots across regions, even though the differences were not significant. This difference could be due to the CRIG-recommended fertiliser application which has a high P content. However, this is not certain as other nutrients did not show such an obvious pattern as P.

Soil pH, OM, CEC and BS are soil chemical properties that play important roles in soil nutrient dynamics. It is clear from Figure 4-2 that the mean pH, although within accepted limits for cocoa production, is very close to the lower threshold, and the soils from several farms were below this threshold. Ghanaian soils in general have been observed to be acidic due to their highly weathered parent material, high rainfall, intensive cultivation and use of acid forming fertilisers (e.g. urea). Although cocoa is known to adapt to soil pH within a range of 4.6 to 7.5, the optimal range is 6.0-7.5 - where most major nutrients and trace elements are more available. pH values below 5.0 are known to limit production (Didier Snoeck, 2016; Opoku-Ameyaw et al., 2010). Increase in soil acidity in tropical soils (linked to possible aluminium toxicity) is known to be one of the major limiting factors to cocoa production (Didier Snoeck, 2016). High levels of available Al and Mn found in the soils which had mean pH less than 6 means that most of added P would bind to these cations and will not be available (Baligar and Fageria, 2005b; Noordiana et al., 2007). Evaluation of effects of soil Al saturation on root and shoot growth of cocoa and its micronutrient uptake parameters (concentration, uptake efficiency ratios, influx and transport) proved that an increase in Al saturation significantly reduces Cu, Fe, Mn and Zn uptake and subsequently root and shoot growth (Baligar and Fageria, 2005a).

Soil OM is an integral component of soil that affects the nutrition of cocoa through its impact on the physical, chemical and biological properties of soils (Didier Snoeck, 2016; Opoku-Ameyaw et al., 2010). OM increases the CEC of soils which, in turn, enables retention of nutrient cations like Ca, Mg, K, Fe, Zn (Bationo et al., 2018; Somarriba et al., 2013), and buffering capacity against changes in pH, which leads to greater biological activities (Curtin and Trolove, 2013; Didier Snoeck, 2016). These relationships explain the positive high correlations observed between OM, pH, BS, CEC and some cations (Ca, Mg and Na) in the soils. Soils cropped to cocoa should contain at least 3% of organic matter by mass, and its preservation is crucial to promote soil and water conservation (Somarriba et al., 2013). Soils across most of Ghana's agro-ecological zones have low organic matter content which affect the level of nutrients, particularly nitrogen and phosphorus, that the soil can hold. The Semi-deciduous Forest Zone, where the 4 cocoa-growing regions are located, have an estimated organic matter content in the range of 2.73 -8.25 % (Jayne et al., 2015). The average OM content (5.75%), observed in this study fell within this range and was slightly above the critical threshold of 3% but total carbon averagely was below the lower threshold. This can be attributed to the high proportions of sand in the soil which makes the soil porous and aids loss of organic matter.

4.4.3. Soil properties have weak relationship with cocoa yield

The measured soil physical and chemical variables did not reveal the expected correlation with yield. The weak relationship observed between soil parameters and yield indicates that other factors such as pest and diseases, water availability and prevailing environmental conditions, may have a greater influence on yield, as explained in other studies (Didier Snoeck, 2016; Lahive et al., 2018; Vanhove et al., 2016). It is also possible that the dependency of some of the variables on others masked their direct effects on yield. For example, low pH affected total N content and the availability of cations such as K, Ca and Mg. While pH was one of the predictors of yield, the properties it affects were not. The effect of N, P or K on yield, measured as number of pods per tree, has been noted by Snoeck et al (2016) to be dependent on a balance in the availability of these nutrients. P has a negative effect when K is deficient, N affects yield positively only when soil P and K are both in ample supply. K has a positive effect which almost triples when N is supplied at the same time. The results of this study reveal a rather weak, but significant, relationship between N and K (R^2=0.25, $p<0.05$), P and K (R^2=0.247, $p<0.05$), but no significant relationship between N and P.

4.5. Conclusions

Soils in the four cocoa growing regions of Ghana have low fertility due to low pH, low total C and N, low cation exchange capacity, relatively low basic exchangeable cations (Ca, Mg and K) and high exchangeable Al and Mn. These conditions persist even on farm plots managed strictly according to the CRIG-recommended fertiliser application programme, supported by the government of Ghana. Considerable differences were observed between the different regions, which supports the notion that a bespoke fertiliser formulation and rate is required for different soil types to optimise the soil fertility of cocoa plantations nationally. We observed no statistically significant differences in the soil fertility of plots according to the soil management practices adopted by farmers and the CRIG recommended practices, highlighting the importance of local knowledge, or the possibility that farmers replicated the practice implemented by the CRIG researchers. Nevertheless. we did not observe a strong relationship between the soil fertility and the yield of cocoa plantations (assessed by counting the number of pods per tree). This observation implies that other factors (e.g. pest and diseases, water availability and prevailing environmental conditions) probably contribute to determining the yield of coca farms to a greater extent. Yield may be improved, though to a lower extent, with soil management practices that increase pH, CEC and organic matter levels. A longer-term study is required to understand better how fertiliser applications on cocoa farms impact on yields.

Chapter 5. DEVELOPING COMPOST FROM COCOA POD HUSKS FOR SUSTAINABLE COCOA PRODUCTION IN GHANA

5.1. Introduction

Declining fertility of cocoa soils worldwide is a major concern for all stakeholders (Franzen and Borgerhoff Mulder, 2007). Sustainable production requires a shift away from soil fertility management strategies that exclusively relies on inorganic fertiliser application towards strategies aimed at improving soil structure and soil ecological functions while reducing negative environmental impacts (Acheampong et al., 2014; Gockowski and Sonwa, 2011). The adoption of organic fertilisers as a route to sustainable production will enable most cocoa producing countries to increase the soil organic matter (SOM) content of cocoa plantations; an important soil attribute that has a major influence on soil properties and ecological functions such as soil water conservation and nutrient cycling (Alvarenga et al., 2017; Coleman et al., 2017; Nigussie et al., 2015). The use of both organic and inorganic fertilisers as part of an integrated nutrient management system is gaining research attention in cocoa production (Afrifa et al., 2009). However, information on the effect of different types and rates of organic fertilisers on soil quality and the performance of cocoa crops is very much limited, particularly in Ghana where cocoa cultivated soils have low organic matter content and fertility due to years of nutrient mining (Asiamah, 2008; Jayne et al., 2015). Knowledge is mostly confined to the response of poultry manure and the ash from burnt cocoa pod husks (CPHs), which is an amendment recommended to cocoa farmers (Opoku-Ameyaw et al., 2010).

CPHs are a farm waste but are also a major potential source of organic matter on cocoa farms. 1.4kg of husks is produced for every 1kg of dry beans and CPHs contain ~0.1% N, ~0.3% P and ~ 5% K (Didier Snoeck, 2016; Hartemink, 2005). Their use as soil amendments has resulted in significant improvements in soil properties and crop growth (Agele and Agbona, 2008; Fidelis and Rajashekhar Rao, 2017; Moyin-Jesu, 2007; Munongo et al., 2017; Ofori-Frimpong et al., 2010; Sosu, 2014). However, most of these findings relate to their use as a fertiliser for arable and horticultural crops or as potting media for cocoa seedlings in the nursery rather than on cocoa plantations where it is vital to return the nutrients mined to produce the husks. Composting, a conventional and environmentally sustainable means of valorising agricultural waste, has been recommended to farmers in Ghana to recycle CPHs into organic fertilisers (Opoku-Ameyaw et al., 2010; van Vliet et al., 2015). The growth of cocoa seedlings was enhanced more when soil was amended with CPH based compost than when used together with NPK 15-15-15 (Ofori-Frimpong et al., 2010). However, widespread adoption in Ghana has lagged behind Nigeria (Agbeniyi et al., 2011), Indonesia (Sriharti and Dyah, 2018), Papua New Guinea (Fidelis and Rao 2017), and Cameroon (Munongo et al., 2017) where research into on-farm composting of CPHs has established that CPH compost application can improve soil fertility and save on-farm costs by reducing the rates of inorganic fertiliser used.

Composting CPH alone may result in slow decomposition due to N immobilisation. However, co-composting CPH with other 'activator' co-amendments such as poultry manure or nitrogen rich green leaves (e.g. Neem tree leaves, Tithonia plants, or grass clippings) has been observed to enhance the quality of CPH composts (Elisée and Emile, 2017; Kayode et al., 2015; Munongo et al., 2017) with a combined effect greater than their individual additions. Poultry manure performs better than the leaves since the former is richer in nutrients, especially N, P and K. Unlike inorganic fertilisers, nutrient release from compost is slow and may not be made immediately available to plants (Bernal et al., 2017a; van Vliet et al., 2015). Furthermore, in some situations (such as on a typical Ghanaian cocoa farm) obtaining some of these 'activator' co-amendments could be challenging. For these reasons some studies have also compared the efficacy of CPHs when co-composted with inorganic fertilisers. When CPHs were composted with urea and or triple superphosphate, the former supressed plant height while latter improved growth (Fidelis and Rajashekhar Rao, 2017). However, using inorganic fertilisers to activate the CPH composting process prevents the direct application of these fertilisers to plantation soils, where they are known to benefit cocoa yield (Snoeck et al. 2016). Research is therefore required to find the most efficient use of the organic and inorganic resources available to farmers that optimises nutrient retention and release in the soil, to meet plant demand.

In this study, the use of CPHs in combination with different rates of NPK fertiliser as an 'activator' was investigated using laboratory composting reactors to estimate the smallest possible amount of the inorganic fertiliser required to obtain the best quality CHP compost for growing cocoa, with minimal losses. The study sought to provide answers to these questions:

i. What is the relationship between the rate of NPK fertiliser applied and the rate of CPH composting?
ii. What is the relative difference in the concentration and amount of available nutrients in composts produced using CPH alone and NPK activated CPH?
iii. Does co-composting CPH with NPK fertiliser result in a compost of higher quality for cocoa plantation soils?

It is hypothesised that CPH compost activated with NPK fertilisers will accelerate the composting process, and provide a compost with greater nutrient availability, capable of improving soil quality to a greater extent than CPH composted alone.

5.2. Methodology

5.2.1. Collection and processing cocoa pod husks (CPHs).

Fresh CPHs were collected from one farm at the Cocoa Research Institute of Ghana, Tafo in the Eastern Region of Ghana (6°13'36.9"N, 0°21'45.1"W) for homogeneity. The husks were chopped into small chunks and thoroughly mixed to form one homogenised composite feedstock. A sub-sample from this composite feedstock was analysed to characterise it prior to composting.

5.2.2. Experimental set-up

Laboratory compost reactors were the apparatus used for composting the CPH. They were constructed based on published design concepts (Chen, 1997; Larsen and McCartney, 2000) but the specification was modified to suit this experiment (Figure 5-1). One litre capacity clip-lock Sistema™ food containers were used to construct each composting reactor. A stainless-steel mesh was placed 15 mm from the bottom of the reactor to hold the feedstock and allow leachate to be collected at the base. A flexible air-line tube (4mm diameter) connected the reactor to a timed aquarium pump that pumped air (1 litre per minute every hour at a pressure of 0.18mbar) through the feedstock to keep it aerated. A non-return valve was fixed to the flexible tube to allow air into the chamber but not from it. The pumped air went out of the chamber through similar tube into an Erlenmeyer flask filled with ultra-pure water which bubbled to monitor the airflow. The water and the non-return valve helped to keep the condition in the chamber fairly constant. An outlet was created at the bottom of the chamber with a straight 4mm diameter connector attached to another flexible air-line tube with a clip that was opened to drain leachate. A 25mm diameter hole was created at the top and closed tight with a rubber Suba Seal™ septum to allow headspace gas samples to be taken. Reactors were mounted in sets of four on stands that allowed each reactor space for their individual connections, stability and for ease of working around them.

400g of the chopped CPH was weighed out into individual laboratory compost reactors and composted for 14weeks in a 30°C temperature-controlled room. The experiment had 4 treatments that consisted of CPH composted alone (without the addition of fertiliser to 'activate' the composting process) and CPH composted with 25%, 50% and 100% of the recommended NPK fertiliser dose for a single cocoa seedling (Bohórquez and Rodríguez, 2016) (Table 5-1). Treatments were replicated 4 times and included 2 blank reactors to which no CPH or fertiliser were added. In all, 18 individual reactors were used, and these were arranged in a completely randomised design. The compost was turned every two weeks to ensure uniformity in the substrate decomposition.

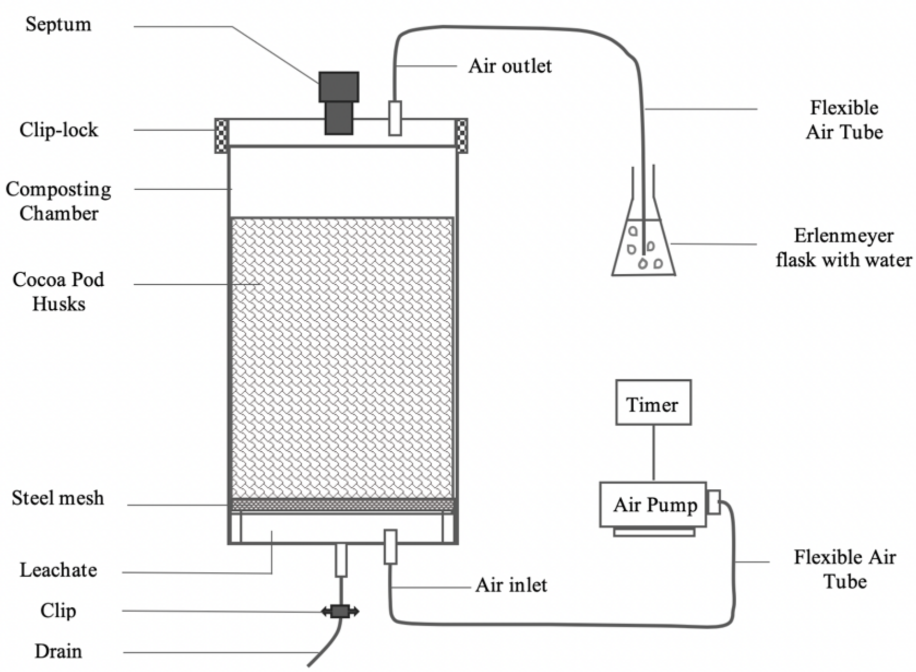

Figure 5-1: Photograph and diagram of the laboratory compost reactors used to produce cocoa pod husk (CPH) composts.

Table 5-1: Experimental treatments indicating the concentrations of inorganic fertiliser added to cocoa pod husks (CPHs) prior to composting

Treatments	Concentration of inorganic fertiliser added (mg/kg)		
	N	P	K
CPH + 0% (control)	0	0	0
CPH + 25% NPK	2298	1535	2354
CPH + 50% NPK	4510	3034	4806
CPH + 100% NPK	9058	5986	9889

5.2.3. CO2 gas sampling method

CO_2 flux was measured weekly to monitor the composting process. Before sampling, the lid of each reactor was opened to the atmosphere for 30 minutes to allow accumulated gases to escape and then closed for an incubation period of 2 hours. A 12 ml syringe connected to a 0.6 mm needle by a two-way tap was pushed through the septum into the reactor's headspace to carefully draw 10ml of air into the syringe. The two-way tap was opened to allow the headspace gases to be drawn into the syringe and then closed afterwards to enclose the gases within it before the needle was carefully withdrawn from the septum. The needle was then inserted into a pre-evacuated Exetainer^{TM} vial and the tap opened to allow the vacuum in the vial to draw the sample out of the syringe into the vial. The vials were stored in a 20° C room and analysed on an Agilent 7890B Gas Analyser calibrated with four replicates of three standards (500ppm 2500ppm and 5000ppm CO_2) injected into Exetainer^{TM} vials using the same method as described above.

5.2.4. Compost analysis and characterisation

The physicochemical properties of CPH composts, as well as the fresh CPH, were characterised. Moisture content was determined by calculating the difference in CPH masses before and after heating at 105^{o}C for 24 hours. pH and electrical conductivity were measured with pH and EC meters respectively in 1:2.5 compost-water slurry. C/N ratio was calculated from total carbon and total nitrogen contents determined using the Dumas combustion method with a Thermo Scientific Flash 2000 Organic Elemental Analyser. Available N (NO_3-N and NH_4-N) was extracted by 1M KCL in a 1:5 fresh compost to extractant ratio while available P was extracted using Olsen P extractant (0.5M $NaHCO_3$) in a 1:20 dry compost to extractant ratio: both were analysed on Skalar SAN^{++} continuous flow analyser. Available K was extracted with a 0.01M $CaCl_2$ and 0.002M DTPA (Diethylenetriaminepentaacetic acid) extracting solution at a ratio of 1:200 and analysed on a Perkin Elmer Optima 7300 inductively coupled plasma-optical emission spectrometer (ICP-OES). Total nutrient concentrations of P, K, Ca, Mg, Mn, Cu and Zn were determined by digesting 0.5g compost samples in a MARS 6 microwave digestion system with 8ml nitric acid and 2ml ultrapure water and analysis of the digests with ICP-OES.

5.2.5. Data Analysis

Data was processed and analysed using Microsoft Excel and Minitab 17 statistical software. Analysis of variance (ANOVA) was used to test for statistically significant differences in composting rate, C/N ratio, and total and available nutrients as affected by NPK addition at a 0.05 significance level. Tukey's Pairwise Comparison was used to compare means of treatments to determine significant differences between them.

5.3. Results

5.3.1. Characterisation of cocoa pod husks (CPHs) prior to composting

The chemical properties of the CPHs used in these experiments are provided in Table 5-2, including the, pH, moisture content, total and available nutrient concentrations, and C/N ratio. The CPHs are particularly rich in K (~3.5%), but only about 10% of this K is in a plant available form, whereas ~85% of the P is available. The C/N ratio of the husks are >30, indicating that N may limit decomposition in the absence of nitrogenous fertilisers.

Table 5-2: Chemical properties of fresh cocoa pod husks (CPHs) (values given to 3 significant figures)

Property	Fresh CPH
pH	7.35 ± 0.1
Moisture content (%)	83.0 ± 2.0
Total C (%)	38.5 ± 1.1
Total N (mg/kg)	7810 ± 280
C:N ratio	51.8 ± 0.8
Total P (mg/kg)	1230 ± 118
Total K (mg/kg)	35300 ± 356
Total Ca (mg/kg)	7570 ± 260
Total Mg (mg/kg)	3920 ± 210
Total Cu (mg/kg)	13.0 ± 0.4
Total Zn (mg/kg)	11.0 ± 0.3
Available N (mg/kg)	23.0 ± 0.1
Available P (mg/kg)	1030 ± 53
Available K (mg/kg)	3240 ± 46

5.3.2. The cocoa pod husk (CPH) composting process.

5.3.2.1. *CO_2 Evolution*

Figure 5-2 shows that mean CO_2 flux from the decomposing CPH for all treatments decreased steeply from 18 µg C-CO_2 g^{-1} h^{-1} in the 1st week to 2 µg C-CO_2 g^{-1} h^{-1} in the 5th week. The composts then remained relatively stable from the 7th week (1.3 µg C-CO_2 g^{-1} h^{-1}) to the 14th week (0.6 µg C-CO_2 g^{-1} h^{-1}), except for the 6th and 12th weeks where a temporary increase to 3.4 µg C-CO_2 g^{-1} h^{-1} and 3.0 µg C-CO_2 g^{-1} h^{-1}, respectively was observed (Figure 5-2). There were no significant differences in CO_2 flux between treatments throughout the composting period.

5.3.2.2. *Mass loss*

The greatest mass loss was observed in compost with 50% NPK addition (which lost 68% of its initial mass), followed by compost with 100% NPK addition (which lost 57%), then compost with 25% NPK addition (which lost 51%) and then lastly, compost with no NPK addition (which lost only 38%) (Table 5-3). These results are similar to the level of mass loss observed by (Fidelis and Rajashekhar Rao, 2017), where CPH compost without nutrient enrichment by an 'activator' also lost the least mass.

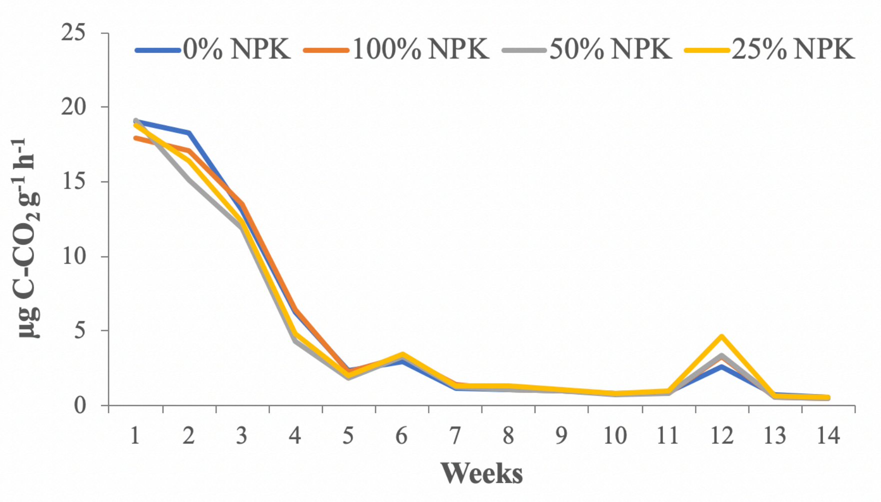

Figure 5-2: CO_2 flux from reactors containing cocoa pod husks (CPHs) composted with 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling over a 14-week composting period.

5.3.2.3. *Temperature*

The temperature of composts did not reach the recommended thermophilic state between 60°C and 70°C (Bernal et al., 2017b; Stoffella and Kahn, 2001) in any of the treatments, as also observed by (Elisée and Emile, 2017). The thermophilic stage of composting is only reached when heat produced by the compost is greater than the heat that is lost to the environment (Bernal et al., 2017b). Heat loss in our reactors was particularly high due to the small compost mass (400g) and volume (1L) which caused heat to be lost quickly to the surrounding environment. The temperature of the composts in all of the reactors throughout the experiment was similar to the surrounding environment, which was maintained at 30°C.

5.3.2.4. *Observations*

The CPH composted in all treatments changed colour gradually during the composting process from a brown colour at the start of the composting process, to a very dark (almost black) colour at the end (Figure 5-3). We also noted a change in the smell of the composts from an offensive odour during the first few weeks, to an earthy-like smell towards the end of the 14 week incubation period, indicating the completion of composting, as explained by (Bernal et al., 2017b).

Figure 5-3: Colour of coco pod husks (CPHs) before composting (left photo), compared to after composting (right photo)

5.3.3. Compost characterisation

The physical and chemicals properties of the composts produced by the various treatments are given in Table 5-3.

5.3.4. C/N ratio

The C/N ratio of fresh CPH reduced from 52 to 27 during the composting process for compost with no NPK added, 24 for compost with 25% NPK added, 21 for compost with 50% NPK added and 18 for compost with 100% NPK added (Figure 5-4). Therefore, C/N ratio of composts decreased with increasing quantities of NPK used to activate the composting process.

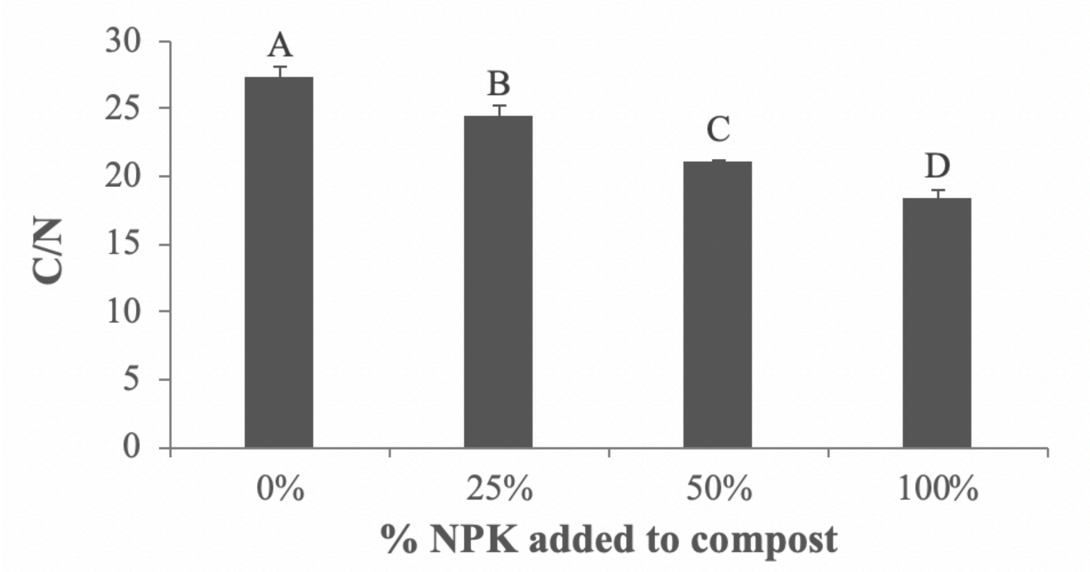

Figure 5-4: C/N ratio of CPH composted with 0%, 25%, 50% and 100% of the NPK requirement of a cocoa seedling. Different letters above columns indicates statistically significant differences between treatments ($p<0.05$).

5.3.5. **Moisture and organic matter content**

Mean moisture content of the composts produced ranged from 77% for compost with 100% NPK to 82% for compost with no NPK (Table 5-3). The highest organic matter content (Table 5-3) was found in the CPH composted with 50% NPK (76.5%), followed by that with 25% NPK (75.0%), no NPK (75.0%), and then 100% NPK (73.9%). While these differences are not large, this finding is an indication that the CPH activated with the 100% NPK treatment has decomposed to a greater extent than the other treatments.

5.3.6. **pH, Electrical conductivity and cation exchange capacity**

Mean pH of composts produced ranged from 10.3 in compost with 100% NPK to 10.7 in compost with 25% NPK (Table 5-3). Mean electrical conductivity (EC) increased with increasing NPK amendments, ranging from 3.04 mS/cm in CPH composted with no NPK added to 5.79mS/cm for CPH composted with 100% NPK added (Table 5-3). Mean CEC was highest in CPH composted with 25% NPK at 392 $cmol_c$/kg and lowest in CPH compost with 50% NPK at 290 $cmol_c$/kg (Table 5-3), revealing no clear relationship with the quantity of NPK used to activate the composting process.

Table 5-3: Physical and chemical properties of composts produced from cocoa pod husks (CPHs) composted with 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling. n = 4, values given to 3 significant figures ± standard deviation.

	Compost only (0% NPK)	Compost with 25% NPK	Compost with 50% NPK	Compost with 100% NPK
Mass loss (%)	37.7 ± 7.4	50.6 ± 2.7	67.7 ± 3.0	57.0 ± 3.4
pH	10.5 ± 0.10	10.8 ± 0.01	10.5 ± 0.03	10.3 ± 0.03
EC (mS/cm)	3.04 ± 0.42	4.96 ± 0.99	4.88 ± 0.32	5.79 ±0 .65
Moisture content (%)	82.1 ± 2.1	77.4 ± 1.2	78.3 ± 2.0	77.0 ± 1.8
Organic matter (%)	75.0 ± 3.8	75.0 ± 2.6	76.5 ± 0.7	73.9 ± 0.3
CEC (cmol$_c$/kg)	347 ± 10	392 ± 21	290 ± 24	301 ± 5.0
Available N (mg/kg)	15.9 ± 8.5	14.1 ± 4.9	156 ± 50	697 ± 31
Available P (mg/kg)	725 ± 100	934 ± 140	1450 ± 240	3704 ± 57
Available K (mg/kg)	3430 ± 59	3390 ± 81	3610 ± 97	3890 ± 360
Total N (mg/kg)	13200 ± 1800	16000 ± 940	18200 ± 100	20400 ± 780
Total P (mg/kg)	1560 ± 110	3320 ± 350	489 ± 38	8200 ± 570
Total K (mg/kg)	36100 ± 540	36000 ± 1100	37900 ± 3900	43700 ± 5500
Total Ca (mg/kg)	10900 ± 890	11900 ± 1600	12800 ± 14005	15300 ± 1100
Total Mg (mg/kg)	5600 ± 460	5430 ± 420	5240 ± 450	4900 ± 230
Total Cu (mg/kg)	21.8 ± 1.8	21.4 ± 1.3	21.5 ± 1.4	21.0 ± 1.5
Total Zn (mg/kg)	20.5 ± 1.8	20.1 ± 1.3	20.2 ± 1.4	19.7 ± 1.5

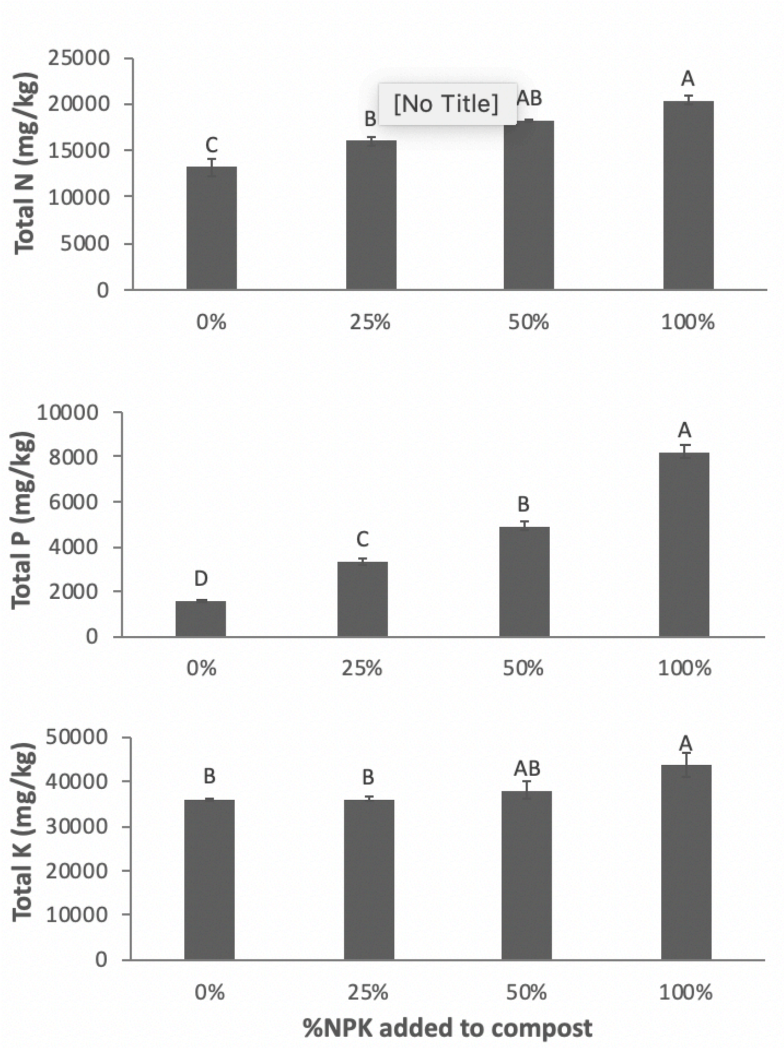

Figure 5-5: Concentrations of total N, P and K in composts produced from cocoa pod husks (CPHs) composted with 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling. Different letters above columns indicates statistically significant differences between treatment (p<0.05). n= 4, error bars are standard errors of the mean.

5.3.7. Nutrient concentrations in cocoa pod husks (CPHs) composted with different quantities of NPK fertiliser.

Figure 5-5 and Figure 5-6 show the total and available concentrations of nutrients in composts produced in each treatment. We observed consistent significant differences between the treatment means that indicate greater total and available N, P and K concentrations in CPH composted with increasing quantities of NPK fertiliser.

Mean total N and P content in composts were significantly ($p<0.05$) greater in treatments co-composted with 25%, 50% or 100% NPK, compared to the treatment composted without NPK used to activate the composting process (Figure 5-5). CPH composted with 100% NPK or 50% NPK contained significantly ($p<0.05$) greater total K content than CPH composted without NPK. The total K in the 25% NPK treatment compost was not statistically different from the 0% NPK control treatment and contained the lowest total K concentration among the four treatments (Figure 5-5).

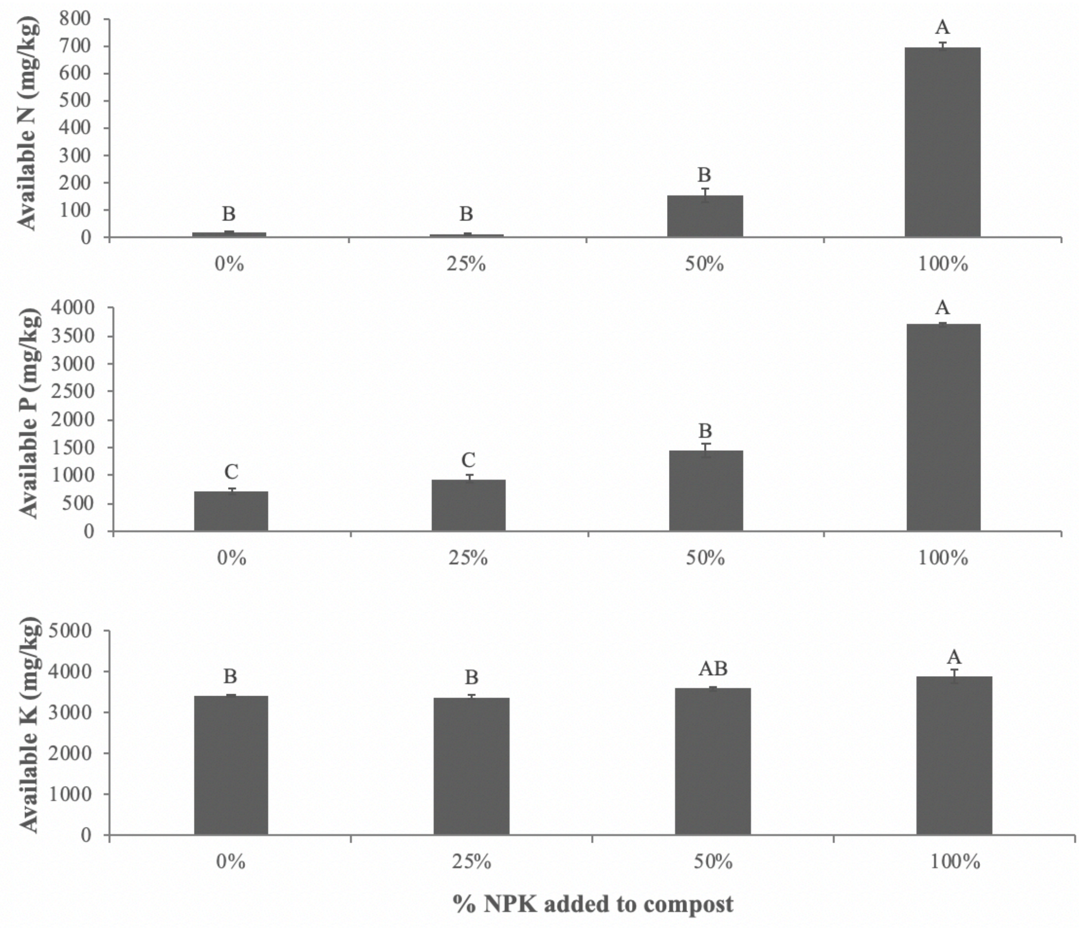

Figure 5-6: Concentrations of available N, P and K in composts produced from cocoa pod husks (CPHs) composted with 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling. Different letters above columns indicates statistically significant differences between treatments ($p<0.05$). n= 4, error bars are standard errors of the mean.

Mean concentrations of available N, P and K in CPH composted with 100% NPK were significantly ($p < 0.05$) greater than CPH composted in the absence of an NPK activator (Figure 5-6). However, only available N and P were significantly greater in the 50% NPK compost treatment, compared to the 0% control CPH compost. Composts produced with 0% NPK or

25% NPK contained the lowest mean available N, P and K and were not significantly different from each other (Figure 5-6).

5.3.8. Total and available N, P and K losses during the cocoa pod husk (CPH) composting process.

The amount of total N in the various composted CPH treatments reduced in the order 100% > 0% > 25% > 50% NPK addition (Figure 5-7). The CPH composted with highest rate of NPK (100%) resulted in a compost containing the highest amount of total N, but only retained 52% of the N added to the reactor (Table 5-4). By contrast CPH compost with no NPK added (0%) retained the 2^{nd} highest amount of N, representing, on average, 108% of the N added to the reactor. It is therefore clear that without the addition of mineral N to CPH during composting, all the N within the CPH becomes immobilised. CPH composted with 50% NPK resulted in a compost containing the lowest amount of total N as well as had the lowest proportion of N (48%) relative to the N added to the reactor.

The amount of total P in the various composted CPH treatments was in the order 100% > 25% >50% > 0% of NPK addition (Figure 5-7), while the proportion of P in the composts, relative the amount added was in the order 0% > 25% > 100% > 50%. The CPH composted with 100% NPK contained the greatest amount of total P but was 3rd highest in terms of P efficiency, with only 49% of the P added being present in the final compost. The 0% NPK compost treatment contained the least total P but was most efficient, retaining 81% of the P added (Table 5-4).

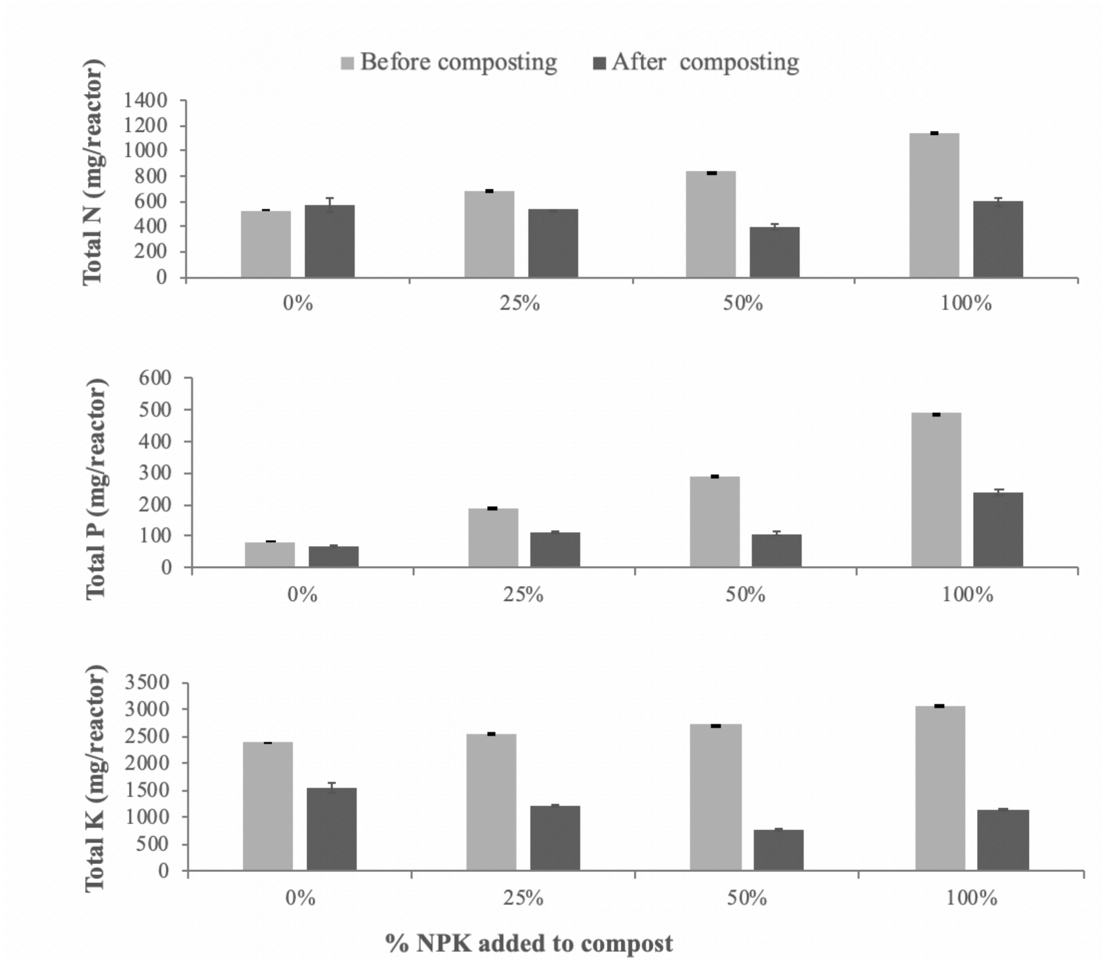

Figure 5-7: Total quantity nutrients (N, P and K) added to each reactor both within the cocoa pod husks (CPHs) and as mineral fertilisers (applied at a rate of 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling), compared to the total quantity analysed in the composts produced after 14 weeks. n= 4, error bars are standard errors of the mean.

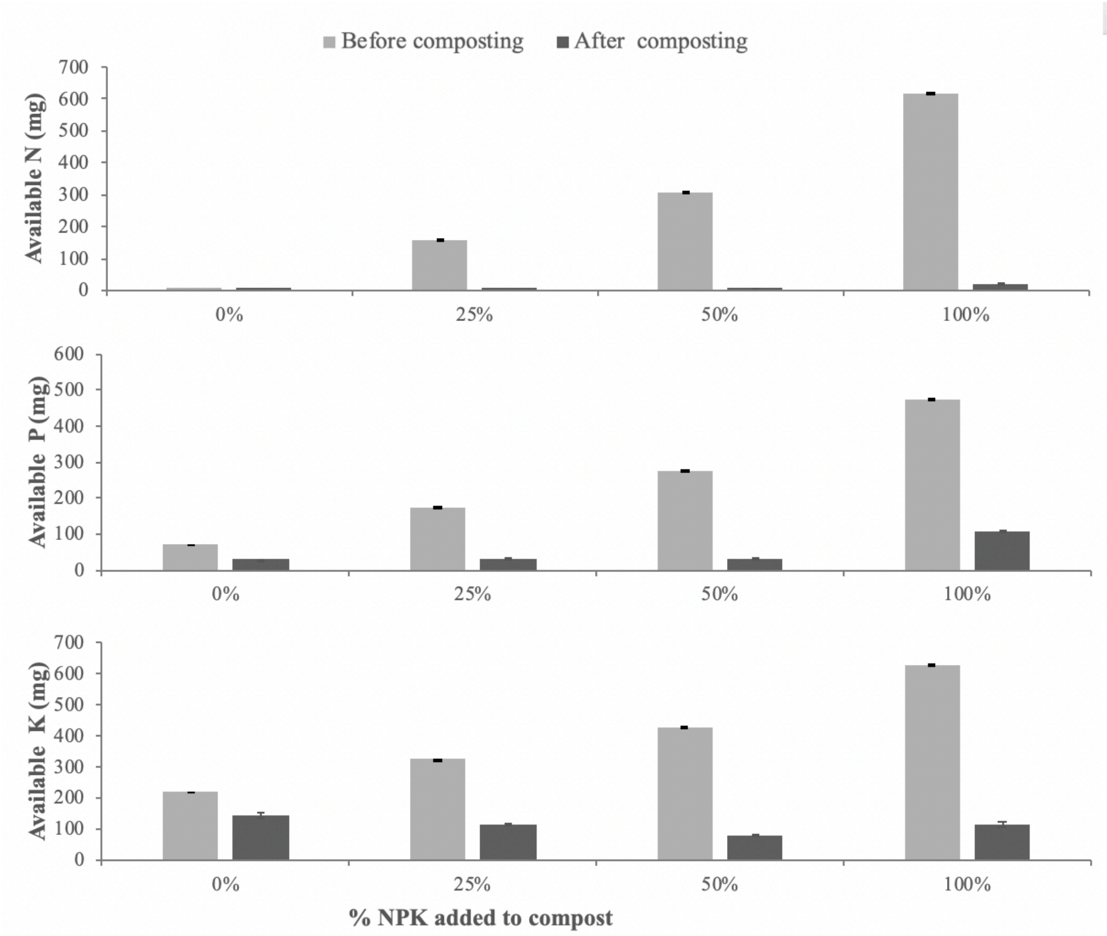

Figure 5-8: Quantity of available/mineral nutrients (N, P and K) added to each reactor both within the cocoa pod husks (CPHs) and as mineral fertilisers (applied at a rate of 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling), compared to the total quantity of available nutrients analysed in the composts produced after 14 weeks. n= 4, error bars are standard errors of the mean.

Table 5-4: Percentage efficiency of the composting process expressed in terms of the percentage (%) of total/available nutrients retained in the composted cocoa pod husks (CPHs), relative to the amount of total/available nutrients added to each reactor, both within the CPHs and as mineral fertilisers (applied at a rate of 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling). Mean values within the same row with different superscript letters indicate statistically significant differences between them (p<0.05). n = 4, values given to 3 significant figures ± standard deviation.

Nutrient	Compost only (0% NPK)	Compost with 25% NPK	Compost with 50% NPK	Compost with 100% NPK
Total N	108 ± 20^{a}	77.9 ± 1.2^{b}	47.8 ± 4.7^{c}	52.0 ± 5.5^{c}
Total P	80.7 ± 8.8^{a}	59.3 ± 3.6^{b}	37.1 ± 4.97^{c}	$48.7 \pm 3.9b^{c}$
Total K	65.4 ± 7.9^{a}	47.3 ± 2.0^{b}	28.6 ± 0.59^{d}	37.6 ± 0.65^{c}
Available N	36.4 ± 19^{a}	0.32 ± 0.09^{b}	1.07 ± 0.19^{b}	3.18 ± 0.12^{b}
Available P	42.7 ± 0.92^{a}	17.9 ± 1.8^{c}	11.5 ± 1.6^{d}	22.7 ± 1.5^{b}
Available K	68.0 ± 8.2^{a}	35.1 ± 1.9^{b}	18.6 ± 1.6^{c}	18.2 ± 3.0^{c}

The amount of total K in composts was in the order 0% > 25% > 100% > 50%. CPH composted with no mineral NPK resulted in the greatest amount of total K in the final compost and was also most efficient at retaining K, with 65% of the added K retained. Losses of K during the composting process were generally greater than N and P losses, indicating that the application of mineral K to CPH during the composting process is unnecessary. Indeed, CPH composted with the 50% NPK treatment contained the lowest amount of K of all the composts and retained only 29% of the K added to the reactor.

The amount of available N, P and K in composts was generally considerably lower than the amount of available/mineral N, P and K added to reactors (Figure 5-8). In the treatments where NPK was added to activate the composting process, available N, P and K was generally less than 5%, 25%, and 40% of the available/mineral N, P and K in the CPH and fertilisers added to the reactors, respectively (Table 5-4). This observation indicates that much of the N, P and K in the mineral fertilisers was immobilised in the microbial biomass/necromass or lost through leaching or volatilisation. The quantity of available N and P in the composts from the various NPK treatments was in the order 100% > 50% > 25% > 0%. The order for available K was 0% > 100% > 25% > 50%, but the proportion of available K in the compost relative to the available/mineral K added was in the order 0% > 25% > 50% > 100% (i.e. 68%, 35%, 19%, and 18%, respectively), indicating that the more K added, the lower is the proportion of this K that is immediately available to plants after composting.

5.3.9. **Chemical indicators of compost quality**

Table 5-5 reports the performance of each of the composts produced in this experiment against a range of compost quality indicators drawn from several acceptable standard indices (ASPC 2001, CCQC 2001, and TMECC 2002). Respiration rate for composts produced with every treatment, measured by CO_2 flux at 14 weeks was 0.58 µg C-CO2/g/h (0.014 mg C-CO2/g/d), below the acceptable upper limit, indicating that the composting process was complete and the final product stable. The pH of all composts produced were above the optimal range of 5-8, but had electrical conductivity (EC) values <6 mS/cm. The moisture content and organic matter content of CPH composts were higher than optimal (30-60% and 40-60% respectively). The C/N ratio of composts were within the optimal range of 10-25 for all composts produced except the compost produced without addition of mineral nutrients (the 0% NPK treatment), for which the C/N ratio was 27. However, the N content of all CPH compost were within the optimal range of 0.5-6.0%. P concentrations, except in the 0% NPK treatment, were also within the optimal range of 0.2-3.0%, but K content was slightly above the optimal range of 0.10-3.5% for all treatments.

Table 5-5: Compost quality indicators for composts produced from cocoa pod husks (CPHs) composted with 0%, 25%, 50% or 100% of the NPK requirement of a cocoa seedling, compared to the optimal range.

	Compost only (0% NPK)	Compost with 25% NPK	Compost with 50% NPK	Compost with 100% NPK	Optimal range[a]
CO_2 (mgC-CO_2/gOM/d)	0.01 *	0.01 *	0.01 *	0.01 *	<2
pH	10.5	10.8	10.5	10.3	5-8
EC (mS/cm)	3.04 *	4.96 *	4.88 *	5.79 *	<6
Moisture (%)	82.1	77.4	78.3	77.0	30-60
Org. matter (%)	75.0	75.0	76.5	73.9	40-60
C/N ratio	27.3	24.5*	21.1 *	18.4 *	10-25
N (%)	1.32 *	1.60 *	1.82 *	2.04 *	0.5-6.0
P (%)	0.156	0.333 *	0.489 *	0.819 *	0.2–3.0
K (%)	3.61	3.61	3.79	4.37	0.10–3.5

[a]Adopted from ASPC (2001), CCQC (2001), and TMECC (2002)

* within optimal range.

5.4. **Discussion**

5.4.1. **Quality and suitability of cocoa pod husk (CPH) compost for cocoa soils in Ghana.**

Generally, a good compost for agricultural use is one that is homogeneous with respect to nutrient concentrations, pathogen-free, has a tolerable smell, and is not toxic to plants (Bernal et al., 2017b; Crohn, 2016). A compost is considered stable when it is resistant to further decomposition (Crohn, 2016; Wichuk and McCartney, 2010). All the CPH composts produced in this experiment were below the maximum CO_2 flux standard specified by CCQC and TMECC, indicating that all the composts were stable after 14 weeks. In fact, the CO_2 flux data reported in Figure 5-2 indicates that the active composting period occurred within the first 4 weeks, followed by a 10-week period of maturity. This observation is supported by the change in colour and odour observed over the 14-week composting period. It is unlikely that the temperature during this laboratory incubation was sufficiently high for a long enough period of time to ensure effective pathogen suppression (Wichuk et al. 2007). However, Doungous et al. (2018) demonstrate considerable disease suppression of cocoa plants after application of CPH-based compost made using larger piles over a three-month period.

Determining the quality of compost depends on its intended use, which in this case is to be applied to cocoa soils as soil amendment. Important parameters such as a moisture content, organic matter content, C/N ratio and pH of the composts were measured to determine the composts produced meet the requirements for good cocoa crop development (Bernal et al., 2017b; Cooperband, 2002; Ozores-Hampton, 2017; Thompson et al., 2002). During composting, microbes use C from the organic matter as energy source and while approximately one third of the C is used together with N to build their cell structure (Brust, 2019), the rest is lost through CO_2 evolution during the microbial activity (Bernal et al., 2017; Chen et al., 2011), so as C is lost the C/N ratio of the substrate reduces. Except for CPH composted in the absence of NPK fertiliser to activate the composting process (i.e. the 0% NPK treatment), the C/N ratio of all CPH composts were within the optimal range of 10-25 (Table 5-5). Microorganisms have, on average, a C/N ratio of approximately 8 and require a C/N ratio of approximately 25 to metabolise organic amendments (Brust, 2019). Decomposition of composts with a C/N ratio greater than 25 (such as those produced in the 0% NPK treatment) results in immobilisation of inorganic N and a reduction in plant available N, while decomposition of residues with a C/N ratio lower than 25 (such as those produced in the 25%, 50% and 100% NPK treatments) results in N mineralisation and thus increases the plant available N. However, it has been reported that enough N is added to cocoa soils through litter decomposition and excess application stresses the crops; especially those under shade (Dawoe, Isaac, & Quashie-Sam, 2009; Hartemink, 2005; Snoeck et al., 2010). Therefore, CPH compost with a C/N ratio higher than 25 may still be suitable as an organic amendment for cocoa plantations, especially those grown under the shade of leguminous trees.

The concentration of K in all the composts produced was slightly greater than the ASCP nutrient content standard for agricultural use (Table 5-5). This is unsurprising since CPHs are known to contain high concentrations of K (Didier Snoeck, 2016; Simpson et al., 1985), although this is subject to a high degree of variability that depends on K availability in soils (van Vliet and Giller 2017). Ghanaian cocoa plantations are suspected of being deficient in K due to high quantities of K removed from soils in beans and husks without replacement (Appiah et al. 1997). Therefore, the high concentrations of K in CPH compost, when applied to cocoa plantation soils, helps to close the nutrient loop and prevent further deficiency.

Generally in composting pH lowers at the first stage as organic acids are produced but as the temperature rises, aerobic microbes take over and breakdown these organic acids and mineralise organic nitrogen, the pH rises but at a pH above 8.5, the possible precipitation of CO_3^{2-} lowers the pH again, so the finished composts is expected to be in a pH range between

5 and 8 (Beck-Friis et al., 2003; Bernal et al., 2017; Cáceres et al., 2018). All the CPH composts produced in this experiment had a pH between 10 and 11, and an organic matter content of about 75%, both of which were above the optimum range stipulated by ASCP, and accordingly may not have matured enough for agricultural use (ASCP, 2002). However, the soils of cocoa plantations in Ghana have low pH, low organic matter content and are inherently low in nutrients, particularly N, P and K (Asiamah, 2008; Bationo et al., 2018; Dossa et al., 2018a; Jayne et al., 2015; Snoeck et al., 2016) due to the removal of organic material (beans and husks) without replacement with sufficient nutrients to balance those removed. Where fertiliser is applied, acidifying fertilisers may exasperate acidity, especially in the Central and Eastern regions of Ghana (Kongor et al., 2018). Fertilisers that contain ammonium acidify the soil because when a plant root takes up an NH_4^+ ion, it releases a H^+ ion to balance its internal pH, resulting in the gradual build-up of H^+ in the soil over time. Therefore, high pH CPH-based compost amendments on these soils may help to raise both soil pH and OM levels as well as providing nutrients to improve cocoa nutrition.

5.4.2. **Co-composting cocoa pod husks (CPHs) with N, P and K fertiliser improves compost quality.**

The differences between the total amount of nutrients added to the reactors (both within the CPHs and as mineral fertilisers) and the amount analysed in the composts produced, taking into account the loss in dry matter (Figure 5-7), allows us to calculate the nutrient losses during the composting process (Table 5-4). Losses may have been due to leaching and/or volatilisation of nutrients, particularly in the case of N losses due to NH_3 volatilisation. Since the CPH composted in the absence of mineral fertilisers (the 0% NPK treatment) produced a compost that retained the greatest proportion of N in the final compost, which had the highest C/N ratio, we can conclude with a degree of certainty that the added mineral N was immobilised within the microbial biomass and that decomposition in this treatment was N limited (Dresbøll and Thorup-Kristensen, 2005).

Even though the use of C/N ratio as an indicator of compost maturity depends on the C/N ratios of the feedstock, in this context, it clearly demonstrates the effect of mineral NPK amendment on the rate and extent to which CPHs were degraded during the composting process. The application of mineral fertilisers acted as an ‘activator’ to increase the relative concentration of N for effective decomposition. Because CPH has a high C/N ratio of 52, more nitrogen is clearly required by the decomposing microbes in order to decompose it. Hence the CPH composted with 100% NPK resulted in the compost with the lowest C/N ratio (Figure 5-4). However, this treatment resulted in 48% of the N added being lost during the composting process (Table 5-4). By contrast, the CPH composted with 25% NPK resulted in 51% mass loss to produce a compost with a C/N ratio of 24 and losses of only 22% of the N applied.

Whereas the amount of P in the final compost increased with greater quantities of mineral P added, the opposite trend was observed for K (Figure 5-7). Higher rates of NPK resulted in lower quantities of total and available K (Figure 5-8) and a lower proportion of the added K in the compost (Table 5-4). Therefore, while recommendations can be made to include to add 25% mineral P to the CPH during the composting process, additions of K are not recommended. The relationship between NPK fertiliser co-amendment rate on the nutrient contents and availability in CPH composts (Figure 5-5, Figure 5-6, and Table 5-3) allows us to make broad predictions regarding the expected elemental composition of composts produced with different levels of NPK. This means that bespoke quantities of mineral N, P or K could be added to CPH prior to composting to ensure that the composition of the end product meets the nutrient requirements of different soil types identified across the different cocoa growing areas in Ghana, for which site specific fertiliser formulations have been suggested (Afrifa et al., 2009; Didier Snoeck, 2016; Snoeck et al., 2010b; van Vliet et al., 2015).

5.5. **Conclusion**

Composting is a suitable method for CPH waste recycling in cocoa plantations, especially when composted with low rates of NPK fertiliser. CPH, when composted with NPK mineral fertilisers, produced composts of a higher quality, according to international compost quality standards set by CCQC, TMECC and ASCP, compared to the composting of CPH without amendment. Composts with 0% NPK resulted in high C/N ratio and low nutrient content. By contrast, CPH composted with 100% NPK contained the lowest C/N ratio and the greatest amount of N and P. Compost produced from CPH and 50% NPK was the least efficient since the proportion of the added N, P and K retained in the final compost was lower than the other treatments. The 25% NPK compost treatment was the most efficient since, although less N and P was applied, this treatment produced a compost more N and P than the 50% NPK treatment. CPH composted with 0% NPK resulted in the highest total and available K quantities and the most efficient recovery of K, suggesting that CPH does not require mineral K amendment during composting.

Composting CPH with 25%, 50% or 100% N and P fertiliser additions will all produce a high-quality amendment for cocoa soils, but lower additions (i.e. 25%) of N and P are more efficient in terms of minimising nutrient losses. Further trials should be conducted at a larger scale because the composts produced in this experiment did not reach high thermophilic temperatures since only 400g of CPH was used in each 1L reactor and heat was quickly lost to the environment, hence pathogen suppression cannot be guaranteed. The composts' high pH and OM also suggest that a longer curing period may be needed. The CPH composts produced also had a high moisture content and so a bulking agent could be added to the CPH when composting or the final product air dried to lower moisture content for easier handling, as suggested by ASCP compost guidelines.

Chapter 6. EFFECTS OF COCOA POD HUSKS (CPH) COMPOSTS AND NPK ON THE GROWTH OF *THEOBROMA CACAO* SEEDLINGS.

6.1. **Introduction: Rationale and Hypothesis**

Ghanaian soils cropped to cocoa are known to be acidic, have a low soil organic matter content, and be deficient in soil nutrients. Efforts to improve the fertility of Ghanaian cocoa soils has been mainly through the use of inorganic fertilisers (Afrifa et al., 2009; Snoeck et al., 2010b; Snoeck et al., 2016; van Vliet et al., 2015). The use of inorganic fertilisers improves cocoa yields, however, continuous use of inorganic fertiliser may deplete SOM and increase soil acidity and therefore amendment with organic materials is necessary (Bationo and Fening, 2018). The scarcity of some organic materials, such as animal manure, can be a challenge because many cocoa farms are far from the sources of such material and their use as fertilisers for other crops leads to competition for resources. Cocoa pod husks (CPHs) are on-farm crop residues produced after pod harvesting and contain about ~1% N, ~0.3% P, ~ 5% K, ~0.5% Ca, and ~0.5% Mg that has been mined from the soil's nutrient stocks (Didier Snoeck, 2016; Hartemink, 2005; van Vliet et al., 2015). There is the potential for CPHs to contribute greatly to soil nutrient stocks if they are returned to the soils and release these nutrients so that they can become available to cocoa plants (Fontes et al., 2014; Hartemink, 2005; van Vliet et al., 2015). The current recommended practice is to burn or compost the husks before applying them to the soil to prevent the spread of fungal diseases (Munongo et al., 2017; Opoku-Ameyaw et al., 2010; van Vliet et al., 2015). Composting of CPHs is preferred to burning because nitrogen is lost through burning (van Vliet et al., 2015).

Composting CPHs alone is challenging because they have a high C/N ratio which slows the decomposition rate and prevents nutrient mineralisation after application. An integrated approach to the use of CPHs with inorganic fertilisers (mostly NPK) has been researched to assess the benefits of their combinations as opposed to their individual use (Fidelis and Rajashekhar Rao, 2017; Munongo et al., 2017; Ofori-Frimpong et al., 2010). However, optimal rates of NPK to be added either to the husks prior to composting (i.e. **co-composting**), or to the soil, alongside CPH compost (i.e. **co-amending**) is currently unknown. Since farmers have a limited supply of inorganic fertiliser and a limited supply of CPHs, it is not known whether optimal nutrient release and uptake by cocoa plants is best achieved by **co-composting** inorganic fertiliser CPH to create nutrient enriched CPH compost, or by **co-amending** soils with CPH compost and inorganic (NPK), applied separately. Hence, in this study nutrient release, plant performance, and plant nutrient uptake were assessed in cocoa seedlings amended with three rates of inorganic (NPK) fertiliser that was (i) **co-composted** with CPH, (ii) **co-amended** to the soil alongside CPH compost, or (iii) applied alone, without compost. It was hypothesised that **co-composting** CPH compost with NPK will ensure slow, consistent nutrient release and prevent leaching, resulting in good plant growth and improved soil quality, more so than **co-amending** soil with CPH and/or NPK applied as two separate amendments.

This study sought to provide answers to the following research questions:

I. Will nutrient release, plant growth, and nutrient uptake by plants be greater in fertilised soils than in unfertilised soils?
II. Will the effects in (I) be greater when CPH compost is **co-composted** or **co-amended** with inorganic (NPK) fertiliser than when compost or NPK are applied alone?
III. Does the method (i.e. **co-composting**, **co-amending**, or applying alone) and rate of NPK application significantly influence nutrient release, plant growth, and nutrient uptake by plants?
IV. Are there any significant interactions between the method and the rate of fertiliser application?

6.2. Methodology

6.2.1. Experimental set-up, treatments and design

The experiment was conducted in a greenhouse located in the Crops and Environment Laboratory at the University of Reading, UK. The temperature within the greenhouse was regulated to reach 20°C at night and 25-30°C during the day to suit the typical growing conditions of cocoa in Ghana. There were eleven treatments replicated five times and arranged in a randomised blocked design with the direction of the sun in the greenhouse used to align the blocks. The treatments are given in Table 6-1, and include CPH compost, three rates of NPK 50-100-50 and six CPH-NPK mixtures (i.e. the three rates of NPK **co-composted** or **co-amended** with CPH) and an unamended control treatment. The NPK was added or applied as Urea, triple superphosphate and potassium chloride mineral fertilisers. The rates were low (25%), medium (50%) and high (100%), representing 25%, 50% and 100% of the recommended NPK fertiliser dose for a single cocoa seedling (Bohórquez and Rodríguez, 2016), as described in Chapter 5. The CPHs were acquired from the International Cocoa

Quarantine Centre (ICQC) at the University of Reading and composted in aerated laboratory reactors for 14 weeks in a constant 30°C room in the Department of Environmental Science laboratory at the University of Reading, as described in Chapter 5.

Table 6-1: Description of treatments and rates of application

Treatment	Description	Application rate (g/pot)			
		Compost (g)	Urea	TSP	KCL
C	CPH compost applied alone	279	-	-	-
$CNPK_{high}$	CPH co-composted with 100% NPK	258	3.2	3.2	3.2
$CNPK_{med}$	CPH co-composted with 50% NPK	287	1.6	1.6	1.6
$CNPK_{low}$	CPH co-composted with 25% NPK	282	0.8	0.8	0.8
$C + NPK_{high}$	CPH compost co-amended with 100% NPK	241	3.2	3.2	3.2
$C + NPK_{med}$	CPH compost co-amended with 50% NPK	258	1.6	1.6	1.6
$C + NPK_{low}$	CPH compost co-amended with 25% NPK	263	0.8	0.8	0.8
NPK_{high}	100% NPK applied alone	-	3.2	3.2	3.2
NPK_{med}	50% NPK applied alone	-	1.6	1.6	1.6
NPK_{low}	25% NPK applied alone	-	0.8	0.8	0.8
Control	Soil only (unamended)	-	-	-	-

6.2.2. **Plant establishment**

Cocoa hybrid seeds (open pollinated progeny of the clone PA 107) were supplied by CRIG. These were pre-germinated and raised in a 1:2:2 (v/v) potting mixture of sand, gravel, and vermiculite (ratio 1:2:2) on 12th and 21st of June 2018 in the International Cocoa Quarantine Centre (ICQC) at the University of Reading. The seedlings were irrigated daily through a drip system with a modified Long-Ashton solution nutrient solution developed for cocoa at the University of Reading (chemical composition of the nutrient solution is listed in Table 6-2) that delivered required water and nutrients to the plants simultaneously. The solution is a mixture of two stock solutions added to water in a mixing tank in equal quantities until an E.C. of 2.0 mS is reached and then an acid solution is also added to attain a pH of 5.6. Seedlings were then transferred two months later to the greenhouse at the University of Reading to acclimatise to the conditions there before transplanting. The cocoa nutrient solution irrigation continued until the seedlings were transplanted into the treatment pots.

Table 6-2: Chemical composition of cocoa nutrient solution

Stock solution 1 (dissolve in 240L water)	Stock solution 2 (dissolve in 240L water)	Acid solution (mixed in 80 litres water)
Potassium Nitrate (KNO_3) (6048g) Ammonium Nitrate (NH4NO3) (5.5L)	Potassium Sulphate (K2SO4) (1680g) Magnesium Sulphate (MgSO4) (3312g) Potassium dihydrogen phosphate (KH2PO4) (2112g) EDTA (480g) Nitric acid (500 ml) Micronutrients: Boric acid (H3BO3) (120g) Manganous sulphate (MnSO4) (68g) Zinc sulphate (324g) Ammonium molybdate (10.4g) Copper sulphate (9.6g)	Nitric acid (2.5L) Orthophosphoric acid (1.25L)

Soil was constituted from 70% sand, 20% kaolinite clay and 10% cocopeat (De Silva and van Gestel, 2009) to mimic the typical texture of soils suitable for establishing cocoa in Ghana. 55 labelled pots (3 L) were each filled with 2 kg of the constituted soil. The compost treatments were thoroughly mixed individually with the soil before being transferred to their respectively labelled pots. 55 healthy plants, each of a similar size, were selected and transplanted into the pots in September 2018. There were two seed sowing dates, one week apart, so plants selected for each treatment had 2 slightly older plants and 3 slightly younger ones. The fertiliser treatments (Table 6-1) were then applied to their respective plants. Watering was done three times in a week in the mornings through a drip irrigator set to deliver 200 ml/min to each pot. Moisture content was monitored with a ProCheck soil water meter (Edaphic Scientific).

The seedlings became infested with spider mites two weeks after planting. Biological control in the form of Anderline AA sachets produced by Bioline AgroSciences containing predatory mites (*Amblyseius andersoini*) were used to control the infestation throughout the six months growing period. Control was gradual but the spider mite population subsided over time.

6.2.3. Plant Data collection

Plant height and girth, as well as photosynthetic rate, chlorophyll fluorescence and total chlorophyll content were measured and recorded on day one of transplanting and then monthly until plants were harvested six months later. Photosynthetic rate was measured with LCpro-SD portable infrared gas analyser (ADC Bioscientific Ltd). Chlorophyll fluorescence was measured with a chlorophyll fluorometer (Handy PEA, Hansatech instruments) on dark adapted leaves with leaf clips beforehand. Total chlorophyll content was measured with chlorophyll meter (Hansatech instruments). These three parameters were measured on the youngest hardened fully matured leaf on each plant.

Seedlings were harvested six months after they were transplanted, and the biomass of each plant was separated into stems, leaves, petioles and roots. The stem was cut off first at the base, then the leaves and petioles were severed off the stem using secateurs. Total leaf area per plant was measured using a WinDIAS 3 Leaf Area Meter (Delta-T Devices Ltd.). The roots were then carefully taken out of the soil, washed thoroughly to remove any loose soil and dabbed with soft paper towels to remove any apparent moisture. The stems, leaves, petioles and roots were weighed immediately to determine their fresh weight. They were then dried in an oven at 70°C for 48 hours and re-weighed to determine their dry weight.

The dry leaves were milled and analysed to determine their total nutrient concentrations (P, K, Ca, Mg, Mn, Cu and Zn). 0.5g of the milled samples were digested with nitric acid in a MARS 6 microwave digestion system, filtered, and analysed with Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Samples were also analysed for their total carbon and total nitrogen contents using the Dumas combustion method with a Thermo Scientific Flash 2000 Organic Elemental Analyser. Plant leaf nutrient uptake was calculated as the product of the leaf nutrient concentration and its dry weight.

6.2.4. **Soil Data collection**

Soil moisture content was determined gravimetrically by calculating the difference in mass before and after heating at 105 °C for 24 hours. pH and electrical conductivity were measured with pH and EC meters respectively in a 1:2.5 soil-water slurry. Soil organic matter was determined by loss on ignition at 500 °C. Soil available nutrients before and after the experiment were determined. Available N (NO_3-N and NH_4-N) was extracted with KCL solution and analysed on Skalar SAN^{++} continuous flow analyser. Available P, K, Ca, Mg, Mn, Fe, Cu and Zn were extracted with a Mehlich 3 extractant and analysed with ICP-OES.

6.2.5. **Data Analyses**

Data was analysed using the Genstat Statistical Package. Leaf P concentration, plant height, dry shoot weight and total biomass data were each subjected to log10 transformations to achieve normality. Analysis of Variance (ANOVA) was used with the treatment structure "Fertiliser/Compost/Inorganic fertiliser/(Method*Rate)" whereby the method (i.e. **co-composting** or **co-amending**) of mixing inorganic fertiliser with CPH and the rate (i.e. 25%, 50% and 100% of the recommended NPK fertiliser dose for a single cocoa seedling) of inorganic fertiliser applied are nested within main fertiliser effects. Repeated measures ANOVA was employed, using the same treatment structure, to analyse differences in chlorophyll fluorescence, chlorophyll content, and photosynthetic rates measured monthly for six months. Dunnett's method of comparison was employed to compare the effects of CPH compost (with and without inorganic fertiliser co-composting or co-amendment) with the application of inorganic fertiliser alone or to the control treatment. Tukey's method was used for pairwise multiple comparisons between and within treatments grouped according to method and rate of fertiliser additions. Linear correlation and linear regression analysis were employed to draw relationships between soil parameters and plant growth, physiological, nutrient uptake and accumulation in leaves and dry biomass production.

6.3. **Results**

6.3.1. **Chemical assessment of composts and soil before experiment initiation**

Chemical analysis of CPH composts and soil indicated that all CPH composts types were alkaline while the soil that was to be amended was slightly acidic and had a relatively lower electrical conductivity (Table 6-3). CPH composts had a very high organic matter and nutrient contents compared to that of the soil.

Table 6-3: Physicochemical properties of CPH (C), CPH co-composted with NPK at high (100%), medium(50%) and low (25%) rates, and soil prior to amendment. (n=3, +/- standard error of means)

	C	$CNPK_{low}$	$CNPK_{med}$	$CNPK_{high}$	Soil
pH	10.54 ± 0.05	10.76 ± 0.0	10.52 ± 0.0	10.32 ± 0.0	6.35 ± 0.0
EC (mS)	3.04 ±0.02	4.96 ± 0.5	4.88 ±0.16	5.79 ±0.32	0.23 ± 0.0
% OM	74 ±2.01	75 ± 1.30	77 ±0.37	74 ± 0.13	3 ± 0.0
C/N	17 ± 0.0	17 ± 0.0	15 ± 0.0	13 ± 0.0	-
%N	2.34 ± 0.01	2.34 ± 0.01	2.60 ± 0.03	2.93 ± 0.0	0.1± 0.0
%P	0.52 ± 0.01	0.69 ± 0.01	0.86 ± 0.03	1.22 ± 0.0	0.1± 0.0
%K	7.05 ± 0.0	6.67 ± 0.0	7.50 ± 0.0	7.89 ± 0.02	0.08 ± 0.0
%Ca	0.54 ± 0.07	0.61± 0.04	0.75 ± 0.04	0.95± 0.0	0.09± 0.0
%Mg	0.33 ± 0.0	0.31± 0.0	0.30 ± 0.01	0.29 ± 0.01	0.001± 0.0

6.3.2. Effects of CPH compost and NPK fertiliser on the soil properties

At the end of the experiment, soil analyses showed significant differences between fertilised and unfertilised (control) soils for P, K, Mg and Zn with concentrations being higher in the former than in the latter (Table 6-4 and Table 6-5). However, no significant differences were observed between treatments in soil available N, Ca, Fe and Cu. The C + NPK_{med} treatment recorded the highest available K concentration at 406 mg/kg and $CNPK_{high}$ the highest available P concentration at 108mg/kg (Figure 6-1, Table 6-4). Soils amended with compost treatments (C and CPH **co-composted** or **co-amended** with NPK) had significantly higher available P, K, Mg, Fe and Zn but lower available Cu, compared to the NPK alone treatments. Adding mineral fertiliser (NPK) to CPH or the method of addition did not have any significant impact on soil nutrient availability, but the rate applied had a significant impact on available P concentration ($p<0.05$) (Table 6-5).

The mean pH, electrical conductivity (EC), organic matter (OM) and water holding capacity (WHC) of soils fertilised with CPH, NPK, or both, was significantly greater than the control soil (Figure 6-1, Table 6-5). Furthermore, soil amended with composts (CPH only and CPH **co-composted** or **co-amended** NPK) also had significantly greater cation exchange capacity (CEC) and base saturation (BS) than soils treated with NPK fertiliser alone (Figure 6-1, Table 6-5). There was no significant difference between **co-composting** or **co-amendment** of CPH and NPK for any of the available nutrients measured.

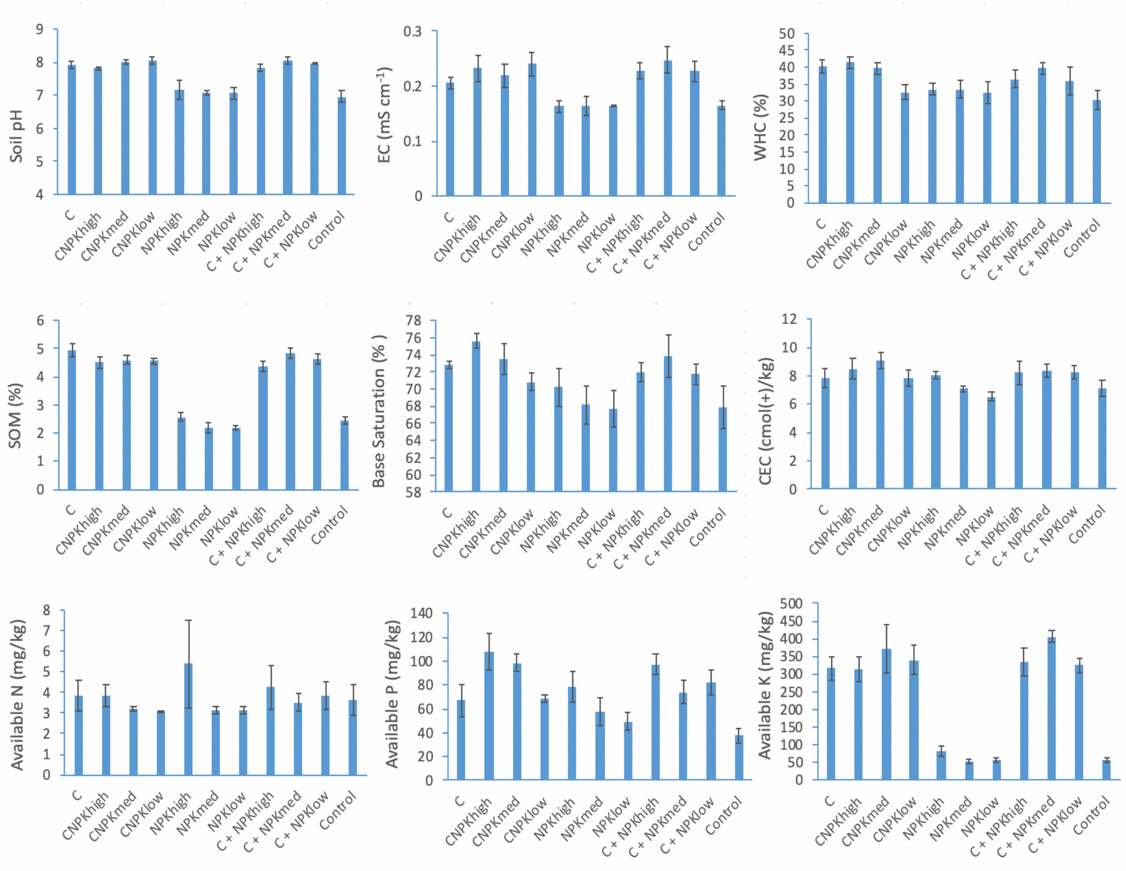

Figure 6-1: pH, Electrical Conductivity, Moisture content, Organic Matter, Base Saturation, Cation Exchange Capacity and Available nutrient concentrations of soils amended with CPH compost, inorganic (NPK) fertiliser at high (100%), medium (50%) and low (25%) rate, or the CPH compost co-composted or co-amended with the inorganic fertiliser, alongside unamended soil (control). Error bars are standard error of means, n=11.

Table 6-4: Mehlich III extractable soil nutrients (mg/kg) of soils amended with CPH compost, inorganic (NPK) fertiliser at high (100%), medium (50%) and low (25%) rate, or the CPH compost co-composted or co-amended with the inorganic fertiliser, alongside unamended soil (control). (mean plus/minus standard error of the means, n=5)

Treatment	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
C	3.87 ± 0.76	67 ± 13	317 ± 32	816 ± 84	98 ± 7	91 ± 10	3.29 ± 0.22	7.42 ± 1.16
$CNPK_{high}$	3.86 ± 0.56	108 ± 15	315 ± 35	951 ± 98	104 ± 8	82 ± 7	4.16 ± 0.22	7.51 ± 1.78
$CNPK_{med}$	3.21 ± 0.11	98 ± 7	373 ± 68	958 ± 85	114 ± 8	97 ± 8	4.13 ± 0.46	7.36 ± 0.72
$CNPK_{low}$	3.06 ± 0.04	68 ± 3	340 ± 41	773 ± 50	93 ± 8	88 ± 2	3.99 ± 0.34	6.51 ± 0.61
C + NPK_{high}	4.27 ± 1.07	97 ± 8	334 ± 37	834 ± 89	106 ± 9	80 ± 4	3.37 ± 0.44	6.95 ± 0.51
C + NPK_{med}	3.51 ± 0.41	74 ± 10	406 ± 17	849 ± 89	111 ± 9	77 ± 6	3.53 ± 0.32	5.99 ±0.49
C + NPK_{low}	3.82 ± 0.67	82 ± 10	325 ± 22	843 ± 52	102 ± 6	84 ± 4	3.56 ± 0.23	6.87 ±0.68
NPK_{high}	3.26 ± 0.17	78 ± 13	84 ± 14	986 ± 40	58 ± 3	78 ± 6	4.71 ± 0.46	5.61 ± 0.80
NPK_{med}	3.14 ± 0.21	58 ± 12	53 ± 6	853 ± 27	51 ± 3	81 ± 10	4.60 ± 0.20	5.41 ± 0.75
NPK_{low}	3.13 ± 0.19	49 ± 8	56 ± 6	777 ± 51	48 ± 3	66 ± 5	4.24 ± 0.34	5.34 ± 0.57
Control	3.63 ± 0.76	38 ± 6	56 ± 7	856 ±101	50 ± 3	75 ±5	4.59 ± 0.92	4.29 ± 0.79

Table 6-5: Analysis of variance table comparing the fertilising effects of CPH composts and NPK fertiliser (including methods and rates of application) on available nutrients, soil pH, electrical conductivity, organic matter (OM) and moisture content (MC) at a 0.05% level of significance. No method and rate interaction effects were detected in any of the observed parameters

Source of variation	d.f.	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Fertiliser	1	0.756	<0.001	<0.001	0.919	<0.001	0.295	0.161	<0.05
Compost	1	0.193	<0.001	<0.001	0.824	<0.001	<0.05	<0.001	<0.05
Inorganic fertiliser	1	0.702	0.058	0.324	0.515	0.354	0.381	0.287	0.561
Method of application	1	0.302	0.369	0.614	0.393	0.618	0.128	0.087	0.469
Rate of application	4	0.823	<0.05	0.202	0.211	0.187	0.456	0.95	0.967
Method/Rate interaction	2	0.998	0.166	0.707	0.365	0.686	0.265	0.914	0.619

Source of variation	d.f.	pH	EC ($mScm^{-1}$)	%SOM	CEC (cmol/kg)	%BS	%WHC
Fertiliser	1	<0.001	<0.01	<0.01	0.15	0.69	<0.05
Compost	1	<0.001	<0.001	<0.001	<0.01	<0.001	<0.01
Inorganic fertiliser	1	0.87	0.138	0.077	0.35	0.16	0.07
Method of application	1	0.954	0.783	0.668	<0.05	<0.05	0.13
Rate of application	4	0.553	1	0.94	0.27	0.38	0.33
Method/Rate interaction	2	0.862	0.409	0.99	0.99	0.99	0.96

6.3.3. **Effects of CPH compost and NPK on cocoa plant physiology, growth and biomass production.**

Figure 6-2 and Figure 6-3 show fluctuating patterns in chlorophyll florescence (CF), chlorophyll contents (CC) and Figure 6-4 shows similar fluctuations in the photosynthetic rates (PR) of most seedlings observed over the six-month growing period. Generally, CF for all treatment means declined after the 2nd month of transplanting, increased in the 4th month and then declined again in the 6th month. CC for all observations generally declined steadily over the growing period. PR for the control remained relatively stable as the treatment means declined in the 3rd month and increased through the 4th to the 5th month, but in the 6th month all treatments plus the control decreased (Figure 6-4). There were no significant differences in CF, CC and PR between the fertilised treatment means and the control (Table 6-6). Neither organic (CPH compost) nor inorganic (NPK) fertiliser, nor their mixtures had any effects on the monthly recorded physiological parameters, except in the 4th and 5th months where **co-composting** method of adding NPK increased CC in plants they were amended with (Table 6-6).

Table 6-6: Analysis of variance comparing the fertilising effects of CPH composts and NPK fertiliser (including methods and rates of application) on chlorophyll fluorescence (Fv/Fm), chlorophyll content (µg/g/cm2) and photosynthesis rate(µmol/m/s) at a 0.05% level of significance. No method and rate interaction effects were detected in any of the observed parameters

Source of variation	d.f.	Chlorophyll Fluorescence (Fv/Fm)	Chlorophyll Content (µg/g/cm2)	Photosynthetic rate (µmol/m/s)
Month	4	p<0.001	p<0.001	p<0.001
Fertiliser	4	0.934	0.597	0.187
Compost	4	0.864	0.463	0.134
Inorganic fertiliser	4	0.137	p<0.05	0.352
Method of application	8	0.727	0.29	0.497
Rate of application	8	0.649	0.263	0.498
Method/Rate interaction	16	0.616	0.974	0.685

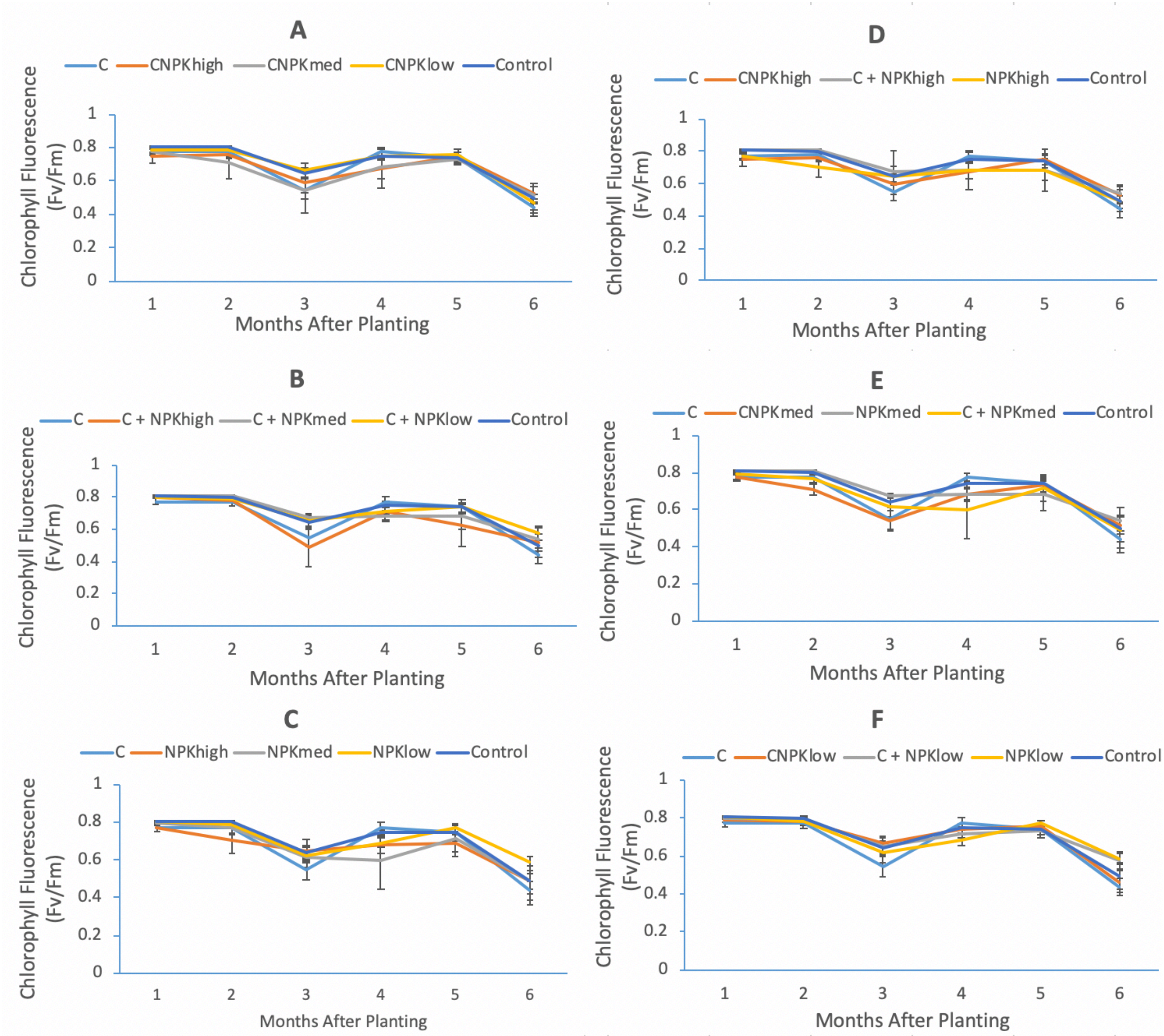

Figure 6-2: Chlorophyll fluorescence of cocoa seedlings observed over the six months growing period. Error bars are standard error of means, n=5

Note:

A= comparison between treatments where NPK was co-composted with CPH ($CNPK_{low}$, $CNPK_{med}$ and $CNPK_{high}$), alongside the control (C) and CPH compost only treatments.

B= comparison between treatments where NPK was co-amended with CPH (C + NPK_{low}, C + NPK_{med} and C + NPK_{high}), alongside the control (C) and CPH compost only treatments.

C= comparison between inorganic (NPK) fertiliser application rates (NPK_{low}, NPK_{med}, and NPK_{high}), alongside the control (C) and CPH compost only treatments.

D= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the high (100%) rate of application, alongside the control (C) and CPH compost only treatments.

E= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the medium (50%) rate of application, alongside the control (C) and CPH compost only treatments.

F = comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the low (25%) rate of application, alongside the control (C) and CPH compost only treatments.

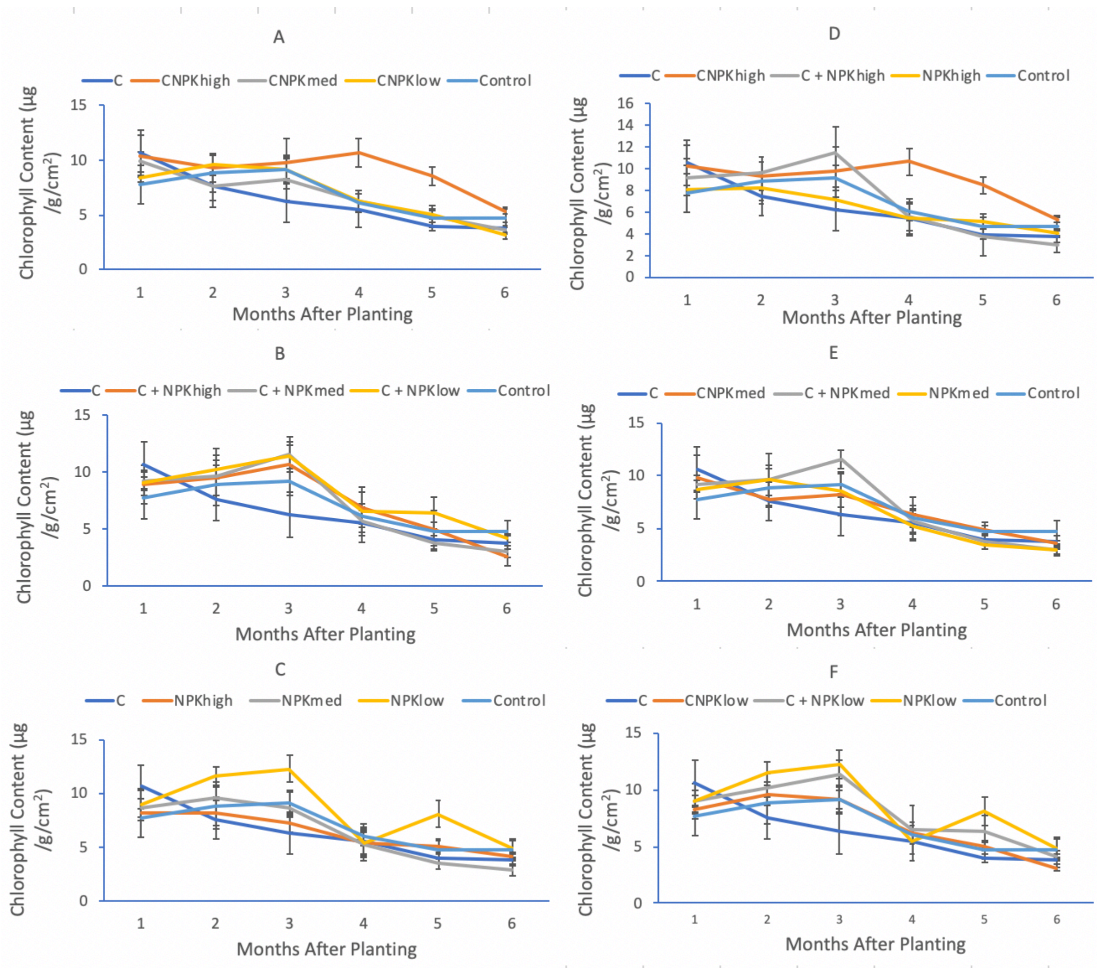

Figure 6-3: Chlorophyll content of cocoa plants seedlings observed over the six months growing period. Error bars are standard error of means, n=5.

Note:

A= comparison between treatments where NPK was co-composted with CPH ($CNPK_{low}$, $CNPK_{med}$ and $CNPK_{high}$), alongside the control (C) and CPH compost only treatments.

B= comparison between treatments where NPK was co-amended with CPH (C + NPK_{low}, C + NPK_{med} and C + NPK_{high}), alongside the control (C) and CPH compost only treatments.

C= comparison between inorganic (NPK) fertiliser application rates (NPK_{low}, NPK_{med}, and NPK_{high}), alongside the control (C) and CPH compost only treatments.

D= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the high (100%) rate of application, alongside the control (C) and CPH compost only treatments.

E= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the medium (50%) rate of application, alongside the control (C) and CPH compost only treatments.

F = comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the low (25%) rate of application, alongside the control (C) and CPH compost only treatments.

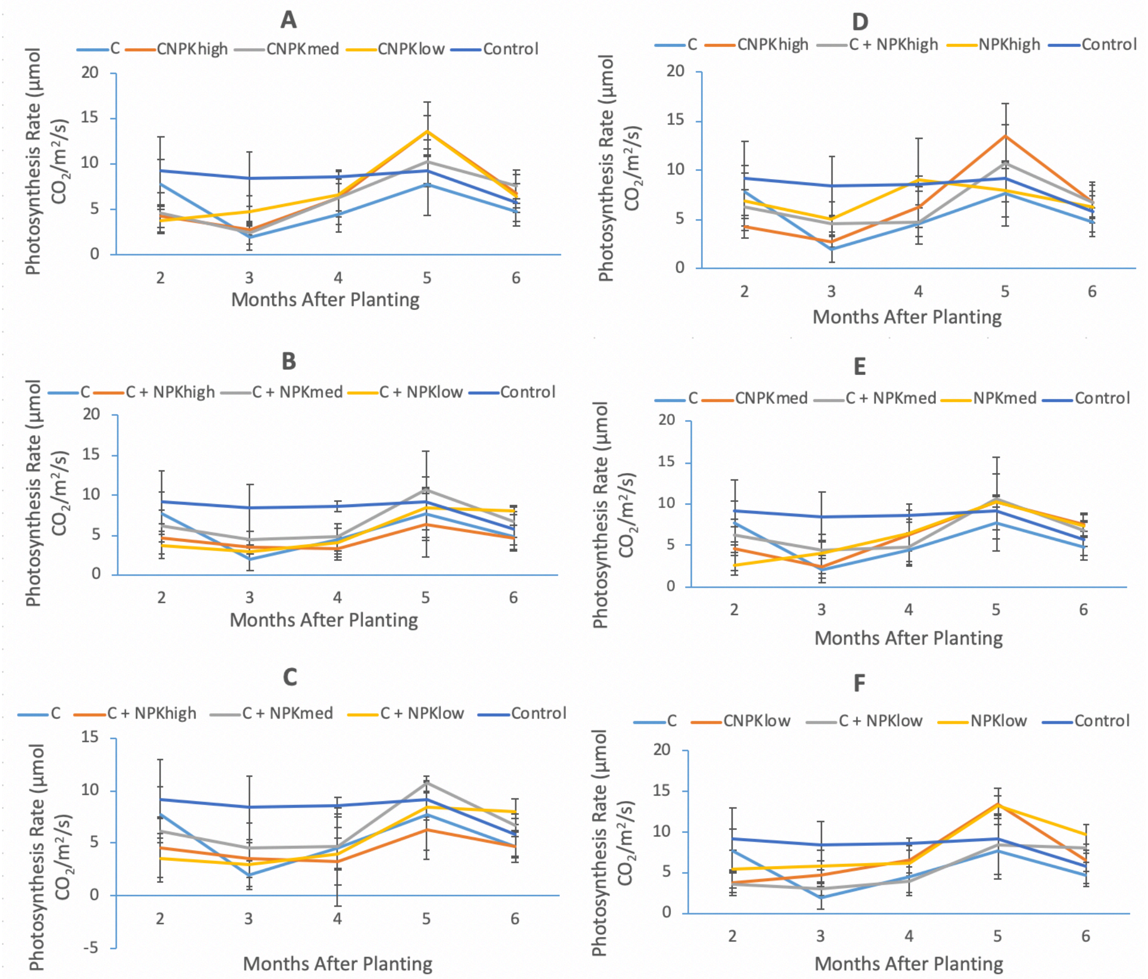

Figure 6-4:Photosynthetic rate of cocoa seedlings observed over the six months growing period. Error bars are standard error of means, n=5.

Note:

A= comparison between treatments where NPK was co-composted with CPH ($CNPK_{low}$, $CNPK_{med}$ and $CNPK_{high}$), alongside the control (C) and CPH compost only treatments.

B= comparison between treatments where NPK was co-amended with CPH (C + NPK_{low}, C + NPK_{med} and C + NPK_{high}), alongside the control (C) and CPH compost only treatments.

C= comparison between inorganic (NPK) fertiliser application rates (NPK_{low}, NPK_{med}, and NPK_{high}), alongside the control (C) and CPH compost only treatments.

D= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the high (100%) rate of application, alongside the control (C) and CPH compost only treatments.

E= comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the medium (50%) rate of application, alongside the control (C) and CPH compost only treatments.

F = comparison between co-composting (CNPK), co-amendment (C + NPK) and NPK applied alone (NPK) at the low (25%) rate of application, alongside the control (C) and CPH compost only treatments.

Apart from when comparing the unamended control treatment to plants grown in soils to which CPH compost and/or inorganic (NPK) fertiliser was applied none of the experimental treatments significantly influenced the growth parameters measured (Table 6-7 and Table 6-8). Compared to the control, the application of compost and/or inorganic fertiliser significantly reduced the change in plant stem girth, shoot weight, root biomass, and total biomass. Differences were not found between mean leaf biomass produced by plants grown in control pots and that produced by plants in other soil amendment pots Inorganic fertiliser, including its method and rate of application did not cause any significant change in any of the growth parameters or in the total biomass produced, including leaf and root biomass.

Table 6-7: Growth parameters and dry weight biomass of cocoa plants grown of soils amended with CPH compost, inorganic (NPK) fertiliser at high (100%), medium (50%) and low (25%) rate, or the CPH compost co-composted or co-amended with the inorganic fertiliser, alongside unamended soil (control). (means of five replicates +/- mean standard errors).

Treatment	Change in Plant Height (cm)	Change in girth (cm)	leaf area (cm^2)	Leaf count	Leaf biomass (g)	shoot weight (g)	Root Biomass (g)	total biomass (g)
C	1.63 ± 0.24	2.78 ± 0.81	346 ± 103	6 ± 0.3	1.44 ± 0.52	1.68 ± 0.25	2.64 ± 0.62	5.89 ±0.89
$CNPK_{high}$	0.65 ± 0.32	2.30 ± 0.27	401 ± 106	8 ± 0.8	2.20 ± 0.74	1.61 ± 0.37	2.18 ± 0.67	3.96 ± 1.21
$CNPK_{med}$	0.37 ± 0.03	3.01 ± 0.74	473 ± 131	7 ± 1.3	1.96 ± 0.56	1.54 ± 0.49	3.83 ± 0.49	7.05 ± 1.74
$CNPK_{low}$	3.00 ± 0.61	2.42 ± 0.99	616 ± 115	5 ± 0.9	1.89 ± 0.54	1.68 ± 0.44	2.81 ± 1.43	4.80 ± 1.43
C + NPK_{high}	0.63 ± 0.16	1.47 ± 0.45	370 ± 150	5 ± 1.6	1.41 ± 0.58	2.26 ± 0.69	1.74 ± 0.58	4.33 ± 1.41
C + NPK_{med}	0.40 ± 0.13	2.44 ± 0.57	359 ± 117	6 ± 1.5	1.24 ± 0.39	1.36 ± 0.32	2.35 ± 0.35	4.08 ± 1.29
C + NPK_{low}	0.63 ± 0.33	3.09 ± 1.14	591 ± 149	8 ± 0.8	3.02 ± 0.17	1.77 ± 0.15	3.17 ± 1.60	6.41 ± 2.38
NPK_{high}	1.05 ± 0.25	2.26 ± 1.04	801 ± 164	9 ± 1.3	2.60 ± 0.51	1.13 ± 0.34	2.27 ± 0.94	3.82 ± 1.18
NPK_{med}	1.38 ± 0.31	2.33 ± 0.95	604 ± 217	11 ± 1.8	2.50 ± 0.93	1.39 ± 0.15	2.35 ± 1.16	5.19 ± 1.43
NPK_{low}	1.18 ± 0.25	2.15 ± 0.53	537 ± 169	6 ± 0.9	2.68 ± 0.43	2.15 ± 0.71	2.66 ± 0.36	6.81 ± 1.00
Control	0.88 ± 0.21	4.18 ± 1.18	699 ± 101	10 ± 1.6	2.92 ± 0.48	3.79 ± 1.36	2.24 ± 0.19	6.32 ± 0.06

Table 6-8: Analysis of variance for the effects of CPH compost and inorganic (NPK) amendments on growth parameters at a 0.05% level of significance. No method and rate interaction effects were detected in any of the observed parameters

Source of variation	d.f	Change in girth (cm)	Change in height (cm)	Leaf area (cm^2)	Leaf number
Fertiliser	1	<0.05	0.23	0.187	0.096
Compost	1	0.68	0.635	0.248	0.409
Inorganic fertiliser	1	0.848	0.5	0.203	0.925
Method of application	1	0.591	0.483	0.675	0.952
Rate of application	4	0.71	0.669	0.777	0.779
Method/Rate interaction	2	0.509	0.538	0.599	0.268
Source of variation	**d.f**	**Leaf Biomass (g)**	**Shoot weight (g)**	**Root Biomass (g)**	**Total Biomass (g)**
Fertiliser	1	0.093	<0.01	<0.05	<0.001
Compost	1	0.303	0.627	0.98	0.453
Inorganic fertiliser	1	0.302	0.873	0.821	0.678
Method of application	1	0.669	0.914	0.975	0.89
Rate of application	4	0.846	0.695	0.796	0.6
Method/Rate interaction	2	0.481	0.713	0.953	0.654

6.3.4. **Effects of CPH compost and NPK amendment on leaf nutrient concentrations and uptake**

Mean nitrogen and potassium concentrations in leaves of plants grown in soils fertilised with CPH compost and/or inorganic (NPK) fertiliser were significantly greater than soils with no fertiliser applied (Figure 6-5, Table 6-9). Plants in unfertilised pots had the lowest N (1.36%) and K (2%) concentrations in leaves while leaves from plants grown in soil amended with the high rate of inorganic (NPK) fertiliser alone (NPK_{high}) had the highest N concentration of 1.89%. Soils **co-amended** with the CPH compost and the medium rate of inorganic (NPK) fertiliser ($C + NPK_{med}$) had the highest K concentration of 4%. No such differences were observed between treatments for leaf phosphorus concentrations. Leaf P concentration in plants fertilised with CPH compost, with or without inorganic (NPK) were not significantly different from those that received only the inorganic (NPK) fertiliser (Figure 6-5). Although the method of used or the rate of NPK fertiliser did not significantly affect N and P concentrations in leaves, **co-amendment** of NPK with CPH compost significantly increased K leaf concentration in plants ($p<0.001$), compared to **co-composting**. The optimum recommended cacao leaf nutrient thresholds according to (Snoeck et al., 2016) are to be within 1.8%–2.5% for N, 0.17%–0.25% for P and 1.2%–2.4% for K. Leaf N concentrations in all treatments (Figure 6-5) apart from NPK_{high} were below its recommended threshold indicating that N was deficient in the growth media. Leaf P concentrations for all treatments were within the recommended optimum thresholds while leaf K was above its optimum for all treatments except for NPK_{med}, NPK_{low} and control. Nutrient uptake of N, P and K by leaves of control and fertilised plants were not significantly different. Adding fertiliser, whichever method or rate did not make any difference to the total amount of nutrients taken up by the cocoa leaves (Table 6-9).

Table 6-9: Analysis of variance for the effects CPH compost and inorganic (NPK) amendments on leaf nutrient concentrations and uptake

Source of variation	d.f.	Leaf N (%)	Leaf P (%)	Leaf K (%)	N uptake (mg/pot)	P uptake (mg/pot)	K uptake (mg/pot)
Fertiliser	1	<0.05	0.325	<0.001	0.326	0.275	0.901
Compost	1	0.694	0.763	<0.001	0.121	0.081	0.768
Inorganic fertiliser	1	0.731	0.954	0.627	0.138	0.145	0.074
Method of application	1	0.069	<0.05	<0.01	0.796	0.78	0.958
Rate of application	4	0.371	0.206	0.362	0.384	0.613	0.649
Method/Rate interaction	2	0.895	0.276	<0.01	0.309	0.656	0.726

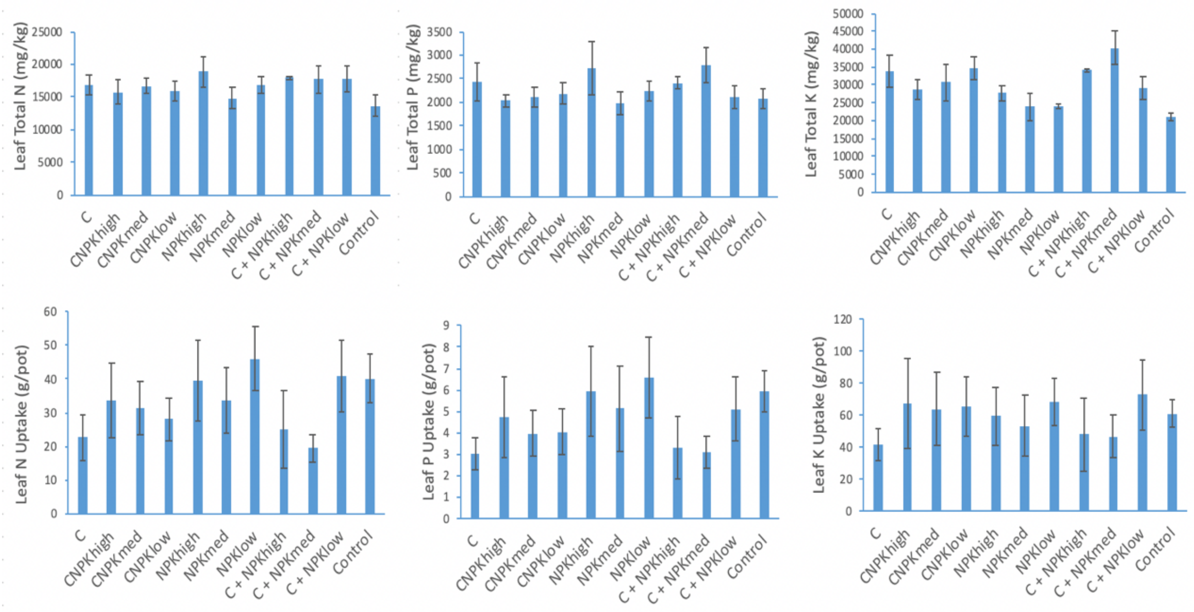

Figure 6-5: Leaf nutrient concentrations (mg/kg) and uptake (g/pot) of cocoa seedlings grown in soils amended with CPH compost, inorganic (NPK) fertiliser at high (100%), medium (50%) and low (25%) rate, or the CPH compost co-composted or co-amended with the inorganic fertiliser, alongside unamended soil (control).. Error bars are standard error of means, n=5

6.3.5. Relationship between soil properties, plant physiology, growth, nutrient uptake and leaf nutrient concentration

A linear regression analysis (Table 6-10) demonstrated that soil moisture content was significantly positively related to plant growth, physiology, dry biomass production and negatively related to nutrient uptake. Soil moisture content also accounted for very small amount of the variation in chlorophyll fluorescence (R^2 =13; p<0.001) and photosynthesis rate (R^2 =22; p<0.01) over the six-month growing period. Soil pH was significantly negatively related to plant growth, physiology, dry biomass production and nutrient uptake but accounted for a relatively small amount of the variation in these parameters (Table 6-10). BS also had a slight but significant negative association with photosynthetic rate (R^2 =11; p<0.05) and uptake of N and P (R^2 =17; p<0.01 and R^2 =17; p<0.01 respectively) and likewise, CEC affected leaf biomass and N uptake (R^2 =11; p<0.05, R^2 =17; p<0.01).

The amount of K contained in leaves was positively but weakly affected by soil available K (R^2 =38; p<0.0001) and to a lesser extent by available P (R^2 =11; p<0.05) (Table 6-10). Apart from these effects, available N, P and K did not have any effects on plant growth, physiology, nutrient uptake, or biomass production.

Table 6-10: Linear regression analysis showing the relationship between soil properties on plant physiology, growth, nutrient uptake and nutrient concentration in leaf at a p<0.5 significant level.

Dependent Parameter	% Moisture Content	
	R^2	p-value
Chlorophyll Fluorescence (Fv/Fm)	0.13	<0.001
Photosynthetic rate (μmol $CO2m^{-2}s^{-1}$)	0.22	<0.01
leaf area (cm^2)	0.43	<0.001
Change in girth (cm)	0.16	<0.01
Change in height (cm)	0.24	<0.001
Leaf biomass(g)	0.52	<0.0001
Shoot biomass (g)	0.45	<0.0001
Root biomass (g)	0.39	<0.0001
Total biomass (g)	0.47	<0.0001
Leaf N uptake (mg/pot)	0.58	<0.001
Leaf P uptake (mg/pot)	0.47	<0.01
Leaf K uptake (mg/pot)	0.55	<0.01
Dependent Parameter	**pH**	
	R^2	p-value
Shoot biomass (g)	0.21	<0.05
Above ground biomass	0.28	<0.001
Dependent Parameter	**Available K ($mgkg^{-1}$)**	
	R^2	p-value
Leaf K (mg)	0.38	<0.00001

6.3.6. Soil nutrient status of CPH and NPK amended and unamended soils comparing with lower and upper thresholds recommended by Snoeck et al (2016).

All the soils amended with CPH compost (with and without inorganic (NPK) fertiliser) had soil K levels above the Snoeck et al (2016) upper threshold value of 150 mg/kg (Table 6-11). However, NPK_{med} and NPK_{low} soils, as well as unfertilised (Control) soils, were below the lower K threshold. For P, soils amended with treatments $CNPK_{high}$ and $CNPK_{med}$, C + NPK_{high}, C + NPK_{low} and NPK_{high} were within the thresholds but C, $CNPK_{low}$, C + NPK_{med}, NPK_{low}, NPK_{med} and Control were below the threshold. For Ca, apart from $CNPK_{low}$ and NPK_{low} which were deficient, all other treatments resulted in soils that were between the upper and lower thresholds, while for Mg soils from all treatments were deficient except $CNPK_{med}$, C + NPK_{high} and C + NPK_{med} which were between the recommended thresholds. Zn concentrations in soils were far above the upper threshold while Fe concentrations were far below the lower threshold. pH for all soils were above the upper threshold, except the unfertilised (Control) soil, which was at the upper threshold of 7. SOM was above the 3% critical low threshold for all CPH compost treated soils, while inorganic (NPK) fertiliser only treatments and the Control treatment were below the lower threshold. CEC for all soils were below the lower threshold of 12 $cmol_c$/kg, whereas BS was about 10% higher than the upper threshold.

Table 6-11: Soil properties of soils amended with CPH compost, inorganic (NPK) fertiliser at high (100%), medium (50%) and low (25%) rate, or the CPH compost co-composted or co-amended with the inorganic fertiliser, alongside unamended soil (control) compared with recommended thresholds (Snoeck et al., 2016).

Treatment	N	P	K	Ca	Mg	Fe	Cu	Zn
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
C	3.87	67[B]	317[A]	816[W]	98[B]	91[B]	3.3[B]	7.4[A]
CNPK$_{high}$	3.86	108[W]	315[A]	951[W]	104[B]	82[B]	4.2[W]	7.5[A]
CNPK$_{med}$	3.21	98[W]	373[A]	958[W]	114[W]	98[B]	4.1[W]	7.4[A]
CNPK$_{low}$	3.06	68[B]	340[A]	773[B]	93[B]	88[B]	4.0[W]	6.5[A]
C + NPK$_{high}$	4.27	97[W]	334[A]	834[W]	106[W]	80[B]	3.4[B]	7.0[A]
C + NPK$_{med}$	3.51	74[B]	406[A]	849[W]	111[W]	77[B]	3.5[B]	6.0[A]
C + NPK$_{low}$	3.82	82[W]	325[A]	843[W]	102[B]	85[B]	3.6[B]	6.9[A]
NPK$_{high}$	3.26	78[W]	84[W]	986[W]	59[B]	78[B]	4.7[W]	5.6[A]
NPK$_{med}$	3.14	58[B]	53[B]	853[W]	51[B]	81[B]	4.6[W]	5.4[A]
NPK$_{low}$	3.13	49[B]	56[B]	777[B]	48[B]	66[B]	4.2[W]	5.3[A]
Control	3.63	38[B]	56[B]	856[W]	50[B]	75[B]	4.6[W]	4.3[A]
Threshold	**-**	**78-468**	**60–150**	**800-3600**	**108-480**	**190–450**	**4–18**	**0.5–2.2**

Treatment	pH	Organic matter	CEC	Base Saturation (Ca, Mg & K)
	-	%	cmol$_c$/kg	%
C	7.9[A]	4.92[W]	7.85[B]	72.76[A]
CNPK$_{high}$	7.8[A]	4.52[W]	8.48[B]	75.62[A]
CNPK$_{med}$	8.01[A]	4.58[W]	9.09[B]	73.49[A]
CNPK$_{low}$	8.1[A]	4.56[W]	7.80[B]	70.85[A]
C + NPK$_{high}$	7.8[A]	4.38[W]	8.20[B]	71.99[A]
C + NPK$_{med}$	8.1[A]	4.84[W]	8.37[B]	73.81[A]
C + NPK$_{low}$	8.0[A]	4.63[W]	8.24[B]	71.72[A]
NPK$_{high}$	7.2[A]	2.57[B]	8.04[B]	70.19[A]
NPK$_{med}$	7.1[A]	2.19[B]	7.10[B]	68.14[A]
NPK$_{low}$	7.1[A]	2.17[B]	6.53[B]	67.74[A]
Control	7.0[W]	2.44[B]	7.08[B]	67.93[A]
Threshold	**5–7**	**>3**	**12–30**	**40-60**

Note:

A= Above upper limit,

B= Below lower limit,

W= within limit.

Soil data below the lower threshold are deficient in the corresponding soil property according to (Snoeck et al., 2016) recommendations for lower and upper thresholds for soil nutrient levels.

6.4. **Discussion**

6.4.1. **CPH compost application with or without inorganic (NPK) fertiliser improves soil fertility**

CPH application with or without inorganic (NPK) fertiliser significantly increased soil pH, EC, SOM, CEC, BS, and WHC (Figure 6-1, Table 6-5). Similar observations were made when soils cropped to cashew were amended with CPH (Agele and Agbona, 2008) and in a CPH ash application study (Ayeni and Adeleye, 2011). CPH compost (organic) and NPK (inorganic) fertilisers, when applied alone, and when **co-composted** or **co-amended** (CNPK and C + NPK) significantly increased the levels of available K, P, Mg and Zn, compared to the unfertilised control soils, but the effects of their combination (**co-composting** or **co-amending**) was greater than their individual effects (CPH alone and NPK alone).

When comparing between soils amended with organic (CPH compost) and inorganic (NPK) fertilisers, more available K and Mg was contained in the former than the latter, while the opposite was the case for P. This comparison indicates that K and Mg in CPH were more easily mineralised than the P, which is less mobile in soil. The short-term bioavailability of P in organic materials, and its sorption/desorption soil surfaces when applied is dependent on its existing form and its concentration in the residue which is purged at >0.3% (Damon et al., 2014). This may explain why increasing rates of mineral P addition to CPH (which contained 0.5% total P) in the form of triple super phosphate resulted in significantly increasing the amount of available P in the soils.

Fertilising with CPH compost, NPK or their combinations (**co-composting** or **co-amending**) did not significantly increase the availability of nitrogen, calcium, iron and copper in the soils. Nitrogen, unlike P, is highly mobile and so is easily lost through leaching and may explain why the organic and inorganic amendments, did not show any effects on N availability in any of the soils. It could also be that N added was immobilised in the CPH compost treatments as available N levels in co-composted treatments were not statistically different from the CPH compost alone treatment.

6.4.2. Soils amended with CPH compost co-composted or co-amend with a high rate of inorganic (NPK) fertiliser meet the recommended soil nutrient thresholds for cocoa soils.

Soils suitable for growing cocoa should have soil nutrient levels sufficient enough to support good growth and give good yield. Snoeck et al (2016) recommended lower and upper thresholds within which good yields can be achieved based on reviews of several fertiliser trials that have shown that nutrient levels below the lower threshold result in crop deficiencies. According to these recommendations, soils from all the treatments were deficient in Fe, low in CEC, but had Zn contents and BS levels above the upper thresholds.

CPH compost application (with or without NPK) increased soil pH from 6.3 (Table 6-3) to around 8 (Figure 6-1), which is above the recommended threshold, making the soils unsuitable for growing cocoa. However, these amendments may help to increase pH in acidic soils that are below pH 5 which is the case for many soils cropped to cocoa in Ghana and elsewhere (Asiamah, 2008; Bationo et al., 2018; Dossa et al., 2018a; Jayne et al., 2015; Snoeck et al., 2016) . Similarly, SOM and available K increased due to the application of CPH compost from values that were below their respective lower thresholds of 3% and 60 mg/kg to almost 5% for SOM and to as high as 400 mg/kg for K. Available K in CPH compost amended soils were more than twice the recommended upper threshold while soils applied with inorganic (NPK) fertiliser alone at the high rate (100%) recommended by (Bohórquez and Rodríguez, 2016) had K levels within the threshold. However, when this rate was reduced to 50% (NPK_{med}) or to 25% (NPK_{low}), K was deficient. These observations imply that, CPH compost does not require co-composting or co-amendment with NPK to raise soils to the optimum levels of K. The disadvantages of high K levels are that it induces senescence in leaves, characterised by leaf fall, and also decreases the effective utilisation of N fertilisers (Didier Snoeck, 2016; Somarriba et al., 2013), and this could have accounted for the lack of effects of **co-composted** or **co-amended** NPK fertiliser on nitrogen availability. However, Ghanaian cocoa soils, for which the use of CPH compost is intended for, is suspected to be deficient in K since most of the soil K is mined to produce the husks (Appiah et al., 1997) and so CPH compost amendments may balance the deficiency and abate the problems associated with low levels of K.

P availability varied within CPH compost treatments such that CPH **co-composted** with 100% and 50% NPK, and **co-amended** with 100% and 25%NPK were within the P thresholds, but soils amended with CPH alone, or soils amended with CPH compost **co-amended** with

50%NPK were deficient in P, just as soils in the Control treatment and soils applied with inorganic (NPK) fertiliser at 50% and 25% rates. It has been observed that compost enhances the efficiency of P mineral fertilisers, thereby increasing the availability of P in soils (Didier Snoeck, 2016; Koko et al., 2013). This implies that to achieve the optimum available P levels in CPH amended soils, they have to be **co-composted** with the highest (100%), or at least the medium (50%) recommended NPK rate.

Unfertilised (Control treatment) soils were deficient in P, K, Mg and Fe and had lower EC and OM than recommended making them unsuitable to grow cocoa. All three rates of inorganic (NPK) fertiliser treatments, when applied alone, resulted in soils that were deficient in Mg and Fe.

6.4.3. Co-composting and co-amending CPH with inorganic (NPK) fertilisers increased the chlorophyll content and nutrient uptake by the cocoa seedlings, but the photosynthetic efficiency of the plants was compromised by spider mite infestation.

Fertiliser application (organic or inorganic) had no effect on plant growth, nutrient uptake and biomass production but increased leaf N and K concentrations. CPH compost **co-amended** with the medium rate of inorganic (NPK) fertiliser significantly increased leaf K content to give the highest leaf K concentrations. The lack of fertiliser effects could be due to the general stress on all plants induced by spider mite infestation which was quite severe in the second month. This stress was depicted in the chlorophyll fluorescence data which dropped in the second and fifth month. However, CPH **co-composted** with inorganic (NPK) fertiliser increased chlorophyll content but did not increase photosynthetic rate. There was a general reduction in chlorophyll content and fluorescence from the first to the sixth month. Since fertilisation resulted in soils with sufficient nutrient reserves but had no significant effect on nutrient uptake and subsequent biomass production, their effects may have been suppressed by other factors. From the regression analyses, it is revealed that water holding capacity negatively affected N, P and K uptake as well as biomass production (Table 6-10). In a similar study both organic and inorganic fertilisers had no significant effect on nutrient uptake (Oyewole et al., 2012).

6.5. **Conclusion**

CPH application, with or without inorganic (NPK) fertilisers, significantly increased soil pH, EC, SOM, CEC, BS, and WHC, but pH and BS were above the Snoeck et al (2016) recommended upper thresholds, while CEC was below. The availability of soil nutrients, except for nitrogen and calcium were also significantly increased. All soils were deficient in Fe but had Zn contents above the upper thresholds. Therefore, Fe fortification may be required. Soils **co-composted** or **co-amended** with CPH with high rate NPK addition meet the recommended soil nutrient thresholds, unlike soils amended with either CPH compost or inorganic (NPK) fertiliser applied alone. Soil P content was within the thresholds when soils were amended with CPH **co-composted** with 100% or 50% NPK or **co-amended** with 100% and 25% NPK.

Plant growth and plant nutrient uptake into the leaves of cocoa seedlings was not directly affected by CPH (organic) and/or NPK (inorganic) fertiliser applications to soils, when compared to unfertilised (Control treatment) soils. Nutrients supplied by **co-composting** or **co-amending** CPH composts with inorganic (NPK) fertiliser increased N and K contents in leaves as well as leaf chlorophyll content, but the photosynthetic efficiency of the plants were compromised by another stress. Our data implies that the stress is water content. The method combining NPK with CPH i.e. **co-composting** or **co-amending** did not affect nutrient release, plant growth, or uptake by plants, but it significantly increased P and K concentrations in leaves. The rate of application of inorganic (NPK) fertiliser amendment, on the other hand, a positive effect on soil available P. It is observed that, CPH compost does not require **co-composting** or **co-amending** with inorganic (NPK) fertiliser to release optimum levels of K in soils, however for optimum available P levels in CPH-amended soils, **co-composting** with the highest (100%), or at least the medium (50%) NPK rate is recommended. There were no thresholds of available for N to be compared with but the lack of an observed effect of CPH compost (organic), NPK (inorganic) or their combination on soil fertility or cocoa seedlings suggest that further research may be required to investigate the most appropriate forms and dose of mineral N needed to **co-compost** or **co-amend** CPH compost for sustainable and efficient cocoa soil fertilisation.

Chapter 7. GENERAL DISCUSSION

This study in chapter one, section 1.3 set out to find out the effects of land management practices on chemical and physical properties of the soils across four cocoa growing regions and to explore the scope for using on-farm wastes to increase the sustainability of Ghanaian cocoa plantations. The first objective was satisfied through reviewed literature (in chapter two) and the preliminary study (in chapter three) by identifying the land management practices and the knowledge gaps in research done in this area (Figure 2-3), and then, in chapter four the chemical and physical properties of the soils across four cocoa growing regions were assessed to find out how they are affected by the identified land management systems i. e. the recommended blanket fertiliser. Again, in chapter four the effectiveness of the blanket fertiliser was tested to satisfy the second objective. The third objective was also satisfied in chapter five where cocoa pod husks (CPH), a farm waste observed in chapter three to be a potential source of soil nutrients was tested, composted and in chapter six applied to cocoa seedlings to test their fertilising ability.

Literature reviewed in Chapter two indicated that cocoa production in Ghana typically begins by clearing the forest to start a cocoa plantation. Through a phenomenon termed as the "Forest rent", the plantation initially utilises the natural soil nutrient reserves associated with the high soil organic matter content of forest soils, but this starts to decline 15-20years after this conversion which prompts farmers to abandon farms and clear another patch of forest to start another cocoa plantation. The overall soil quality of plantation soils must be fully understood using the physical, chemical and biological indicators to develop sustainable strategies for replacing mined nutrients and ensuring the future sustainability of Ghanaian cocoa plantations (Figure 2-3). In Ghana, soil quality assessment is skewed towards the use of physio-chemical properties as the main indicators based on the assumption that supplying sufficient nutrients to soil to balance the cocoa nutrient requirement alone will increase the quality of the soil. This practice has led to an intervention that is solely reliant on the use of a single formulated mineral fertiliser supplied nationally for use on all plantations (irrespective of soil type) but only suits 6% of the cocoa growing areas when their nutrient needs and preferences were assessed. However, studies that assessed the nutrient status of cocoa soils assumed to be fertilised annually showed that soils were mostly acidic, had low organic matter content and had insufficient nutrient reserves to sustain yield, hence the annual fertilisation. The lack of use or misuse of the fertilisers (wrong time of application or applying less of what is recommended)

by farmers had been blamed for the low soil quality.
While the recommended fertiliser's ability to improve yield has been established in research trials, it lacks the ability to improve the overall soil quality by increasing the soils ability to self-regulate its ecological functions for efficient nutrient use. Research into cocoa soil is focused on getting the right composition and application rates of mineral fertilisers to increase yield without studying the soils to understand the interplay between soil quality indicators towards the long-term maintenance of soil fertility. In Chapter four, for the first time, the effectiveness of the nationwide fertiliser in improving soil fertility, besides yield, was assessed by comparing the soil nutrient status of farmer managed plots to researcher managed plots where recommended management practices were strictly adhered to. The results revealed that there were no significant differences between the nutrient levels of both plots. The results, when compared to upper and lower nutrient thresholds recommended by Snoeck et al (2016) for sustainable cocoa yields, indicated that soils on both plots had low pH, low OM, and were inherently low in nutrients, particularly N and K. Available K was the only nutrient that had a direct and significant positive relationship with yield. This meant that sustainable strategies for long term fertility management should aim towards increasing pH, OM and K levels in soil.

Intervention strategies to improve the pH, OM and available K levels were developed, based on the observations reported from the preliminary observations made in Chapter three. It had been gathered from reviewed literature that mineral fertiliser is most effective in soils with high organic matter content. Therefore, integrating organic fertilisers in nutrient management systems will increase soil organic matter (SOM) content and pH which will subsequently improve soil water conservation and nutrient cycling. Also, the developed strategy should improve soil structure and soil ecological functions while reducing negative environmental impacts. The most accessible and affordable forms of organic materials are those generated on farm. Field observations identified that abundant waste is generated on farm, primarily cocoa pod husks (CPH). Cocoa Research Institute of Ghana (CRIG) has recommended that these husks should be composted or burnt to ash and incorporated into the soil, but across the 24 farms visited during the preliminary study, only half the farmers spread CPH across the farm, but without burning or composting. This could increase the spread of black pod disease (*Phytophthora megakarya*) which could otherwise be prevented if the husks were composted. CPH contains ~0.8% N, ~0.1% P and ~ 4% K (Table 5-2) but has a high C:N ratio and the nutrients contained in it may not be readily available for plant uptake, whereas mineral fertilisers provide readily available nutrients, but are costly and susceptible to leaching. Chapter five introduces the second phase of the research which involved integrating the two main nutrient resources available to the farmers, i.e. CPH and NPK fertilisers, such that the disadvantages of one are complimented by the other's advantages and vice versa to address the soil fertility problem identified in Chapter four. The use of CPH and inorganic fertilisers together as an integrated nutrient management approach is gaining research attention in cocoa production. However, basic information on the optimum combining ratios and standard composting processes did not exist. A study to find the optimum proportions of NPK that combines with CPH was needed to ensure the consistent release of nutrients in soil. 400g of CPH was composted with 0%, 25%, 50% and 100% of the recommended full dose of NPK 50-100-50 for nursery seedlings in fabricated laboratory-scale reactors in an aerobic condition for 14 weeks. This study was different from other integrated CPH and mineral fertiliser studies in that, in previous studies, CPH was composted with a single rates of NPK or of either mineral N or P, whereas this study varied the quantity of NPK from low rate to high rate to be added to CPH to identify the maximum nutrient recovery that meets the nutrient requirements of cocoa. The results indicated that CPH composted with NPK mineral fertilisers (25%, 50% and 100%), were of higher quality than CPH composted alone, according to international compost quality standards, with 25% NPK enriched compost being the most efficient in retaining most of its nutrients after the composting period. Mineral K addition to CPH did not make any difference on compost quality suggesting that mineral K addition is not needed. The composts had high pH and organic matter contents above accepted standards but since the Ghanaian soils are acidic and have low organic matter, this may rather be advantageous in improving the soils.

In Chapter six, the effects of CPH, NPK and their combination amendments on cocoa seedlings is reported. It introduces a new dimension to CPH and NPK integration studies by also comparing the effects of the combining methods termed in this study as **co-composting** (adding NPK to CPH before composting) and **co-amending** (applying NPK to soils alongside CPH compost). The findings were that CPH amendments improve soil quality to meet the recommended standards required for good cocoa growth and development to achieve higher yields when they are **co-composted** with 100% or 50% P or **co-amended** with 100% and 25% P. Mineral K addition to CPH was not necessary as available K levels were too high. Though, N addition is needed to offset N immobilisation of CPH compost, the amount required could not be clearly established. Therefore, further research is recommended to investigate the most appropriate forms and dose of mineral N needed to **co-compost** or **co-amend** CPH composts. Soil moisture content had an inverse effect on plant growth, physiology, nutrient uptake and biomass accumulation when CPH was applied to soils. Therefore, further research is also recommended to determine the optimum amount of water needed to unleash the full potentials of CPH amendments to benefit cocoa plants.

7.1. Contributions of study to cocoa production in Ghana and recommendations for future work.

I discovered in this study that CPHs, which are produced in abundance on farms after harvesting cocoa pods is a good source of soil nutrients, particularly K, that is easily mineralised in soils when composted and applied as an amendment. The K and P forms in CPH are easily mineralised into plant available forms meaning that if it is integrated with the recommended fertiliser for mature cocoa trees on farms (NPK 2-21-17+4S+10CaO+5MgO+0.1B+0.3Zn), based on the findings of this research, K may be excluded, P and Zn amounts may be reduced and since the CPH increased pH drastically, the liming agents may also be excluded. To be sure this can be done, field trials are recommended to know the practical application rates that can be employed to achieve this. For every 1kg of cocoa beans produced, 1.4kg of husk are generated on farm (Snoeck et al., 2016) and as reported in chapter five, it contains ~0.8% N, ~0.1% P and ~ 4% K (Table 5-2). Ghana's average annual yield is 450kg/ha (COCOBOD, 2019), meaning that 630kg of husks are produced on a hectare of farmland which contributes 5 kg of nitrogen (N), 0.6 kg of phosphorus (P) and 25 kg of the K to the farms nutrient budget.

This research has provided an innovative way to compost smaller quantities of CPH in the laboratory using fabricated composters that allowed a standard monitoring of the composting process to make sure it was environmentally safe. The protocol developed for this work will provide the basics for future advancement of this technology. For example, the apparatus allowed leachates to be collected but as this was the first-generation system, there were challenges with leakages that prevented me from totally quantify the exact amount of nutrient loss and therefore could not be included in this report. Thermophilic state too could not be attained due the size of the composters and the CPH composted so whether disease causing organisms such as the pod rot organism Phytophthora megakarya could be eliminated during this composting could not be established. Therefore, insulating the composting chamber is required to prevent heat loss. If this technology is advanced, an on-farm version can be created for field trials and with time this technology can be passed on to farmers. CPH compost can be used in all growing areas as a soil amendment, but due to the high pH and OM contents, soils should be tested before application to ensure these properties remain within their recommended thresholds. For example, acidic soils, such as those found in the Western region will benefit more from CPH amendments. Also, the chemical composition of husks may differ from one site to another, indicating that husks must be characterised first to know which and how much mineral fertilisers should be added when co-composting or co-amending.

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Chapter 9. APPENDICES

9.1. **Soil Texture**

Particle size distribution was determined using the Mastersizer 3000 laser particle size analyser.

9.2. **Soil pH**

Soil pH was conducted using pH meter. 10g of soil was weighed into a 50ml centrifuge tube, 25ml ultra-pure water was added and Shaken in an end-over-end shaker for 30 min. A digital pH meter was calibrated using 4 and 7 and then the soil solution was measured.

9.3. **Soil organic matter**

Soil organic matter was determined using Loss on ignition. 10g of air-dried soil was weighed into a crucible, both weighed together, oven-dried at 105°C overnight, removed and then reweighed to determine moisture loss. The oven dried soil in the crucible was placed in a muffle furnace set at a temperature of 500°C and left overnight. Both the ignited soil and crucible were weighed after it had been allowed to cool in a desiccator. Loss on ignition was calculated and expressed as g per 100g oven-dried soil.

9.4. **Total Nitrogen and carbon**

Total carbon and total nitrogen were analysed using the Flash combustion Elemental Analyser. 5 g of the soil from each sample was milled in a ball mill grinder for 2 minutes to obtain a consistent homogenous. Approximately 10mg of the milled soil from each sample was weighed in a tin capsule with a micro spatula and carefully folded (to avoid crushing the capsule and spilling the content) into a tight ball with forceps. Approximately 1mg, 2mg and 3mg of aspartic acid standards and 10mg each of two certified referenced soils were also weighed individually into tin capsules and sealed in similar manner as the samples. Three empty tin capsules were also sealed and used as blanks. The sealed tin capsules of soil samples, standards and blanks were transferred unto an auto-sampler tray and analysed. Results were expressed as percentages (%N and %C) of the exact weight of each sample.

9.5. **Available nutrients**

Mehlich 3 extraction method was used to extract major, minor and trace nutrients. Mehlich 3 extracting solution was prepared from 0.2 M Acetic acid, glacial (CH_3COOH), 0.25 M Ammonium nitrate (NH_4NO_3), 0.015 M Ammonium fluoride (NH_4F), 0.013 M Nitric acid (HNO_3), 0.001 M Ethylenediamine tetra acetic acid [EDTA, ($C_{10}H_{16}N_2O_8$)] (Pierzynski, 2000). 2 g of soil was weighed into acid washed 50ml centrifuge tubes. 20 ml of Mehlich 3 extracting solution was added to each tube (including three blanks). The solution was shaken on an end-over-end shaker for 5 minutes. Extracts were then filtered through Whatman 42 filter papers into acid washed universal tubes. Matrix matched Inductive Coupled Plasma (ICP) calibration standard solutions were prepared from Merck IV and Phosphorus stock solutions. To correct for copper interference of phosphorus wavelengths additional phosphorus and copper standards were used to set up an MSF (multicomponent spectral fitting) model. Nutrients were expressed as mg/kg of soil. Cation exchange capacity (CEC) was calculated from the results as the sum (in milli-equivalents per 100g) of all cations. Base saturation was also calculated as the sum of the K, Ca, and Mg expressed as a percentage of CEC.