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HOUSEHOLD ENERGY AND SOIL NUTRIENT; IMPLICATIONS FOR CROP PRODUCTION, HOUSEHOLD FINANCES AND GREENHOUSE GAS EMISSIONS IN THE CENTRAL HIGHLANDS OF ETHIOPIA

BY

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Household Energy and Soil Nutrient; Implications for Crop Production, Household Finances and Greenhouse Gas Emissions in the Central Highlands of Ethiopia

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This is to certify that the thesis prepared by Dugassa Negash, entitled: **'*Household Energy and Soil Nutrient; Implications for Crop Production, Household Finances and Greenhouse Gas Emissions in the Central Highlands of Ethiopia*'** and presented in fulfillment of the requirements for the Degree of Doctor of Philosophy in Geography and Environmental Management (Specialization in Environment and Natural Resources Management) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Declaration

I the undersigned declare that this PhD thesis entitled ***'Household Energy and Soil Nutrient; Implications for Crop Production, Household Finances and Greenhouse Gas Emissions in the Central Highlands of Ethiopia'*** is a result of my work investigations. Sources of information other than mine have been acknowledged and therefore included in the appended reference list. I hereby confirm that this work has not been previously submitted to any other university for award of any type of academic degree.

Name: Dugassa Negash Muleta Signature: ____________ Date: _______________

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List of Abbreviations and Acronyms

ATA	Agricultural Transformation Agency
Av.P	Available Phosphorus
BD	Bulk Density
BS	Bioslurry
BSC	Bioslurry Compost
C:N	Carbon to Nitrogen Ratio
Ca^{2+}	Exchangeable Calcium
CRBD	Completely Randamized Block Design
CCT	Controlled Cooking Test
CEC	Cation Exchange Capacity
CH_4	Methane
Cm^3	Centimeter Cube
CO_2e	Carbon Dioxide Equivalent
CSA	Central Statistical Authority
CSA	Central Statistical Agency Authority
DAP	Diammonium Phosphate
DARC	Debre Zeit Agricultural Research Center
EARO	Ethiopian Agricultural Research Organization
EAS	Ethiopian Academy of Sciences
ETB	Ethiopian Birr
FAO	Food & Agriculture Organization
FDRE	Federal Democratic Republic of Ethiopia
FN	Nitrogen Fertilizer
FP	Phosphorus Fertilizer
GDP	Gross Domestic Product
GHGE	Greenhouse Gas Emission
Ha	Hectare
IEA	International Energy Agency
IEW	International Energy Workshop
IF	Inorganic Fertilizer
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
ISFM	Integrated Soil Fertility Management
IPCC	Intergovernmental Panel for Climate Change
K	Potassium
Kg	Kilogram
KPT	Kitchen Performance Test
M	Meter
MWIE	Ministry of Water, Irrigation & Energy
N	Nitrogen
NGOs	Non Governmental Organizations
Na^+	Exchangeable Sodium
NBPE	National Biogas Program Ethiopia

NMSA	National Meteorological Services Agency
NP	Nitrogen and Phosphorus
NRCCA	Northeast Region Certified Crop Adviser
NUC	Total Nitrogen Uptake in the Control plots
NUE	Nitrogen Use Efficiency
NUF	Total Uptake of Nitrogen in fertilized plots
OC	Organic Carbon
P	Phosphorus
PBS	Percentage Base Saturation
PUC	Phosphorus Uptake for the Control plot
PUE	Phosphorus Use efficiency
SNNP	Southern Nations Nationalities and Peoples
SNV	Netherlands Development Organization
t	ton
TAGBA	Total Above Ground Biomass
TAGBM	Total Above Ground Biomass
TLU	Tropical Livestock Unit
TN	Total Nitrogen
US$	United States Dollar
UNDP	United Nations Development Program
WWAO	Walmara Woreda Agricultural Office
YC	Yield of the Control plot
YF	Yield of Fertilized plot
yr^{-1}	per year

Abstract

This study tries to assess household energy and soil nutrients with particular emphasis on implications for crop production, household finances and greenhouse gas emissions in the Central Highlands of Ethiopia. Household survey, focus group discussions, key informant interviews, observations and measurements were used for data collection. Kitchen Performance Test and Controlled Cooking Test were applied for assessing stove efficiency. On-farm trials were established to evaluate effects of fertilizers on soil and yield. Descriptive statistics, a paired sample t-test, one way ANOVA, correlation coefficients and linear regression were employed for statistical analysis. Microsoft excels and SPSS version20 were used for data presentation and analysis. Crop residues and dung cakes accounted for 80(±3) % by energy content and 85(±4) % by dry mass weight of total biomass fuel consumption. Mean per household nutrient losses were 109(±8) kg yr^{-1}nitrogen, 26(±2) kg yr^{-1} phosphorus, (150(±11) kg yr^{-1} potassium and 3000(±300) kg yr^{-1} organic carbon. Rich farmers lost significantly more carbon and nutrients in fuel than farmers in other wealth groups. However, these losses were spread over a larger area, so losses per land area were significantly higher for medium and poor than for rich farmers. This means that the land of poorer farmers is likely to become degraded more rapidly due to fuel limitations than that of rich farmers, so increasing the poverty gap. The estimated financial loss per household due to not using dung and crop residues as organic fertilizer was 162(±8) US\$ yr^{-1}. However, this is less than their value as fuels, which was 490(±20) US\$ yr^{-1}. Therefore, farmers will only be persuaded to use these valuable assets as soil improvers if an alternative, cheaper fuel source can be found. Substitution of a three-stone open fires with improved stoves resulted in significant improvement of fuel use efficiency ($p<0.01$) with the highest saving in biomass fuel achieved by the mirt stove together with biogas (53.6%) and lowest by the mud-stove without biogas(32.1%) and respective reduction in greenhouse gases emissions were 4534 (±32) kg CO_2e yr^{-1} and 7661 (±43) kg CO_2e yr^{-1}; and financial savings from fuel were 471(±2.6) US\$ yr^{-1} & 279(±4) US\$ yr^{-1} *per household. Soil texture of the trial fields were suitable for cereals (clay to clay loam) but high to very high in bulk density implying the existence of soil compaction problem. The trial fields were characterized by very low to low total nitrogen, available phosphorus, organic carbon while the C: N ratios, cation exchange capacity and base saturation were within the optimum ranges. The soil pH at Doliyo was strongly acidic (5.10) whereas that of Kumbursa was nearly neutral (6.89). The post-treatment soil test data revealed that application of bioslurry and bioslurry compost individually as well as in combination with inorganic fertilizer tended improve the soil bulk densities and chemical properties with relatively better performance in nutrient uptake. Both total above ground biomass and grain yields linearly increased with increased application rates of nitrogen & phosphorus for all of the treatments with the highest and lowest responses respectively obtained from bioslurry compost combined with inorganic fertilizer and bioslurry only. Wide scale dissemination of improved cookstoves combined with biogas technology is recommended for enhancing availability of organic fertilizer. Integrated application of organic and inorganic fertilizer should be encouraged for maintaining soil fertility and improving crop yield. Finally, further experimentation is required on application rates of different fertilizer types on different soil types in different agroecologies.*

Key words: Ethiopian Highlands, biomass fuel, household energy, crop residues, dung cakes, cookstove, soil nutrients, agronomic response, nutrient use efficiency, apparent nutrient recovery

Chapter 1

Introduction

1.1. Background: Agricultural context of Ethiopia and agricultural residues removal for fuel

Agriculture is a single most dominant economic sector employing more than 80% of the workforce (Lulseged *et al.*, 2017; Tegbaru, 2016). It contributes about 40% to the national GDP and accounts for more than 60% of the export earnings (Tegbaru, 2016). The Ethiopian government's green development goal of reaching a middle-income status by 2025 requires raising up of per capita income, from 691USD in 2014/15 to at least the level of the lower threshold for middle income status i.e., 1,000 USD requires improvement of agricultural productivity (FDRE, 2016). However, in spite of the two decades of policies that placed high priority on boosting agricultural productivity, several millions of Ethiopians are still food insecure and forced to rely on food aids (FDRE, 2016).

Mixed crop-livestock smallholder agriculture provides the basic means of livelihood for about 12 million farmers; and it accounts for 96% of the total farmland areas (Tegbaru, 2016). The Ethiopian agriculture is characterized by small holding size, with 40% of smallholder farmers working on less than 0.50 ha, 64% on less than 1.00 ha, 80% on less than 1.52 ha and 87% on less than 2.00 ha (FDRE, 2016). Under rain-fed agriculture and present traditional farming, an average family size of 6 people requires 2.5 ha to 2.8 ha to meet its annual food requirement (FAO, 2011). Therefore, intensification of inputs is required to scale-up production volumes since no arable land is available for expansion of cultivated land areas.

Cereal crops are dominantly produced in Ethiopia, and among the cereal crops, teff, maize, wheat, barley and sorghum account for 75% of cultivated area (Tegbaru, 2016). Of the total fertilizer consumption, 90% is applied to cereal crops (IFPRI, 2012). However, the smallholder farms are characterized by low-input and hence stagnating productivity mainly due to soil fertility decline and nutrient depletion (Mulugeta *et al.,* 2017; Workneh, 2015). Application rates of inorganic fertilizers in Ethiopia is lower than the average rate for East Africa, and the use of manure is also almost nil (Mulugeta *et al.*, 2017). Thus, crop yields have remained sluggish with average yields below 2t ha^{-1} for cereals and 0.8t ha^{-1} for pulses (ATA, 2013).

Due to deforestation and dwindling firewood supplies, there has been large scale switch to dung cakes and crop residues for fuel in the Highlands of Ethiopia (Kassahun *et al.,* 2013; Zenebe, *et al*., 2006). In many rural societies and urban peripheries of the Ethiopian Highlands, cattle dung and agricultural residuals constitute the dominant proportion of fuel source (Abebe *et al.,* 2015). Thus, there is apparent breakup of the traditional soil fertility replenishment with organic resources due to the large scale shift towards using agricultural wastes especially crop residues and dung cakes as fuel sources instead of applying them to farmland for soil amendment (Getachew, 2006). So soils of the Ethiopian Highlands are characterized by low organic carbon (OC) content, mainly because farmers remove crop residues and animal manure without adding enough nutrients (Amare, 2005; Assefa, 2005; Balesh, 2006; and Hailu, 2010).

Biomass fuel makes up over 90% of the total energy demand of Ethiopia (Dawit, 2012; EUEI, 2013; Getamesay *et al.*, 2015; Gudina & Nonhebel, 2015; Gwavuya *et al.*, 2012). The use of inefficient three-stone open fire by about 92% of the Ethiopian households (Abebe *et al.,* 2015) has also been contributing to the increased removal of agro-residues and livestock manure for fuel instead of applying to farmlands. Thus, the prevailing low crop productivity in the Highlands of Ethiopia has been exacerbated by a downward spiraling relationship between agricultural production, energy use and soil fertility management (IEA, 2011; IOB, 2013; Winrock International, 2007).

1.2. Statement of the problem

Reduction in land size under natural forest and plantations due to increasing population pressure in the Highlands of Ethiopia have resulted in serious firewood scarcity (Dawit, 2012; Fekdau, 2015). As a result, cooking fuels have become scarce and increasingly expensive (Ahmed & Tebarek, 2017). Despite some efforts to overcome fuel wood scarcity through peri-urban plantation, and community woodlots with fast-growing trees mainly eucalyptus, firewood demand is still by far greater than supply forcing the community to resort to agricultural wastes for fuel in order to fill the demand gap (Dawit, *et al.,* 2015).

The switch to agricultural wastes for fuel due to fuel wood scarcity (Kassahun *et al.,* 2013) together with inadequate inorganic fertilizer application due to hardly affordable price by the resource poor smallholder farmers (Akilu, 2006) were identified as responsible factors for low soil fertility; and meager crop productivity improvement. Even if farmers get adequate access to inorganic fertilizer, it has been argued that sustainable crop production without complementing it with organic fertilizer is a failure. For instance, Dejene (2015) reported that despite the increase in inorganic fertilizer application to teff, yield increase remained little. It has been reported that on average, the agricultural gross domestic product (GDP) of Ethiopia has declined by as much as 7% due to the loss of soil nutrients associated with burning animal manure and other agricultural wastes (IFPRI, 2010). Inefficient utilization of the available biomass resource for fuel i.e., use of three-stone open fire by about 92% of the Ethiopian households (Abebe *et al.*, 2015) is responsible for such extensive removal of agro-residues and livestock manure; which implies decreased availability of organic resources for soil fertility improvement.

This study was therefore, instigated because there is a paucity of empirical literature in the Central Ethiopian Highlands, on household energy use and the associated impacts on soil nutrients and carbon recycling in typical rural Villages, where farm households almost entirely depend on their respective landholdings for food, feed and fuel. Most studies of household energy have so far emphasized implications for indoor air pollution and related health impacts (Avery *et al.*, 2014; Semple *et al.*, 2014; Yongabi *et al.*, 2014), deforestation (Badege, 2001; Fekadu, 2015; Mulu *et al.*, 2016; Subedi *et al*., 2014), and loss of biodiversity (Adugnaw, 2014; Debela, 2007), determinants of allocating dung for fuel and fertilizer (Alemu & Kohlin, 2008), and the impacts of the shadow price on allocating farmyard manure for multipurpose uses (Hailemariam, 2011), while only gross implications for soil nutrient loss have been addressed (Aklilu, 2006; Kassahun *et al.*, 2013; Smith *et al.*, 2014). Besides, studies conducted so far have emphasized the contributions of improved cookstoves in improving financial saving (Abebe *et al.,* 2015; Getamesay *et al.,* 2015); reducing deforestation (Abe

ra, 2016; Abraham *et al.*, 2015; Elizabeth *et al.*, 2014); and mitigating indoor air pollution (Lambe *et al.*, 2015; Semple *et al.*, 2014) while the implications for increasing the availability of organic resources for soil amendment has been insufficiently treated.

Thus, field–based kitchen performance test and controlled cooking test were undertaken for assessing the implications of improved cookstoves and biogas digesters on availability of agricultural wastes for application to farmland, improving household finance and mitigation of greenhouse gases emissions to the atmosphere. Besides, biogas digesters are appreciated for provision of clean energy while the value of its by-product *i.e.* bioslurry as fertilizer usually fails to get the required attention (Getachew *et al.*, 2006; Mulu *et al.*, 2016). So the effects of sole bioslurry and bioslurry compost as well as in integration with inorganic fertilizer on agronomic responses and improvement of soil quality were evaluated by establishing On-farm trial plots experiment on the two most dominant cereal crops (teff and wheat) in the Highlands of Ethiopia.

1.3. Justifications

Today there emerges an inextricable downward spiral in household income and food security due to the link between household energy and agricultural productivity in the Ethiopian Highlands; and this suggests the need for joint efforts to address food security and energy challenges (Gwavuya *et al.*, 2012; Hailemariam, 2011). The already existing problem of soil nutrient deficit has been worsened by biomass removal from farmland resulting in the prevailing low crop productivity in smallholder farms of Ethiopian Highlands (Aklilu, 2006; Dawit et al., 2015 Kassahun et al., 2013).

The other serious bottleneck associated with fertilizer utilization in Ethiopia is absence of the appropriate rates to be applied to crops. Locally tailored and crop specific fertilizer recommendation is absent; and the only available rate so far has been the one given as blanket recommendation by the Ministry of Agriculture and Rural Development i.e., 64/46 kg ha^{-1} NP (Alemu *et al.,* 2016) while empirical evidences on the optimum amounts of organic fertilizers are almost entirely absent (Hailu, 2010; Lulseged *et al.,* 2017). Moreover, the soil fertility management practices in the Ethiopian Highlands rarely consider the local soil; agroecological and socioeconomic conditions (Amare *et al.*, 2006). So the blanket recommendation rate of nitrogen from DAP and Urea falls short of considering crop need, dynamics in soil nutrient stocks and local agroecologies (ATA, 2013). This implies that locally tailored fertilizer prescription and application is required for obtaining optimum crop yields on sustainable basis.

Crop production on sustainable basis also requires continuous modification of fertilizer recommendation in response to soil test results (Abebayehu and Eyasu, 2011; Mesfin and Tekalign, 2011). In the Highlands of Ethiopia, efforts made so far on optimization of fertilization rates using On-farm experimentation has been very rare (Haftamu *et al.*, 2009). There is lack of up-to-date data on fertilizer use, and the interventions made so far have been based on the national survey data of 1980s and macro nutrient studies of 1950s to 1960s (IFRI, 2010).

In Ethiopia, DAP and Urea have been the only chemical fertilizers in use for the last four decades with application rates lower than the average for East Africa while utilization of manure for soil amendment for cereal crops production except maize is almost nil (Mulugeta *et al.*, 2017). Hence, soil fertility amendment inputs need to be optimized to achieve economic fertilizer recommendation and to mitigate pollutions that may arise from excessive fertilizer application. Soil fertility management should also be modified and adapted to conditions that change overtime (Amare *et al.*, 2006). This is because economically more profitable agricultural production on sustainable basis requires continuous modification of fertilizer recommendation in response to soil test results (Mesfin and Tekalign, 2011). Unbalanced fertilization due to overuse and underuse results in unsustainable agricultural productivity (IFRI, 2010). Thus, judicious soil nutrient management should be based on pre-treatment soil test since this is vital for determination of right types and amounts of fertilizer (Vanlauwe *et al.*, 2014).

Thus, this study tried to quantify the amounts of nutrients and carbon loss through utilization of dung cakes and crop residues for fuel under business as-usual-scenario. Then the potential contributions of biogas digesters and improved cookstoves in improving the availability of agricultural wastes for application to farmland were assessed using field-based stove performance tests. Finally, impacts of the three different rates of sole bioslurry, sole bioslurry compost as well as in combination with inorganic fertilizer were assessed using On-farm trial plots experiment on the two major cereal crops (wheat and teff) cultivated in the Highlands of Ethiopia. The On-farm trial plots experiment was undertaken to recommend on the optimum rates of N and P required for vertisol in Kumbursa Village for wheat and teff production and for wheat production in nitosols of Doliyo Village as well as to assess the effects of these fertilizers on some selected soil physical and chemical properties.

1.4. Objectives

The general objective of this study was to assess the dynamics of the interactions between household energy and soil nutrients recycling and implications for sustainable crop production, household finances and mitigation of greenhouse gases.

Specific objectives

The specific objectives of the study were to:

- quantify losses of nutrients and carbon from farming systems with removal of crop residues and dung cakes for household energy.
- assess the potential impact of mud-stoves and *mirt* stoves, with-and-without biogas stoves, on the biomass fuel saving, availability of agricultural residues for soil improvement, household finances & mitigation of GHGs emissions.
- evaluate the Pre-treatment and post-treatment status of some selected soil physical and chemical properties.
- determine optimum rates of fertilizers for optimum wheat and teff production
- compare and contrast the agronomic responses and nutrient use efficiencies of the different fertilizer rates and types.

1.5. Basic research questions

- How much nutrients & carbon are lost with use of dung cakes and crop residues for fuel?
- Does substitution of traditional three-stone open fires with improved cookstoves significantly reduce biomass fuel consumption?
- What is the status of some selected soil physical and chemical prosperities when compared against their respective standardized values from literature?
- Are there significant variations in the considered soil physical & chemical properties between the pre-treatment and post-treatment values?
- Is the blanket recommendation rate of N & P from the different fertilizer types optimum level for wheat and teff production?
- Are there variations in agronomic responses, nutrient use efficiencies and apparent nutrient recoveries of wheat and teff for the different types and rates of fertilizer?

1.6. Scope and limitations

Spatially, the study was limited to Kumbursa Village which covers an area of about 1000 ha for household energy survey. The On-farm trial experiments were confined to plots level which were undertaken over a period of two successive cropping seasons. The selected crops for the On-farm trial experiments were wheat and teff at Kumbursa site; and only wheat at Doliyo site. The trial plots experiments were conducted for the purpose of evaluating agronomic responses and nutrients use efficiencies of sole bioslurry, sole bioslurry compost, sole inorganic fertilizer, bioslurry combined with inorganic fertilizer and bioslurry compost combined with inorganic fertilizers at the rates 50%, 100% and 150% of the blanket recommendation rate.

The results from the different stove efficiency tests that were undertaken at only Kumbursa Village could also be replicable to wider geographical areas with similar biomass fuel consumption characteristics. The outputs obtained from the On-farm trial plots experiments and the impacts of the different fertilizer types on the different soil parameters were also deemed be extrapolated to other areas with similar agroecologies.

Conceptually, the study was delimited to the quantification of nutrient and carbon loss with burning of crop residues and dung cakes for household energy among the different wealth groups of the farm households; and its implications on recycling of nutrients and carbon to the soil. The study also conducted comparative evaluations among traditional three-stone open fires, improved cookstoves (mud-stoves and *mirt* stoves) with and without small scale biogas stoves; and assessed implications on availability of crop residues and dung for soil fertility amendment, household finances and mitigations of greenhouse gases emissions. The status of selected soil physical and chemical properties were assessed for comparing against known standards from literatures and for investigating impacts of the different fertilizer types on the considered soil parameters. The plots level On-farm experiments were also carried out for checking whether the blanket recommendation rate was optimum rate for obtaining the maximum possible wheat and teff yield or not. Besides the different fertilizer types were compared in terms of their impacts on agronomic responses, nutrient recovery efficiencies as well as soil physical and chemical properties.

Conducting the stove efficiency tests during the different seasons is helpful for obtaining more representative data and hence to finally come up with more precise results. However, in this study, stove efficiency evaluation was conducted only once because of its costly nature. Though conducting long-term experiment over several years is required to investigate impacts of fertilizer on soil physical and chemical properties, the on-farm trial experiments in this study were only limited to two cropping seasons. Moreover, the on-farm experiments did not involve field replications at both Doliyo and Kumbursa sites because of financial constraint and because of anticipated difficulty of managing more than one field. In order to deeply investigate impacts of different fertilizers and to arrive at more reliable research outcomes, it is necessary to conduct On-farm experiment on different soil types and different crop types. However, due to shortage of time and budget, the trial experiments were limited to only the dominant crop types (wheat for Doliyo Village of Walmara District, and both teff and wheat for Kumbursa Village of Ada'a District). Likewise, only the dominant soil types (Nitosol at Doliyo and Vertisol) at Kumbursa Village were considered for the on-farm experiment. Furthermore, to arrive at more robust conclusions regarding the impacts of fertilizers on the soil, it is advisable to exhaustively consider the different soil physical and chemical properties. Nonetheless, the laboratory cost of analyzing all the physical and chemical soil parameters was found very expensive and hence prohibitive. So only the major soil physical and chemical properties were considered in this study.

1.7. Significance

The potential audiences that can benefit from the findings of this study include academicians, researchers, policy makers, NGOs as well as any other practitioner working in the fields of energy, agriculture and environment.

With regard to contributions to the academic areas, the results of this study adds updated knowledge to the existing literature related to the dynamics of interactions among household energy, soil nutrients recycling and crop productivity. The quantification of the loss of nutrients and carbon with burning of agricultural wastes for fuel provides empirical literature for individuals and institutions to take intervention measures as well as for conducting research on related topics.

The findings from the comparative evaluations of stove efficiency tests in enhancing the availability of agricultural wastes for application to cropland, improving household finance and mitigation of greenhouse gases emissions will serve as important reference material for researchers interested to undertake further studies on household energy. The results of the study on effects of different types and rates of fertilizer on agronomic responses will benefit the academicians working in agricultural sector to conduct further investigations on fertilizer optimization. Comparative evaluation of the different fertilizers as well as comparing against the national blanket recommendation rates contributes to the efforts made to determine the optimum rates of each fertilizer type to be applied to wheat and teff.

The study also tried to shed light on the impacts of the different types and rates of fertilizer on the different physical and chemical properties of soil; this helps agriculturalists and other concerned bodies to take corrective measures that ensure sustainable soil productivity.

Quantification of nutrients and carbon loss due to removal of crop residues and livestock manures for fuel helps agricultural experts and other bodies concerned with soil fertility management to investigate more sustainable intervention mechanisms that help to reverse the adverse effects on soil fertility. The comparative evaluation of the efficiency levels of improved cookstoves and biogas stoves against the traditional three stone open fires helps agriculturalists, development agents and farmers to be aware of the type of cookstoves to be used by the rural farm households to increase the availability of agricultural wastes for application to cropland.

Finally, as this study dealt with cross-cutting issues connecting household energy, agriculture and environment. So the findings are expected to contribute to the raising of awareness among the policy makers working in the sectors of energy, agricultural development and environmental protection to make concerted efforts and to apply holistic approach in taking any intervention measure.

1.8. Organization of the dissertation

This thesis is divided into nine chapters. Chapter one presents brief background information for the study starting with the wider national context, and then briefly describes the study sites. This chapter also contains the study objectives, research questions, rationale of the study and the thesis outline.

Chapter two is devoted to the reviews of conceptual, theoretical and empirical literatures related household energy, soil fertility management and characterizing features of smallholder agriculture in the Highlands of Ethiopia.

The third chapter briefly presents the research methodology beginning from the broader philosophical foundations and research approaches to specific issues related to sampling, tools of data collection, presentation of results and statistical analysis.

In chapter four the background information was briefly given. More specifically, locations of the study sites, topographies, climates, soils, household energy and charactering features of the farming systems were presented in this chapter.

The fifth chapter assessed household energy consumptions and quantified nutrients and carbon loss from the farming system with the utilization of crop residues and dung cakes for household energy for the different wealth groups of farm households in Kumbursa Village.

Chapter six deals with comparative evaluation of the biomass fuel use efficiencies of the traditional three-stone open fires, mud-stoves and improved cookstoves with-and-without biogas The comparative advantages of mud-stoves and mirt stoves with and without biogas stoves were evaluated in terms values for increasing the availability of crop residues and dung for soil fertility improvement, improving household finances and reduction of greenhouse gases emissions.

In chapter seven, selected physical and chemical soil properties for the plough level (the top 20cm depth) of soils used for the On-farm trial experiment of wheat and teff were analyzed for comparing the selected soil properties against the known standard values from literature as well as for examining the impacts of the different fertilizer types used for the On-farm trial plots experiment on the considered soil parameters.

The eighth chapter presents the impacts of the different fertilizer types on the total above ground biomass, grain yields, nutrient use efficiencies and apparent recoveries of nitrogen and phosphorus applied from the five different fertilizer types.

This chapter also tries to check whether the nationally recommended nitrogen and phosphorus rates are appropriate rates for obtaining the maximum possible wheat and teff yields or not.

Finally, chapter nine presents the synthesis of the major contents of the thesis by synthesizing main findings of each chapter. This chapter helps the reader to have the holistic understanding of the interactions among cross-cutting issues i.e. household energy, soil fertility and crop productivity.

Chapter 2

Review of related literature

This unit mainly focuses on literature reviews related to impacts of removing agricultural wastes for fuel and its implications for soil fertility and crop productivity. The major issues treated under this unit include degree of reliance on biomass fuel, causes and consequences of switching from fuelwood to agricultural wastes for fuel, the potential environmental and socio-economic benefits gained from improving biomass fuel use efficiency. Furthermore, paradigm shifts in soil fertility management, challenges facing successful implementation of integrated soil fertility management, characterizing features of smallholder farms in Ethiopia and the need for optimizing application rates of fertilizer were discussed under this unit.

Finally, based on the reviewed literature, the conceptual frameworks focusing on household energy consumption models (energy ladder and energy stacking) as well as household energy-soil nutrients recycling-crop production nexus were briefly presented.

2.1. Removal of agricultural wastes for fuel and its implications for recycling of nutrients and carbon to the soil in the Highlands of Ethiopia

Biomass fuel constitutes about 90 to 98% of the total residential fuel consumption in most of Sub-Saharan countries, and Ethiopia ranks second, only preceded by Nigeria in terms of biomass fuel consumption rate (Idiata *et al*., 2013). Biomass fuel reportedly makes up over 90% of the total energy demand of Ethiopia (Dawit, 2012; EUEI, 2013; Getamesay *et al.*, 2015; Gudina & Nonhebel, 2015; Gwavuya *et al.*, 2012), providing almost all of the energy demand of rural households, and accounting for approximately 85% of the total cooking fuel consumed by urban households in Ethiopia (Abebe *et al.*, 2011).

The estimated total annual production potential of dung and crop residues in Ethiopia is 33.0 and 22.4 million tons, respectively; 60% of this, 22.8 and 10.3 million tons respectively, are used as fuel (EUEI, 2013). The prevailing intense competition between use for fuel and fertilizer of cattle dung and crop residues (Abebe *et al.*, 2015; Gwavuya *et al.*, 2012; Smith *et al.*, 2014) has severely threatened agricultural productivity in many areas (Aklilu, 2006; Assefa *et al.*, 2007;

Dawit, 2012). For instance, the use of cattle dung for fuel instead of using it as fertilizer is estimated to have reduced agricultural gross domestic product (GDP) by ~7% (IFRI, 2010).

Unfortunately, it is also likely that the demand for locally sourced biomass fuels, including livestock manures and crop residues, will keep increasing into the foreseeable future; and based on business-as-usual scenario projections, the mean annual firewood deficit of Ethiopia will be 5.6 million tons by the year 2030 (EUEI, 2013).

Ethiopia is ranked as one of the four countries in the world with the highest per capita biomass fuel consumption, disease burden from indoor air pollution and use of biomass fuels (Bailis *et al.,* 2015). It also has the second highest reliance on traditional fuels of all countries in Africa, only preceded by Nigeria (Idiata *et al.*, 2013), and with ~ 94% of its total energy demand derived from solid biomass (Kooser, 2014). Under a business-as-usual scenario, biomass fuel demand in Ethiopia is projected to increase by 65% by the year 2030; this has been linked to deforestation of 9 million ha forestland (FDE, 2011).

Generally, the longstanding culture of recycling nutrients with application of organic resources has been almost entirely interrupted in the Highlands of Ethiopia due the large scale switch to crop residues and dung cakes for fuel (Aklilu, 2006; Kassahun *et al.*, 2013). There is a likelihood of increased demand for agricultural wastes as fuel mainly due to the utilization of inefficient three stone open fires, fast population increase and stagnant shift to improved energy sources (Abebe *et al.*, 2015). The dominant majority of the households in the Highlands of Ethiopia rely on traditional biomass fuel, and the use of improved cookstoves and biogas digesters have remained very low (NBPE, 2008). In summary, it could be learned from the reviewed literature that both improved cookstoves and biogas digesters need to be promoted due their values in fuel saving efficiencies and hence increasing the availability of dung for application to farmlands.

2.2. Causes and consequences of switching from firewood to agricultural wastes for fuel in Ethiopian Highlands

In many highland areas of Ethiopia, there has been immense shift from wood to agricultural wastes for fuel including dung cake and crop residues due to scarcity of wood supply (Abebe *et al.,* 2015; Zenebe *et al.*, 2014). Such traditional source of energy has been one of the factors responsible for a number of adverse environmental, social and economic impacts (NBPE, 2008). As reported by Mulu (2016), dung and crop residues generate low-grade fire, less heat, and more smoke thereby causing health risk and make cooking chore time consuming and less pleasant. Excessive reliance on biomass fuel, compounded by inefficient combustion technologies in the Highlands of Ethiopia, has been contributing to increased deforestation, scarcity of fodder and depletion of soil fertility (Abraham *et al.*, 2015). Biomass energy use leads to deforestation, heavy workloads and respiratory diseases (IRENA, 2018). Large scale traditional biomass fuel utilization also exacerbates land resources degradation, desertification and biodiversity loss (Abera, 2016; GIZ, 2014; Idiata *et al.*, 2013). Large scale reliance on biomass collected from farmlands for energy has been identified as one of the primary factors for soil fertility depletion and loss of agricultural productivity (Kassahun *et al.,* 2013). Large amounts of nutrients are exported from the farming systems through the sale of cow dung and stover for energy; and loss of N and P resulting from the use of dung and crop residues for fuel is equivalent to the total amount of commercial fertilizer use (ATA, 2013).

Furthermore, it is likely that the growing demand for biomass fuels due to population growth will result in future increased rates of deforestation and greenhouse gas (GHG) emissions (Lemlem, 2016). Increased firewood scarcity (Dawit, 2012; Getamesay *et al.*, 2015), inefficient utilization of the available biomass fuel resources (Dagninet *et al.*, 2015; Getamesay *et al.*, 2015); and limited access to alternative modern energy sources (Kassahun *et al.*, 2013; Smith *et al.*, 2014) have generally contributed to the ever increasing shift to dung cakes and crop residues as fuels at the expense of application to farmland for soil fertility improvement.

In the Ethiopian Highlands, dwindling woody biomass supplies have resulted in the widespread shift towards using cattle dung and crop residues as fuels at the expense of applying them to farmland (Abebe *et al*., 2015; Kassahun *et al*., 2013; Woldeamlak, 2003).

This immense switch to using dung cakes and crop residues for fuel has become a serious limitation to the success of the Ethiopian government targets to intensify agriculture and build a green economy through promotion of organic fertilizers (FDRE, 2011). As reported by Dagninet *et al*. (2015) and Dawit *et al*. (2015), high demand for biomass fuels and consequent acute scarcity of firewood in the Highlands of Ethiopia has compelled many rural farm households to change their fuel source to agricultural residues.

Under the current condition of unaffordable and increasing oil prices, and limited access to electricity, agricultural waste is the only fuel option available to many households (Abebe *et al*., 2015). Fuel wood crisis is now widespread in the Central and Northern Highlands of Ethiopia, and many households are struggling to get even enough dung and crop residues to meet fuel demands (Mulu, 2016). Competition over agricultural residues for fuel and fertilizer was also identified by Assefa (2005), Dawit *et al*. (2015) and Hailemariam (2011) as one of the primary causes for the loss of carbon and nutrients from crop-livestock mixed farming systems of the Ethiopian Highlands. So the availability of agricultural residues (crop residues and dung) for use as animal feeds and organic fertilizers has been dramatically decreased (Abebe *et al.,* 2015; Aklilu, 2006; Amare, 2005). Soil nutrient deficit, which has been worsened by biomass removal from farmland has been identified as one of the most important underlying causes for the prevailing low crop productivity in smallholder farms of Ethiopian Highlands (Aklilu, 2006; Assefa and Keulen, 2009; Balesh, 2005; Dawit *et al.,* 2015; Kassahun *et al.,* 2013).

Extensive use of biomass fuels also adds to the burden of women in collecting increasingly scarce biomass fuels; and exacerbates gender inequality by taking away time that could have been used for productive activities (SEI, 2013). Indoor air pollution from traditional biomass fuels has a disproportionate impact on women and is listed among the three top causes of death in most countries of Sub-Saharan Africa (Lambe *et al.*, 2015). Various health related problems of many rural and some urban households in Ethiopia are associated with excessive smoke released from traditional biomass burning in unventilated traditional kitchens and houses (Getachew *et al.,* 2006; NBPE, 2008; Winrock International, 2007).

2.3. The potential environmental and socio-economic benefits of improving biomass fuel use efficiency

In order to alleviate the detrimental environmental and socio-economic effects associated with traditional biomass fuel utilization in Ethiopia, increasing use efficiency by substituting the three stone open fires with improved solid biomass cookstoves and biogas have been recommended as potential approaches (Gaia, 2012; Gwavuya *et al*., 2012; Kassahun *et al.*, 2013; SEI, 2013). This is because the shift towards modern energy sources like electricity in the short term is unrealistic for the extremely scattered rural Villages of the Ethiopian Highlands (Abebe *et al.*, 2015; FDRE, 2011; Hilawe *et al.*, 2011). So substituting the traditional three-stone fires with improved cookstoves and biogas digesters could be viable alternatives (Kassahun *et al.*, 2013; Mulu *et al.*, 2016). However, most rural households in Ethiopia are still dependent on inefficient three-stone open fire cooking (Gaia, 2012); and as reported by Abebe *et al.* (2015), three-stone fires account for 92% of all cooking, while the coverage of improved cookstoves is only 8%.

Improved cookstoves and small scale biogas digesters have the potential to narrow the gap between energy demand and supply through their increased efficiency and consequent enhancement of biomass fuel availability (Getachew *et al*., 2006; Seid *et al*., 2014). Improved cookstoves that are currently in use in Ethiopia include locally made “mud-stoves”, as well as the more efficient, government designed “lakech” (“excellent”) improved charcoal stove and the “mirt” (“best”) improved biomass *injera* stove. Mud-stoves are enclosed stoves made up of mud mixed with straw or hay by local artisans in the location where they will be used (Accenture, 2015). *Lakech* and *mirt* stoves were developed by a UK-based company, Energy for Sustainable Development, and the Ethiopian Ministry of Water and Energy in the early and mid-1990s (Energy for Sustainable Development, 2017).

Substitution of the traditional three-stone open fires by improved cookstoves was recommended as a means to increase the availability of agricultural wastes for soil amendment (Dawit *et al*., 2015).

Improved cookstoves can either be used to burn wood or charcoal, or can be adapted to burn biogas (Tumwesige *et al.*, 2014). Biogas is a clean fuel, produced by anaerobic decomposition of organic wastes, leaving a nutrient rich “bioslurry” residue that can be used as an organic fertilizer (Getachew *et al.,* 2006; Gwavuya *et al.*, 2012; Smith *et al.,* 2014). Application of bioslurry to agricultural fields from biogas digesters could also greatly increase the carbon content of the soil, thereby improving soil fertility and crop productivity as well as for reducing net GHG emissions (Abubaker, 2012; Smith *et al.*, 2013).

In order to enhance the availability of agricultural wastes for recycling to farmlands, Mulu *et al*. (2016) suggested the substitution of traditional household energy with improved cookstoves and installation of household based biogas digesters. As reported by Aklilu (2006), Amare (2005) and Dawit *et al.* (2015) substituting the current poorly efficient open fire stoves with more efficient improved solid biomass stoves and biogas stoves can significantly contribute to increased availability of dung and crop residues for applying to farmland.

The transition to improved solid biomass cookstoves and biogas digesters is likely to enhance the availability of manure and crop residues for use as organic fertilizers, which in turn, contributes to the enhancement of agricultural productivity (Alemu & Kohlin, 2008; Assefa *et al.*, 2007; Smith *et al.,* 2014). Besides, the potential benefits that could be obtained from the shift to more efficient biomass fuel utilization technology are improvement of household finances and greenhouse gases emissions (Smith *et al.*, 2014).

In order to enhance the availability of crop residues and livestock manure for application to farmland, increasing the efficiency of biomass fuel by replacing the traditional three stone fires with improved cookstoves and small scale biogas digesters have been suggested (Getachew *et al.,* 2006; Mulu *et al.,* 2016). Ethiopia has tremendous potential for adopting household based small scale biogas digesters with about 3.5 million rural households in the four major regions (Tigray, Amhara, Oromia and SNNP) that have both sufficient cattle dung and water to operate a domestic biogas installation (Getachew *et al.,* 2006).

Having realized the high potential and multiple benefits of small scale biogas, some efforts have been started by the Ethiopian government under the National Biogas Program of Ethiopia

(NBPE) and the Netherlands Development Program (SNV) (NBPE, 2008). Nevertheless, the uptake level so far has remained very negligible with only 10,000 plants (NBPE, 2008). Likewise, the uptake of improved cookstoves has also been very low with only less than 10% of the rural households that utilize improved cookstoves while more than 90% are still using traditional three stone open fires for cooking (Abebe *et al.*, 2015).

Thus, large scale dissemination of small scale biogas digesters is a potential approach to reverse the adverse environmental and socio-economic effects of traditional biomass burning in the Highlands of Ethiopia (Getachew *et al.*, 2006). Biogas technology also contributes to sanitation through treatment of organic wastes before application of bioslurry to agricultural fields (Bonten *et al.*, 2014; NBPE, 2008; Tumwesige, 2011).

With respect to GHG emission reductions, improved cookstoves and biogas, could benefit Ethiopia through carbon financing which is provided by the Clean Development Mechanism (CDM), Reduced Emission from Deforestation and Forest Degradation (REDD+) and World Bank Forest Carbon Partnership Facility (WB-FCPF) (Zenebe *et al.*, 2012).

2.4. Paradigm shifts in soil fertility management in Sub-Saharan Africa

In Sub-Saharan Africa (SSA), soil fertility management paradigms have undergone several changes since 1960s (Sanginga & Woomer, 2009). During 1960s and 1970s, external inputs such as inorganic fertilizers, lime and irrigation water was the dominant paradigm for soil fertility management while organic resources were believed to play only minor role (Vanlauwe *et al.*, 2009). The external input paradigm in SSA was stimulated by the Green Revolution in Southeast Asia and Latin America which was supported by extensive use of fertilizer due to subsidization of price (Bationo *et al.*, 2006). However, this paradigm ended up with little success due to low capacity of the poor smallholder farmers to afford the high cost of the external inputs and little agronomic efficiency due to the already deteriorated soil fertility which required interventions beyond application of fertilizer (Fairhurst, 2012).

Even if accessibility is not a challenge, reliance on mere application of inorganic fertilizer is not effective when its long term use is considered (Raj *et al.*, 2014). This is because continuous application of inorganic fertilizer adversely affects sustainability of soil productivity by causing problems of soil acidification as well as soil nutrient imbalance (Dubey *et al.,* 2012; Titilola, 2006). Aguilera *et al.* (2012) and Ogundijo *et al.* (2014) also reported that over application of chemical fertilizers result in a number of unforeseen problems such as soil acidification, impoverishment of soil biota, soil nutrient imbalances and environmental pollutions. For instance, over use of N fertilizer does not only lead to reduced uptake efficiency but also causes serious environmental pollution (Zhong *et al.*, 2014; Hartemink, 2006). The study conducted by Raj *et al.* (2014) also revealed the deleterious effects of inorganic fertilizer on soil earthworms. Excessive use of ammonia fertilizer reduces soil PH and low soil PH in turn decreases availability of all macro nutrients while exacerbating iron and manganese toxicities (NRCCA, 2016).

Exclusive dependence on inorganic fertilizer was seriously challenged by the proponents of low-external-input sustainable agriculture (LEISA) (Hartemink, 2006; Sanginga & Woomer, 2009; Vanlauwe et al., 2014). LEISA (Low-external-input sustainable agriculture) was appreciated because of its reliance on accessible organic resources by poor smallholder farmers as well as little use of agrochemicals (IFPRI, 2010; Vanlauwe *et al.*, 2009). Thus, in 1980s, a shift towards low-external-input biological soil fertility management occurred, and utilization of inorganic fertilizer as well as other external inputs served as a key entry point (Fairhurst, 2012). Organic fertilizer is usually preferred to inorganic fertilizers due to gradual release of nutrients as well as because of its contribution to the improvement of soil qualities (Vanlauwe, 2010); Hailu 2010; Balesh, 2006) and Raj *et al.*, 2014). Organic resources play significant role in soil quality improvement besides supplying nutrients thus having benefits that cannot be obtained from inorganic fertilizers (IFPRI, 2010). Dubey *et al.* (2012) reported that the use of NPK from inorganic fertilizer resulted in depletion of micro nutrients such as boron and zinc, and hence recommended the integrated use of inorganic fertilizer and organic fertilizer to alleviate the problem.

The acceptance of low-external-input paradigm gradually declined owing to limitations such as inadequate availability of organic resources, intensive labor requirement and low level of awareness (Vanlauwe *et al.*, 2010).

Thus, the combined application of organic and inorganic fertilizer emerged in 1994 as a new paradigm for soil fertility management (Sanginga & Woomer, 2009). As reported by Vanlauwe (2010), the limitations associated with sole application of chemical fertilizer and organic fertilizer can be surmounted through integrated utilization of both. Complementary use of organic and inorganic fertilizers is also recommended for intensifying agriculture since it increases yield response and ensures sustainable soil fertility (Titilola, 2006).

This paradigm was justifiably supported for soil fertility management as organic resources are not adequately available for soil fertility replenishment unless supported by inorganic fertilizer (Killham, 2010). Today, integrated soil fertility management (ISFM) is considered as part of integrated natural resources management (INRM), and it normally involves combined use of organic and inorganic fertilizers with multiple stakeholders focusing on social, economic and political dimensions (Sanginga & Woomer, 2009). ISFM is the application of soil fertility management practices and the knowledge to adapt these to the local conditions which maximize fertilizer and organic resource use efficiency and crop productivity (Sanginga & Woomer, 2009; Vanlauwe *et al.*, 2010). As reported by Killham (2010) and Vanlauwe *et al.* (2014), the practices of ISFM necessarily include appropriate fertilizer and organic input management in combination with the utilization of improved germplasm.

The basic characterizing features of ISFM include: a) the judicious application of purchased fertilizer, b) the efficient management of available organic resources, c) wider integration of nitrogen-fixing legumes into cropping systems, and d) the conservation of soils, their biota and organic matter (Sanginga & Woomer, 2009). ISFM should be implemented by smallholder farmers of SSA because if properly implemented, it can integrate local suitability, economic profitability, adaptability and sustainability (Vanlauwe *et al.*, 2010). Combined application of inorganic fertilizer and locally available organic residues results in the improvement of agronomic efficiency while protecting soil quality (Lulseged *et al.*, 2017; Sanginga & Woomer, 2009). ISFM deters excessive inorganic fertilizer application and hence avoids agronomic inefficiency and environmental pollution (Rufino, 2008; Spielman *et al.*, 2012). Adapting the technologies of ISFM normally relies on 'Socio-ecological nitche' and should therefore adjust itself to the local social, economic and agroecological conditions (Sanginga & Woomer, 2009).

Use of inorganic fertilizer in conjunction with organic resources improves agronomic efficiencies of crops (Vanlauwe *et al.,* 2014). Widespread adoption of ISFM has been considered by Sanginga (2012) as the most preferable pathway for narrowing the prevailing gap between the observed and potential agricultural yields in SSA.

2.5. Challenges facing implementation of integrated soil fertility management practices in Ethiopia

Integrated soil fertility management (ISFM) is a means to enhance crop productivity while maximizing the agronomic efficiency (AE) of applied inputs, and can thus contribute to sustainable intensification (Vanlauwe *et al.,* 2015). To enhance crop productivity on sustainable basis, and ensure food security in Ethiopia, soil nutrient stocks should be improved through increased application of inorganic fertilizer as well as recycling of organic resources (Abebayehu and Eyasu, 2011). A study conducted by Dereje and Assefa (2015) and IFRI (2010) also capitalized on the need for intervention beyond the application of chemical fertilizers such as recycling of agricultural wastes in order to amend soil fertility. Soil amendment with organic and inorganic fertilizer for maintaining soil fertility and crop productivity was also commended by Teklu & Hailemariam (2009).

However, chemical fertilizers are underutilized due to the limited purchasing power of smallholder rural farm households, supply shortage and tardy arrival (IFRI, 2010; Kefyalew, 2011). As also reported by Tadesse (2017), the sub-optimal fertilizer application is attributed to escalating costs. Applications of chemical fertilizer in Ethiopia are usually constrained by the low purchasing powers of the poor rural farm households while the recycling of organic matter into cropland is limited due to the competing demands on animal manure and crop residues for household energy consumption (Aklilu, 2006; Hailu, 2010). Although most smallholder farmers appreciate the benefit of fertilizers, they rarely apply at the recommended rates and at the appropriate time because of unreliable returns, high cost, lack of supportive policy to access, and limited knowledge about their efficient use (Lulseged *et al.,* 2017).

The application of organic fertilizer to farmlands in the Highlands of Ethiopia is also limited because of the competing use of crop residues for feed and fuel; and cattle dung for fuel (IFRI, 2010).

Studies conducted by Abebe *et al*. (2015), Aklilu (2006) and Kassahun *et al.* (2013) also disclosed that there are almost total interruption of nutrient recycling from agricultural wastes due to use as fuel instead of applying to farmlands for soil amendment.

Another serious challenge facing crop production in Ethiopian Highlands is soil acidity. About 40% of the total area of Ethiopia is covered with acid affected soil; and the depletion of soil organic matter and increased reliance on nitrogen fertilizer (DAP & Urea) further exacerbates the already critical problem of soil acidity (IFRI, 2010). Dwindling firewood supplies due to deforestation and the consequent switch to dung cakes and crop residues for fuel in the Highlands of Ethiopia has also generally jeopardized agricultural productivity (Zenebe, *et al*., 2006).

In short, the reviewed literatures suggest that the use of agricultural wastes for fuel instead of applying to farmland has already become a serious hurdle to the successful implementation of ISFM in the Highlands of Ethiopia. As a result, the agricultural yields are continuing to stagnate despite the increasing trends in application rates of inorganic fertilizer.

2.6. Characterizing features of smallholder farming in Ethiopian Highlands

Smallholder agriculture accounts for about 96% of the cultivated area (Tegbaru, 2016). The smallholder farming in the Highlands of Ethiopia is characterized by low-input and hence stagnating productivity mainly due to soil fertility decline and nutrient depletion (Mulugeta *et al.,* 2017; Workneh, 2015). Unbalanced nutrient input and output, and consequent soil nutrient depletion is another characterizing feature presenting serious impediment to sustained agricultural productivity (Amare *et al.,* 2006; Teklu & Hailemariam, 2009). Negative nutrient balances and decreasing nutrient stocks have also been reported by several researchers including Amare, *et al*. (2006), Assefa, *et al.* (2009), Balesh (2005), Bogale (2014) and Hailu (2010). Low soil fertility in Ethiopian Highlands due to continuous monocropping, crop residue removal and limited fertilizer use has also been witnessed by Abebe & Deressa (2017). In the high-rainfall humid areas, soil acidity is a severe constraint to crop productivity affecting about 43% of agricultural land in the Ethiopian Highlands (ATA, 2013).

Ethiopia is one of the most vulnerable countries in Africa with over 7 million of its citizens facing food insecurity (FDRE, 2011) which can in part be attributed to low agricultural productivity because of insufficient external inputs and subsequent soil nutrient depletion. Soil nutrient depletion in Ethiopia is so severe and as reported by Amare *et al.* (2005), all the soil macro-nutrients showed negative balances and the prediction was twice as high as the average value for SSA. A study on small scale farms in the Northern Highlands of Ethiopia reported net negative balances for N, P and OC (Assefa and Van Keulen, 2009). These negative balances are due to very low amounts of inflow of nutrients compared to outflows from agricultural systems, meaning that the human-soil interaction is unsustainable, with only small quantities of organic materials used for fertility improvement.

In Ethiopia, the progress in agricultural productivity has remained sluggish with average yields below 2t ha^{-1} for cereals and 0.8t ha^{-1} for pulses (ATA, 2013). This extremely low crop productivity specially in intensively cultivated Ethiopian Highlands is predominantly attributed to soil nutrient depletion coupled with insufficient nutrients replenishment (Alemayehu and Eyasu, 2011; Assefa, 2009; Demiss *et al.*, 2017; Okubay *et al.*, 2014). Smallholder farms in Ethiopian Highlands are also known for inadequate fertilizer application which is mainly responsible for the prevailing low crop productivity and consequent food insecurity problem (Abebayehu and Eyasu, 2011; Debela, *et al*., 2011). Application rates of inorganic fertilizers in Ethiopia is lower than the average rate for East Africa, and the use of manure is also almost nil (Mulugeta *et al.*, 2017). The dramatic increases in agricultural production in Southeast Asia (Green Revolution) was achieved through higher inputs resulting in higher yield per area, while the observed lower yield increases in Africa including Ethiopia was achieved due to expansion of area under crop production (Henao & Baanante, 2006). As also reported by IFRI (2010), the observed increase in agricultural production in Ethiopia has been due to bringing more and more land under cultivation than yield improvement per area of agricultural land. In order to reverse the prevailing yield stagnation, combined application of inorganic and organic fertilizers has been recommended (Balesh, 2006; Hailu, 2010; Raj *et al*., 2014). Complementary use of organic and inorganic fertilizers is advocated especially in intensive agriculture for increasing yield response as well as for sustainable soil fertility management (Titilola, 2006).

Integrated application of organic and inorganic fertilizers performs better than their individual application (Vanlauwe, 2010). Moreover, the problem associated with inadequate use of chemical fertilizer due to limited purchasing capacity, supply shortage, and late arrival can at least be partly alleviated through integrated application of organic and inorganic fertilizers (Kefyalew, 2011).

Though combined use of organic and inorganic fertilizers is at its infancy with limited geographic coverage in terms of its dissemination (Dereje and Assefa, 2015); it has been proven significant for improving soil fertility and crop productivity (Balesh, 2006; Hailu, 2010). As reported by Bationo *et al.* (2006), integrated use of chemical and organic fertilizers should be scaled up and widely adopted not only for narrowing the prevailing gap between the potential and actual crop productivity but also because of its eco-friendliness and easily adaptable nature to the varying biophysical and socioeconomic conditions.

2.7. The need for optimizing application rates of fertilizer

Blanket fertilizer recommendation is over-generalized and it neglects locally specific socio-economic and biophysical conditions (Sanginga & Woomer, 2009). Fertilizer underutilization is common problem for almost all countries of Africa with consumption rates of less than 5kg ha^{-1} in about 55% of SSA countries, and this is far below the optimum level (Sanginga & Woomer, 2009). Gradient in soil fertility due to inherent soil fertility status and/or management discourages the adoption of blanket fertilizer recommendation (Tegbaru, 2016). The approaches in fertilizer utilization so far have not significantly increased yield mainly due to lack of national soil information and unbalanced use of fertilizers (Tegbaru, 2016). The blanket recommendation is considered as poor approach as it rarely considers the diverse agroecologies and soil characteristics (Tegbaru, 2016).

In fact fertilizer recommendation should normally be preceded by soil fertility test results since one needs to know the status of each nutrient in order to take appropriate soil fertility amendment measures (Hertemink, 2006).

Diagnosis of soil nutrients status requires understanding of soil fertility decline which can be expressed in terms of nutrient depletion (larger removal than addition of nutrients); nutrient mining (large removal of nutrients and no inputs); soil acidification (lower pH and/or an increase in exchangeable Al); the loss of organic matter and increase in toxic elements (Hartemink, 2006). Be it inorganic, organic or combination of both, appropriate fertilizer application management is required for improving crop productivity while also maintaining soil fertility for sustainable use (Dong *et al.*, 2012; Raj *et al*., 2014).

In Ethiopia, determination of the optimum dose of fertilizer has been almost entirely neglected so far (Kefyalew, 2011). For the past four to five decades, fertilizer consumption in the country has been limited to DAP and Urea that supply only N and P; and there has been mere reliance on the blanket recommendations regardless of differences in crop need, soil types and agroecologies (ATA, 2013).

This is because both unsuitable fertilizer type and dose can result in soil quality deterioration and reduced crop yield (ATA, 2013). Hence, there should be a need to pay critical attention on the selection of the type and determination of the optimum rate of fertilizer to be applied to farmlands (Qiu *et al.*, 2014).

However, fertilizer utilization in the Highlands of Ethiopia is untailored; and it has only been dependent on the blanket application of DAP and UREA which falls short of considering crop need, dynamics in soil nutrient stocks and local agroecologies (Abay *et al*., 2011; Amare *et al*., 2006; ATA, 2013). Blanket application of nutrients fails to target crop types, landscape position and drought regimes, and when farmers are advised to use the blanket application, irrespective of their soils and landscape position, the return will be limited, prompting smallholder farmers not to adopt this practice (Lulseged *et al.*, 2017). This implies that information on locally tailored and scientifically proved optimum fertilizer rates in the Highlands of Ethiopia is generally scarce. So a carefully assessed and locally tailored fertilizer prescription and application is required for obtaining optimum crop yields on sustainable basis. The fact that there is wide variability in soil fertility status from locality to locality implies the need for little reliance on blanket fertilizer recommendation (Mesfin and Kassa, 2015).

For instance, Demiss *et al.* (2017) confirmed considerable variability in teff and wheat yields under constant rates of potassium fertilizer application in different topographic and climatic conditions. Mesfin and Tekalign (2011) also stressed on the importance of indexing phosphorus fertilizer for different soil types found in different agroecologies.

In a nutshell, evidences from the reviewed literatures imply that soil fertility management falls short of optimizing fertilizer application rates. No attempts have been made so far to determine optimum fertilizer rates to specific localities. The only recommended fertilizer rate available so far is the blanket recommendation rates (64 kg N & 46 kg P) for DAP and urea while such attempt of fertilizer determination is totally absent for compost and bioslurry. So fertilizer application should be optimized since unscientific use (under and over application) is a serious threat to sustainable crop production which in turn results in risks of lower profit and soil health deterioration (Singh *et al.*, 2017).

2.8. Sole application of inorganic fertilizer and its effects on crop yields: evidences from Ethiopian Highlands

DAP and urea have been the only chemical fertilizers used for the last four decades (Mulugeta *et al.*, 2017). It has been argued that sole application of chemical fertilizers in the Highlands of Ethiopia has at least partly contributed to the low agronomic responses regardless of increased application rates (ATA, 2013; Mulugeta *et al.*, 2017). For instance, application rate of chemical fertilizer has increased fivefold since 1980s resulting in yield increase of only 10% (IFRI, 2010). Spielman (2011) also reported that mean yield to fertilizer ratio declined from 3.74 to 1.91 for teff and 4.24 to 2.18 for maize from the years 1992 to 2008. As disclosed by ATA (2013), the use of DAP and Urea in Ethiopia increased by 10% while crop yield increased only by 5% between the years 2003/4 and 2010/11; and the value cost ratio of fertilizer is greater than 2 only for maize while it ranges between 1.27 and 1.86 for wheat and teff. As suggested by IFPRI (2010), interventions beyond chemical fertilizer application including increased application of agricultural wastes are needed in order to improve soil fertility and crop productivity. To restore depleted soil organic carbon and nutrients in the Highlands of Ethiopia, Hailu (2010) and Getamesay *et al.* (2015) suggested increased application of available organic resources to farmlands. Studies undertaken by Winrock International (2007) also reported that the carbon content of soils in the Highlands of Ethiopia is below the critical limit; and hence highlighted the need to add organic matter so as to enhance soil fertility.

2.9. Improved biomass cookstoves in Ethiopia

2.9.1. Types, fuel use efficiency and uptake level

In Ethiopia, the common solid biomass cookstoves currently in use include lakech, Gonziye, mud stoves and mirt stoves (GIZ, 2014). The lakech stove is made of ceramic and metal (Hedon, 2017), while the mirt stove is made of cement (Energypedia, 2017). Gonziye is used for injera baking and it is made of ceramic mostly by the local potteries. Mud-stove is prepared from mud and its design is mostly similar with that of *mirt* stove. *Mirt* stoves are specifically designed for baking the staple food, *injera*, a pancake like thin bread made of teff flour which is native to Ethiopia and accounts for ~65% of fuel consumption (Yosef, 2007). They can also be used to cook and boil food while baking without the use of additional fuel (Kindu Trust, 2017).

Significant improvements in biomass fuel use efficiency can be achieved with substitution of the traditional three stone fires with improved cookstoves and/or biogas. For instance, the conversion of 14.44 million rural and urban households to *mirt* and *lakech* stoves is estimated to have resulted in an annual firewood saving of ~7, 778,800 t per year, which is equivalent to 137,192.24 ha of forest clear cutting (EPA, 2004 in Abebe and Kotch, 2011). Improved cookstoves also have the potential to contribute up to 13% to 18% of the GHG mitigation targets of the Ethiopian government to be achieved by 2030 (FDRE, 2011).

Despite some efforts made since the 1970s to introduce and disseminate improved cookstoves and small scale biogas digesters in Ethiopia, adoptions have been limited (Kooser, 2014). For instance, by 2014, only 11% of households in Borena woreda of North Central Ethiopia were using improved stoves and, of these, 90% were mud-stoves (Amogne, 2014). In the Enqulal watershed of Northern Ethiopian Highlands, only ~4% of rural households used locally produced mud-stoves, while the remaining 96% used traditional three-stone open fires for baking injera (Amogne, 2014). Over the last two decades, use of improved cookstoves in urban centers has grown, but adoption in rural areas still remains very slow (Alemu *et al.*, 2009; Gaia, 2012).

Only 1.2 million people of low-income households in Ethiopia have access to improved cookstoves, and unavailability of stoves was given as a limiting factor in 64% of households not using improved stoves (GIZ, 2014). In the Amhara region of Ethiopia, the high price of *mirt* stoves was also given as the reason for non-adoption (Amogne, 2014).

2.9.2. Efforts made by the Ethiopian government to disseminate improved cookstoves and small scale biogas digesters

Though the uptake level so far has been very low, the Ethiopian government is working towards dissemination of about 20 million improved cookstoves by 2030 (FDRE, 2011). Similarly, the Ethiopian government is introducing small scale biogas digesters under the National Biogas Program of Ethiopia (NBPE) and the Netherlands Development Program (SNV) (NBPE, 2008).

A feasibility study, conducted in the four major regional states of Ethiopia i.e., Tigray, Amhara, Oromia and SNNP, identified 3.5 million rural households that have both sufficient cattle dung and water to operate a domestic biogas digester (NBPE, 2008). If Ethiopia was to fully exploit the potential of its organic wastes for biogas production, it could save 6,722 t of wood, on daily basis (Betelhem and Wondwossen, 2016).

2.10. Conceptual frameworks

2.10.1. Determinants of household energy choice in Developing Countries

Transition to more efficient household energy in developing countries including Ethiopia is crucial for sustainable household energy utilization. Household energy use could be best described by the theory of consumer behavior. However, there is little consensus in the literature on the factors determining choice of household fuel because fuel choice and consumption characteristics are highly specific to the local context (Remigios, 2014).

The most commonly used theoretical frameworks for analyzing household energy transition are the ‘energy ladder’ and ‘fuel stacking’ models which respectively refer to the perfect and partial substitution of one energy source with another one (IEA, 2014). The energy ladder hypothesis is one of the most common conceptualizations of energy use dynamics among households; and it postulates that low income households generally use traditional stoves and cooking fuels such as animal dung, charcoal and wood, while those households with higher income use modern cooking technology and fuels (Ogwumike *et al.*, 2014).

When income increases, households not only consume more of the same good they also shift to more sophisticated goods with higher quality (Ogwumike *et al.,* 2014). The energy-ladder hypothesis emphasizes the role of income in determining fuel choices. However, it appears to imply that a move up to a new fuel is simultaneously a move away from previously used fuel(s) (Ogwumike *et al.,* 2014).

The energy-ladder model refers to complete abandonment of the inferior fuel, and hence a total shift to the superior fuel; it assumes universal access to all energy sources among which consumers rationally choose based on their income (Risseeuw, 2012). The fuel stacking model, on the other hand, refers to addition of new energy sources and superior fuels upon existing fuels, hence resulting in multiple fuel use; it considers multiplicities of fuel choice and consumption dictating factors, among which, income is only one (IEA, 2014; Remigios, 2014; Tebelier, 2012).

The fuel stacking model better explains energy use behavior in Sub-Saharan African countries in general and that of Ethiopia in particular as households tend to use multiple fuels instead of abandoning previous fuel sources due to unreliable supply and limited affordability (Alemu &Kohlin, 2008; Ogwumike, 2014; Trebier, 2012). Moreover, universal access to all fuel sources is rare and consumers are far from being rational in fuel choices; a number of non-economic factors (socio-cultural, institutional and environmental) can influence fuel choice and consumption (Trebier, 2012).

The consumption of “dirty” fuels, including biomass fuels, which result in poor indoor air quality, tends to decrease with increasing household income (Masera *et al.*, 2000; Omojolaibi, 2015; Onoja, 2012). There is generally a positive correlation between the adoption of new energy sources and household wealth status (IEA, 2014; SEI, 2008), but Jan *et al.* (2011) in Pakistan; and Samuel (2002) in Ethiopia, found no significant positive relationship between wealth status and uptake of modern energy.

In India, Hanna & Oliva (2013) observed that even where cleaner alternative energy sources were available, rich households tended to use more cow dung than the poor because they owned more cattle.

Because use of biomass fuels is so deeply ingrained in the cultures of many rural societies of developing countries, transition to modern energy sources is often delayed (Risseeuw, 2012). Households may persistently use biomass fuels, despite adequate access to modern energy sources (Jan *et al.*, 2011). Unreliable supply of modern energy sources, such as electricity, may also result in households reverting to biomass fuels (Mulu *et al.*, 2016; Ogwumike, 2014; Treiber, 2012). Furthermore, price fluctuations may force households to shift from dirty fuels (firewood) to dirtier fuels (cattle dung and crop residues) (Hanna & Oliva, 2013; Tebelier, 2012). Poor energy policies and institutional frameworks are another possible hurdles to successful rural energy development (EUEI, 2013); the attention given to rural energy development by the Ethiopian government is very little compared to rural road construction, education and health (Wolde-Giorgis, 2002).

In general, there is backward shift in biomass fuel utilization from fuel wood to inferior sources i.e. agricultural wastes instead of upward shift towards improved energy sources such as electricity and biogas.

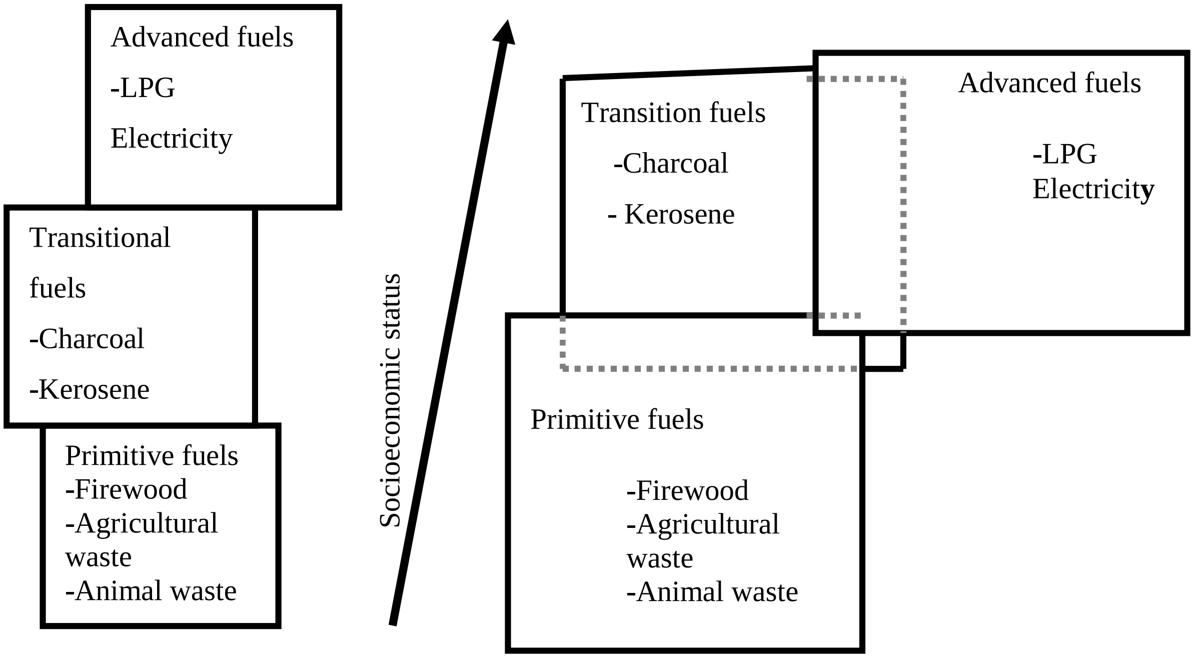

Figure 2.1. The energy transition process (adopted from Van der Kroon *et al.,* 2013)

Understanding household fuel choice and fuel switching is of vital importance in search for policies to support this transition process (Masera et al., 2000). Fuel switching is a central concept in the energy transition process, referring to the displacement of one fuel by another (Van der Kroon et al., 2013). The process of climbing the energy ladder is described by a linear movement with three distinct phases (Figure 2.1). As families gain socioeconomic status they abandon technologies that are inefficient, less costly and more polluting and move from universal reliance on biomass fuels to transition fuels such as kerosene, coal and charcoal in the second phase (Van der Kroon et al., 2013). In the third and last phase, households switch to fuels such as LPG and electricity (Figure 2.1). The assumption behind the energy ladder is that more expensive technologies are locally and internationally perceived to signify higher status and hence there is a general shift from backward and dirty fuel source to more advanced and clean energy source with increase in household income (Hanna & Oliva, 2013). It is generally understood that the energy ladder model portrays wood as an inferior economic good and this implies a strong correlation between income and fuel choice (Van der Kroon *et al.,* 2013). However, evidences from empirical observations suggest that the correlations between fuel choice and income level are rarely as strong as assumed by the energy ladder; hence a broader spectrum of influential factors besides income should be considered (Masera *et al.,* 2000; Van der Kroon et al., 2013). These empirical observations have led to the development of alternative models to describe the energy transition process. The fact of erratic supply, culture and traditions play a critical role in constraining a complete transition to modern fuels (Hanna & Oliva, 2013; Van der Kroon *et al.,* 2013). Traditional methods of cooking are often rooted in local cultures preventing the use of modern fuels (Masera *et al.,* 2000). Thus, "*multiple fuel use patterns in households are the result of complex interactions between economic, social and cultural factors*" (Masera *et al.,* 2000). Studies in rural areas have not found such results and report only partial switching behavior along income segments (Alemu and Kohlin, 2008). Fuel wood remains a very important energy source irrespective of household income (Alemu and Kohlin, 2008). So one needs to look beyond income to explain household energy choices since there are myriad of factors that shape the environment in which households make their decisions. So the energy ladder remains somewhat of a myth, not observed empirically; instead the ongoing transition process is best described by multiple fuel use representing an energy portfolio (Van der Kroon *et al.,* 2013).

The energy stacking behavior can be seen as a livelihood strategy through which households cope with irregular income flows, protect themselves from unstable markets and hold on to their cultural practices, while benefitting to some extent from modern fuels (Van der Kroon *et al.,* 2013).

2.10.2. Household energy-soil nutrients recycling-crop production nexus; implications for the livelihoods, environment and household finances

The conceptual frameworks presented below are developed based on the ideas and concepts obtained from different related literatures. The fact that bioenergy is related to agriculture, forestry, environment, finance and business sectors implies the need for searching possible alternative mechanism that helps to realize sustainable rural bioenergy supply so as to enhance food security and benefit social welfare and environmental integrity (IRENA, 2018). The steadily growing population pressure and agricultural expansion inevitably increase the forest resources utilization (construction and fuel wood, etc) leading to forest depletion (Fekadu, 2015). Utilization of dung for fuel in the Ethiopian highlands is serious cause of health problems, mainly through indoor air pollution (Alemu & Kohlin, 2008). Due to the ongoing deforestation, households need to change to other energy sources; and to cover this need, a large amount of people are using residues from agriculture straw, manure instead (Gudina *et al.,* 2015).

Figure 2.2 demonstrates implications of biomass cookstove technologies on the environment, soil fertility and crop productivity and rural household's livelihoods. Biomass cookstove technologies determine the fuel consumption rate and hence influence the amounts GHG emissions. Biomass cookstove technologies also affect availability of agricultural wastes for applying to croplands especially in areas where crop residues and dung cakes are widely used as fuel source. Large scale reliance on traditional biomass energy leads to excessive deforestation, loss of biodiversity, soil degradation, soil fertility depletion and loss of agricultural productivity. As the farmers remove crop residues and animal manure without adding enough nutrients to the soil the soil becomes increasingly infertile (Aklilu, 2006). So soil nutrients and OC depletion in Ethiopian Highlands has partly been caused by limited applications of organic materials including crop residues and manure, because these resources are widely used for household energy (Assefa, 2005; Hailu, 2010; Woldeamlak, 2003).

The amount of biomass fuel including crop residues and dung cake needed is strongly affected by the technology used through influencing the fuel saving efficiencies. The traditional three stone fires require at least two times as much resource than the more advanced technologies; and up to 4 ha of land or 15 cows are needed to provide enough straw and manure to cook on the traditional three stone fires (Gudina *et al.,* 2015).

As portrayed in Figure 2.2, biomass fuel utilization technology is related to the environment through its effects on land degradation, deforestation, greenhouse gas emissions and pollutions of different kinds. For instance, substitution of traditional biomass fuels and kerosene with biogas energy enabled the biogas-user households to reduce GHG (greenhouse gas) emissions on average by about 1.9 t of CO2 equivalents per digester per year (Mulu *et al.,* 2016). The reduced use of chemical fertilizer due to substitution with organic fertilizer also contributes to GHG emission reductions. Improvement of biomass fuel utilization technology helps in reducing depletion of woody biomass and hence mitigates deforestation through improving efficiency of energy use and energy substitutions (Mulu *et al.,* 2016). Reliance on traditional biomass fuel utilization has been recognized as having significant effects on natural resource degradation, harmful health hazards and negative economic consequences (Dagninet *et al.,* 2015).

Traditional biomass fuel utilization has serious effects on climate change and biodiversity degradation. Under the current conditions, it is impossible to avoid the dependence on wood for fuel due to lack of alternative energy sources especially electricity. There has generally been limited success in promoting improved energy sources, such as biogas in rural areas of Ethiopia. Biogas gives economic potential as an alternative in addressing both energy and food security challenges in Ethiopia (Gwavuya *et al.,* 2012). In the case of poor economies like Ethiopia quality of life and energy consumption are tidily conjoined (Dawit, 2012). Heavy reliance on traditional form of energy is a threat to forest ecosystems and a recipe for accelerated land resource degradation (Dawit, 2012. Due to the increasing scarcity of fuelwood resources, rural communities have shifted to utilization of crop residues and cattle dung; which otherwise, are resources for soil fertility improvement (Isabel *et al.,* 2011; Kassahun *et al.,* 2013).

The scarcity of fuel wood has led to an increased use of dung and crop residues as a fuel source for cooking; these residues could have otherwise been used to enhance the soil nutrient status and other soil qualities.

Dung cakes and agricultural residues are also rapidly becoming a commercial energy source in many urban households of the highlands of the country (Aklilu, 2006; Balesh, 2005). As a result, a high proportion of the plant nutrients are exported from the smallholder farming systems by the burning of biomass (Aklilu, 2006; Assefa, 2005; Balesh, 2005). On an average, a farm household exports about 43.5 kg N, 9.0 kg P, and 41.4 kg K y^{-1} through the sale of the dung-cakes (Aklilu, 2006).

Application of bioslurry to farmland has great potential to increase carbon sequestration by supplying organic matter to the soil (Smith *et al.,* 2014). Increasing the recycling of organic wastes in form of bioslurry from biogas digesters could have a profound impact on C sequestration (Smith *et al.,* 2014). So win-win solution can be achieved through utilization of organic residue as feedstock to produce biogas, so as to increase C inputs to the soil in addition to the provision of an improved household fuel supply (Smith *et al.,* 2014). Organic residues and bioslurry can also be composted under aerobic conditions to provide an important organic fertilizer (NBPE, 2008). Due to dependence on biomass fuel for almost all household energy requirement of the country, there has been suffering from massive depletion of indigenous biomass resources (Dawit, 2012). This heavy reliance on this form of energy is a threat to forest ecosystems and a recipe for accelerated land resource degradation (Kassahun *et al.,* 2013). Due to the increasing scarcity of fuel wood resources, rural households have shifted to utilisation of crop residues and cattle dung; which otherwise, are resources for soil fertility improvement (Kassahun *et al.,* 2013). With increased scarcity of fuelwood, rural households are left with no alternative source of energy other than depending on locally available resources such as crop residues and cattle manure (Kassahun *et al.,* 2013). Improved cookstoves (called MIRT) can generate about 22% to 31% in fuel saving as compared to a traditional three stone stove (Zenebe *et al.,* 2014). As reported by Zenebe *et al. (*2014), improved cookstoves contribute to the reductions in time spent for gathering of fuel wood while also potentially contributing to REDD+ goals. Deforestation and forest degradation account for between 12% and 20% of annual GHG emissions and the Federal Government of Ethiopia is promoting the use of fuel-efficient biomass cook stoves as a key part of its REDD+. In the 1970s – 1990s the focus of disseminating cookstoves was on fuelwood shortages, but this has embraced an emphasis on the pollutants emitted by cookstoves (Zenebe *et al.,* 2014).

The MIRT stove is one of the improved cookstoves that has been promoted in Ethiopia since 1998 by the German aid agency GIZ (Zenebe *et al.*, 2014). The improved cookstove technologies have been disseminated in Tigray, Amhara, Oromia and SNNPR because these regional states represent 80% of the population and over 70% of the land area of Ethiopia (Zenebe *et al.,* 2014). Use of traditional three stone open fire is not only a time consuming task due to collection of biomass fuels and constraining women to engage in income generating activities but also it causes serious health problems due to the carrying heavy loads and indoor air pollution (Zenebe *et al.,* 2014). To overcome these negative effects and enhance the livelihood situation of the poor, a transition towards cleaner and more efficient forms of energy is needed (SEI, 2013).

Identification of alternative rural energy sources that provide multiple environmental and socio-economic benefits to the rural households should to be an urgent item on the research agenda. Large scale dissemination of biogas digesters is suggested as a potential approach to reverse the adverse environmental and socio-economic effects of traditional biomass burning in the highlands of Ethiopia (Getachew *et al.*, 2006; NBPE, 2008). Small scale biogas digesters and improved cook stoves have potential to narrow the gap between energy demand and supply while simultaneously maintaining improved soil fertility and supplying clean household energy (Mulu *et al.,* 2016).

Biogas energy has multiple environmental and socio-economic benefits. Environmental benefits of biogas technology include mitigation of global warming through reduced greenhouse gas emissions, reducing the problem of land degradation and environmental pollution (Mulu, 2016). Socio-economic advantages of biogas energy include reduced expenditure on chemical fertilizers through substitution with bio-slurry from biogas digesters (NBPE, 2008), improved societal health due to utilization of safe and clean energy (Smith *et al.*, 2014), reduced workload on females and children and hence reduction of gender gap and reducing cost on traditional fuels. At least partial substitution of traditional biomass burning by biogas digesters for fuel and the use of improved cook stoves can play a significant role in improving living standards of the rural farm households by reducing expenses on energy, fertilizer and health, providing long term benefits to natural ecosystem (Smith *et al.,* 2014).

Aklilu (2006) highlighted that the outflow of nutrients through the sale of dung-cakes for fuel is so high that it has become a threat to households' food security and agricultural development in Ethiopian highlands.

Due to reduced availability of crop residues and cattle dung for soil amendment, there has been increased reliance on inorganic fertilizer (Kassahun *et al.*, 2013). Reliance on mere application of inorganic fertilizer carries risks like deficiency of secondary and trace nutrients also deteriorating soil physical and biological qualities. Deterioration of soil qualities in turn leads to reduced agricultural productivity and hence exacerbation of food insecurity problem.

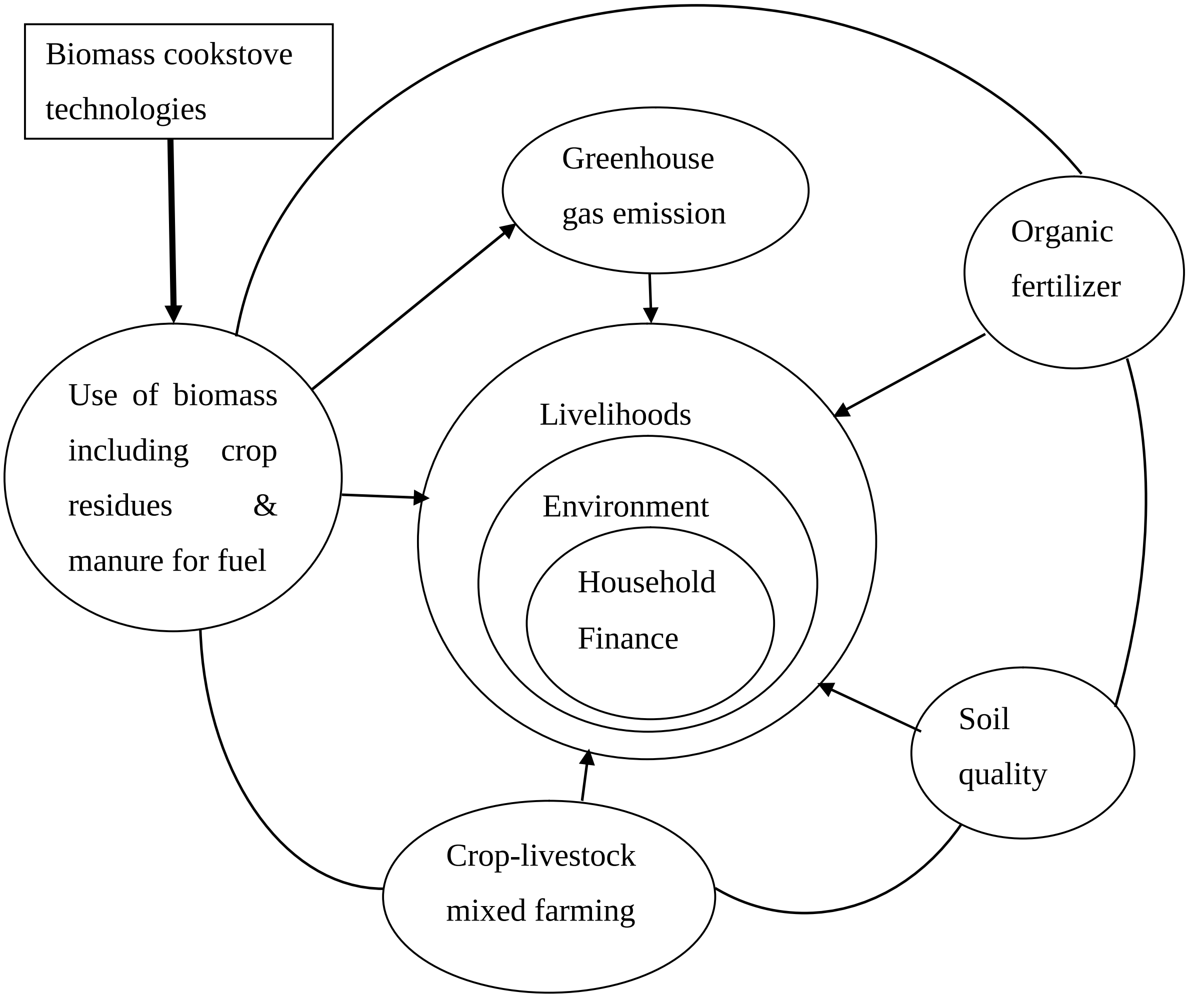

Figure 2.2. A schematic representation of the detrimental environmental and socio-economic impacts of inefficient three-stone open fires.

As depicted in Figure 2.3, substitution of the traditional three stone fires with improved cookstoves and small scale biogas digesters has the potential to increase biomass fuel use efficiency hence reduces fuel consumption rates. The reduction in biomass fuel consumption implies creating opportunities for increased availability of crop residues and cattle dung for application to farmland while also contributing to the mitigation of GHGs emissions to the atmosphere.

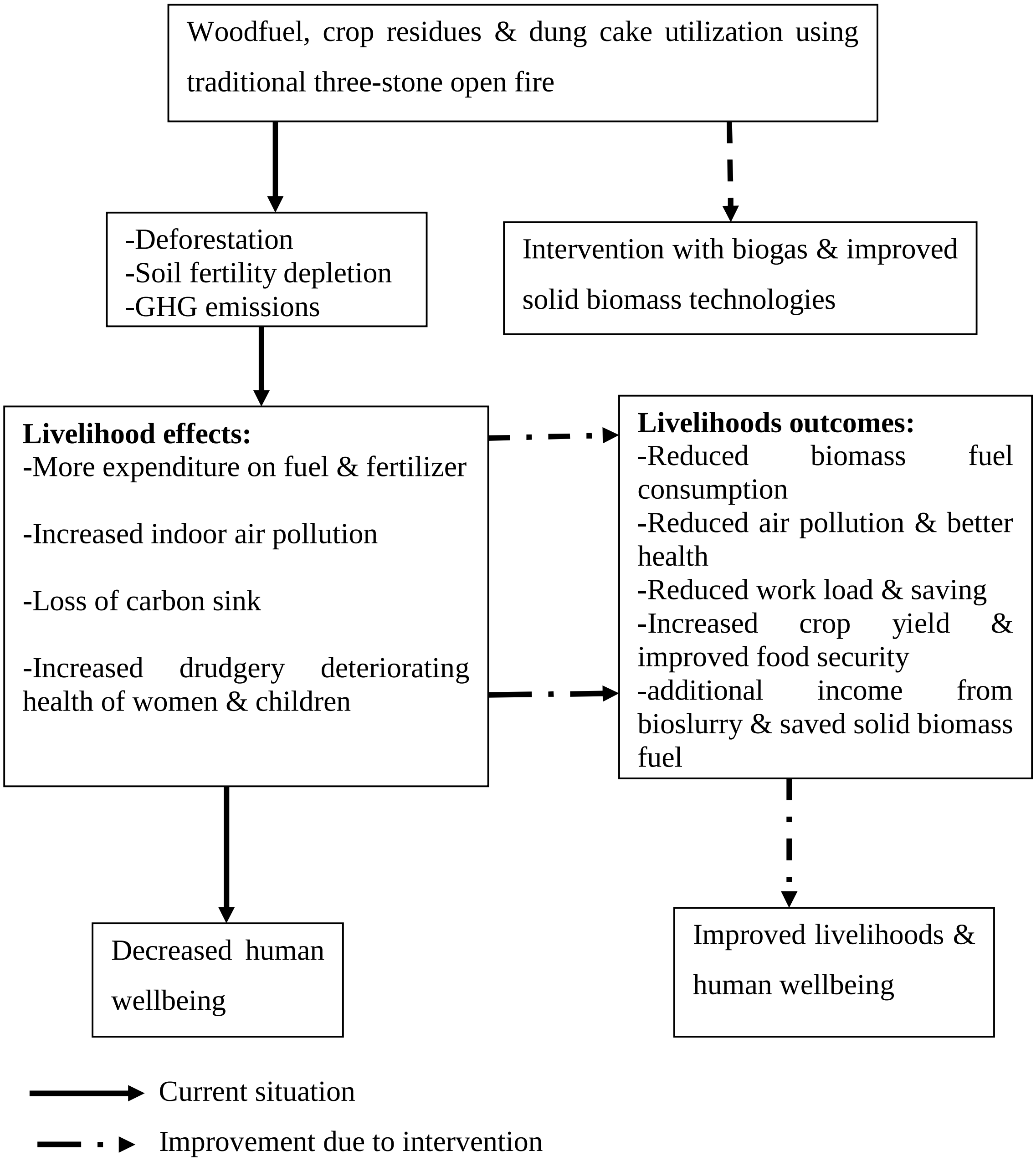

Figure 2.3. Biomass fuel-livelihood interaction under current situation and after intervention with improved biomass technologies (modified from Wachera, 2014)

Figure 2.3 depicts that in order to use livestock manures and crop residues for soil fertility amelioration, a sustainable and efficient means of household energy provision, the traditional and less efficient biomass burning should be substituted with small scale biogas digesters and improved solid biomass cook stoves.

Different studies have highlighted the effectiveness of bio-slurry in improving soil fertility and different soil condition (Abubaker, 2012; Getachew, 2006; Smith et al., 2013a; Winrock International, 2007).

Assefa (2005) reported that introduction of energy-saving stoves can help to reduce the use of cattle dung for fuel and consequently increasing manure availability for field application. So the change in the farm households' livelihoods due to switching from utilization of traditional biomass fuel to biogas technology and improved cookstoves is important for improving the wellbeing of the rural communities.

The use of inefficient three stone fires by the dominant majority of the households has led to deforestation and consequent fuel wood scarcity in the Highlands of Ethiopia. So forests are already mined forcing people to turn to crop residues and livestock dung for fuel.

As a result, the recycling of nutrients to the soil has been interrupted causing serious damage to crop productivity. Utilization of the large quantities of biomass fuel also leads to increased GHGs emissions which intensifies climate change and increased hazards of drought, erosion, etc.

The change in local climate in turn contributes to soil quality deterioration and reduced agricultural productivity. The scarcity of firewood due to deforestation results in increased fuel wood demand, and consequent high level of expenditure on biomass fuel causing reduced wealth of households and exacerbation of food insecurity problem.

Use of crop residues and cattle dung for soil fertility amendment by increasing availability through transition to biogas and improved cookstoves not only reduces household expenditure on inorganic fertilizer but also results in improvement of soil qualities ensuring sustainable agricultural productivity. Savings from the costs on inorganic fertilizer and possible income that can be generated from carbon trade leads to improved household finance and hence realization of food security.

Generally, there are strong linkages among household energy, soil fertility management and crop production in the Highlands of Ethiopia. This implies the need for making concerted efforts to solve the problems associated with inefficient utilization of agricultural wastes for fuel, soil fertility depletion and reduction of agricultural yields. This is because the less the efficiency of agricultural wastes utilization for fuel implicates reduced availability of organic resources for soil fertility amendment and hence resulting in dwindling of crop productivity and the vice versa.

The very high degree of dependence on wood and agricultural residues for household energy has impacts on the social, economic and environmental well-being of society (Van der Kroon *et al.*, 2013). Growing demand for biomass together with increased demand for agricultural output (land for crop production, livestock feed) has resulted in reduced access to wood fuels (EUEI, 2013). Improving the efficiency of household cookstoves could provide significant environmental, social and economic benefits (SEI, 2013). It has been estimated that potential greenhouse gas emission reductions through improving fuel use efficiency could exceed 1 billion tons of carbon dioxide equivalent (CO2e) per year (SEI, 2013). Fuelwood collection can also pose risks to personal safety and keeps women and children away from school or income-producing work, and it puts significant pressure on forests and scrubland (EUEI, 2013). Moreover, traditional biomass burning produces greenhouse gases (GHGs) and black carbon, contributing to climate change (SEI, 2013). By reducing these risks and pressures, improved cookstoves can yield numerous health, economic and environmental benefits (SEI, 2013).

Chapter 3

Methodology

In this chapter, the research methodology is briefly explained. The chapter begins with the research approaches and designs used for conducting the study; and ends up with extended explanations of the research methods.

The research methods used in this study are divided into three sub-sections. The first sub-section is devoted to the explanation of methods applied for surveying household energy utilization characteristics and quantification of nutrients and carbon loss with burning of crop residues and dung cakes as fuel. The second sub-section discusses the major method used for efficiency tests of the different stoves. The third sub-section briefly elaborates the procedures followed in determination of fertilizer effects on soil properties and agronomic parameters of wheat and teff.

Accordingly, survey and experimental designs have been applied for conducting this research. Hence, this study was mainly concerned with quantification of biomass fuel consumed by households as well as nutrient losses with burning of crop residues and dung cakes. Experimental observations were also carried out on fuel saving efficiencies of different stoves and the impacts of the different fertilizer types on agronomic responses of wheat and teff. Generally, the study is mostly based on the positivist methodology which is based on viable evidence via direct experience and observation.

3.1. Research Approach and Design

Philosophically, the study is based on the ontological position of positivism which adheres to the view that reality exists independent of the knower; and what a researcher has to do is simply discovering the hidden reality (Cohen, *et al.*, 2007; Creswell, 2009). Positivist methodology is directed at experimental research which is based on cause and effect relationships (Cohen, et al., 2007).

Mixed research approach, which normally makes use of both quantitative and qualitative skills was used for achieving the research objectives and answering the basic research questions raised in the study. Quantitative and qualitative methods address different but complementary aspects and hence it is commendable to use them combined (Creswell, 2009). So this study mostly relied on quantitative data which were complemented with some qualitative evidences for the purpose of triangulating evidences and raising the credibility of the findings.

Survey and experimental research designs were used for undertaking this study. Survey design is important for covering large number of respondents on a given research issue (Creswell, 2009). Thus, household energy utilization characteristics were investigated using household survey.

3.2. Sources and types of data

The major sources of data used in surveying household energy of Kumbursa Village were household heads, key informants, focus group discussants and direct observations. Data on the losses of nutrients and carbon from the farming systems were obtained from crop residues and dung cakes. With regard to the type of data, both qualitative and quantitative data were used.

Qualitative data included reasons responsible for the shift from fuel wood towards agricultural wastes for fuel; reasons for using crop residues and dung for fuel instead of applying to farmlands; and brief historical background of household energy use characteristics.

Quantitative data were collected from both household survey and laboratory analysis of crop residues and dung cakes. The types and amounts of fuels used by households were determined using household survey. The nutrients and carbon losses were quantified through laboratory analysis of crop residues and dung cake samples.

Data for the comparative evaluation of fuel saving efficiencies were derived from traditional three stone open fires, mud-stoves, mirt stoves and biogas stoves. Biomass fuel utilization data sources included firewood, crop residues and dung cakes. Greenhouse gases emissions were estimated from the amounts of firewood, crop residues and dung cakes used for fuel based on their respective emission factors from literature. The prices of these biomass fuels were determined based on their present market values in the local markets. The amounts of nutrients and carbon savings by the different stoves were derived from crop residues and dung cakes through laboratory analysis. Household heads, cooks and focus group discussants were sources of data related to stove preferences, and uptake constraining factors of improved cookstoves and biogas digesters.

Sources of data for the soil physical and chemical properties were the trial fields of wheat and teff. Data of the nitrogen and phosphorus contents of bioslurry and bioslurry compost were obtained through analysis of the nutrient contents in laboratory. Sources of data for determining the nutrient uptake efficiencies of wheat and teff were sample grain and straw analysis in laboratory.

3.3. Data collection methods, sampling, instruments and procedures

3.3.1. Household survey of household energy and quantification procedures

3.3.1.1. Household Survey

A single time cross-sectional survey was carried out to collect data on the family size, resource endowment (landholding size, livestock number and amounts of annual crop production) and household energy (sources of energy and consumption rates).

A semi-structured interview questionnaire was used for the survey. The questionnaire was pre-tested using the split-half method with 10% of the sample respondents in order to check for internal consistency (Drost, 2011).The sex and age composition of the respondents was 97 (81%) male and 23 (19%) female, with minimum and maximum ages of 28 and 78 respectively and average age of 48. The household survey data were supplemented by key informant interviews, focus group discussions, and observations and measurements.

Preliminary surveys indicated that farm households in Kumbursa Village were relatively homogenous, all of them being engaged in mixed crop-livestock farming, and being dependent on biomass resources from their own landholding for the majority of their household energy.

However, differences were observed in wealth status, so this was used as a criterion for purposeful sampling. Furthermore, the objectives of the study were to focus on the relationship between wealth status and fuel use, so sampling by wealth status was required.

Spatial variation was not considered because the study Village covers a total area of nearly 1000 ha with very small altitudinal variation (between 1878m and 1892m above sea level) and a flat to slightly undulating topography. Therefore, using a participatory wealth ranking method (Assefa *et al.*, 2007; Balesh, 2005), households of the Village were stratified into three wealth groups (rich, medium and poor) based on (i) number of oxen owned, (ii) landholding size and (iii) amount of annual crop production available for household consumption, sale and stockpiling. Households with one ox or no oxen at all, up to 1.25 ha landholding size, and not enough annual agricultural production to feed members of their household throughout the year were categorized as being in the poor wealth group. Households with two to three oxen,1.26 to 2.00 ha landholding size, enough annual agricultural production to feed members of their household throughout the year and sell part of their produce, but not enough to stockpile for the following years were categorized in the medium wealth group. Households with greater than three oxen, greater than 2.00 ha landholding size, and enough annual agricultural produce to feed members of their household throughout the year and sell part of their produce with surplus to stockpile for following years were categorized as rich. In order to be categorized as rich, medium or poor, a farm household was expected to satisfy at least two of the three criteria listed above. Using a proportionate-stratified-random sampling procedure over the wealth groups (Assefa *et al.*, 2007; Balesh, 2005), 120 farm households (i.e. 45%) were selected out of the total 258 households of Kumbursa Village.

Table 3.1. Summary of the number of households, sample size and number of composite samples of crop residues and dung cakes in each farm wealth group

Farm wealth group	Household heads in each wealth group	Sample household heads in each wealth group	Composite crop residues and dung cakes samples			
			Teff	Wheat	Chickpea	Dung cake
Rich	47	22	3	3	3	3
Medium	157	73	3	3	3	3
Poor	54	25	3	3	3	3
Total	258	120	9	9	9	9

3.3.1.2 Sampling crop residues and dung cakes for analysis of nutrient contents

Composite samples were collected for laboratory analysis for crop residues and dung cakes as shown in Table 3.1, with each composite sample consisting of seven sub-samples. The residue samples were taken from the three major crops (teff, chickpeas and wheat), which together constituted more than 95% of the cropped area in the Village. Equal allocation (Mathew *et al.,* 2013) was used to sample residues and dung cakes; hence samples were evenly distributed across the three farm wealth groups (poor, medium and rich) as well as the three major crops (teff, chickpeas and wheat).

This is a small number of crop residue and dung cake samples compared to the number of farm households and the total area of the Village, but care was taken to ensure that samples obtained were representative of the typical situation in the Village. As is common practice in Ethiopia, the crops belonging to the household from different areas were brought to one place during threshing; this results in mixing of residues, making them relatively homogenous, and allowing representative samples to be obtained immediately after threshing. To enhance the representativeness of the sampling, seven sub-samples were taken and bulked together to provide a composite sample for analysis. Dung cakes are made by collecting and mixing cattle dung, resulting in homogenous nutrient concentrations; again seven sub-samples were taken and mixed to provide a composite sample. As it is expected, the nutrient concentrations of residues and dung cakes vary across different farm wealth groups due to differences in agricultural inputs and field management, the samples were evenly distributed across the three farm wealth groups.

3.3.1.3. Quantification of household fuel consumption

The household head and the person responsible for cooking were asked to specify the amounts of dung cakes, firewood and charcoal used to cook meals each day and each week. The respondents expressed these quantities as the number of dung cakes used per meal, number of sacks of dung cakes, crop residues or charcoal used per week, and number of bundles of firewood used per week. The weights of a single dung cake, crop residues or charcoal, and a typical bundle of firewood were measured using a weight balance across a sample size of 42. This provided weights of 0.45 (standard error = ± 0.02)kg per dung cake, 21(± 1) kg per sack of dung cakes, 10(± 0.4) kg per sack of crop residues, 16(± 0.7) kg per sack of charcoal, and 28(± 2) kg per bundle of fuel wood. This allowed the average weight of fuel used per year to be quantified for each farm wealth category. Data on grain yields were collected through the household survey, while the amounts of dry matter in crop residues were indirectly determined for each crop using mean harvest indices; the total amounts of dry matter in crop residues produced by the farm households were quantified using the following equation:

$$M_{res,x} = \frac{\sum_{n}\left(\frac{M_{grain,x}}{H_{i,x}} - M_{grain,x}\right)}{n} \qquad (1)$$

where $M_{res,x}$ is the mean dry matter produced by a typical household in crop residues for crop x (kg yr^{-1}), x stands for any of the three crops (teff, wheat and chickpeas); $H_{i,x}$ is the harvest index for crop x, $M_{grain,x}$ is grain yield of crop x (kg yr^{-1}), and n is the number of households in the wealth group. Harvest indices were assumed to be 0.24 for teff (Ketema, 1997; EARO, 2001), 0.41 for wheat (Bayeh, 2010) and 0.37 for chickpeas (Tilahun *et al.*, 2015).

3.3.1.4. Quantification of carbon and nutrient loss through removal of crop residues and dung cakes

The annual nutrient and OC losses for each household were obtained from the total dry matter in crop residues and dung cakes and the average nutrient contents of each product as follows:

$$L_{res,y} = \frac{\sum_{1}^{n_h}\left(\sum_{x}\left(M_{res,x} \times p_{y,x}\right)\right)}{n_h} \qquad (2$$

$$L_{dung,y} = \frac{\sum_{1}^{n_h}\left(M_{dung} \times p_{y,dung}\right)}{n_h} \qquad (3)$$

where $L_{res,y}$ is the average loss of y (where y is N, P, K or OC) in crop residues and $L_{dung,y}$ is the average loss in dung (kg yr^{-1}); $M_{res,x}$ is the amount of crop residue x used by a household for energy(where x refers to the crop type; teff, chickpeas or wheat) and M_{dung} is the amount of dung cakes used by a household for energy (both within the household and sold) (kg yr^{-1} dry matter); $p_{y,x}$ is the proportion of y in crop residue x, and $\mathrm{p}_{y,dung}$ is the proportion of y in dung; and n_h is the number of households in each farm wealth group (rich = 22, medium = 73, and poor = 25).

The Tropical Livestock Unit (TLU), which represents a hypothetical animal of 250 kg live weight, was used to determine livestock number, which was needed to determine the wealth group; conversion factors 0.01, 0.1, 0.5, 0.7, 0.8 and 1.1 TLU were used for chickens, sheep/goats, donkeys, heifers, cows and oxen, respectively (Gryseels, 1988).

Market values of inorganic fertilizers in Kumbursa Village in 2015 were used to determine the fertilizer equivalent monetary values of the crop residues and dung cakes removed for household energy; diammonium phosphate = 15 Ethiopian Birr (ETB) kg^{-1} (0.72 US$ kg^{-1}) and urea = 13 ETB kg^{-1} (0.62US$ kg^{-1}).

Local market prices of different fuels in March 2015 were used to determine fuel monetary values; firewood =1.8ETB kg^{-1}(0.09US$ kg^{-1}), charcoal = 10ETB kg^{-1}(0.5US$ kg^{-1}), crop residues = 2.1ETB kg^{-1}(0.1US$ kg^{-1}), dung cakes = 2ETB kg^{-1}(0.1US$ kg^{-1}) and (kerosene = 16ETB dm^{-3}(0.76US$ dm^{-3}).

The energy contents of different fuel sources were determined using their corresponding conversion factors; wood =16.2MJkg^{-1}; dung cakes = 10.8MJkg^{-1}; cereal straw = 14.4MJkg^{-1}; charcoal = 25.2MJkg^{-1} and kerosene = 36MJ dm^{-3}) (INFORSE, 2006).

3.3.2. Stove performance testing procedures

3.3.2.1. Types and description of cookstoves used by the households in Kumbursa Village

A preliminary survey was undertaken to identify the types of stoves and biomass fuels used, major types of food cooked, family size, wealth status of the households, and identification of the person primarily responsible for cooking in the households. Most households in Kumbursa village were using traditional three stone open fires for cooking with very small proportion of them utilizing locally prepared mud-stoves and *mirt* stoves. The major cookstoves currently in use in Kumbursa Village are three stone open fires, mud-stoves and *mirt* stoves (Table 3.2).

Table 3.2. Types and description of cookstoves selected for fuel performance assessment at Kumbursa Village

Cookstove type	Description
Traditional three-stone open fire	A three-stone open fire is made of three-stones, bricks or inverted clay pans. Stones are locally collected by households. Bricks or inverted clay pans are made by semi-skilled rural handicrafts and sold at local markets. The three-stone open fire forms a circular area with average height of 40 cm, but with varied diameter. Since the stones are not fixed, the area can be set relative to the material that can be used for cooking. This is the most common method used for cooking in Kumbursa. A *mitad* (a circular griddle made from clay with a diameter of approximately 60cm) is used for baking *injera.*
Mud-stove	An enclosed stove, made of mud mixed with straw or hay by the local artisans in the kitchen. The mud-stove is fixed with average diameter of 80 cm and height of 65 to 110cm. Mud-stoves are mostly used for *injera* baking, although some households also include a chamber for cooking of *wot* (an Ethiopian stew), making tea and coffee, and boiling water.
Mirt stove	*Mirt* means ‘best’ in Amharic. It is a type of improved manufactured stove which has been promoted by GTZ since 1990s. Its design and function is similar to a mud-stove. It is usually prepared from cement and sand with an enclosed chamber for combustion having a small opening for adding biomass fuel and to let in air. It is circular in shape with average diameter of 120 cm and height of 75 cm. It has an extra small chamber of 45 cm width, which is used for resting a pan used for cooking *wot* or kettle used for making coffee.
Biogas stove	A metal stove connected by a biogas pipe to the biogas digester. It is used for cooking *wot*, boiling water, and making coffee and tea.

3.3.2.2. Selection of stove performance testing methods

The three most common methods used to evaluate stove performance are the Water Boiling Test, Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT), also respectively known as efficiency, effectiveness and efficacy tests (Bailis et al., 2007). Each of these three approaches has its own benefits and limitations.

The Water Boiling Test evaluates stove performance by boiling a measured quantity of water in a standard pot and the shorter the time required and the lower the quantity of fuel used for boiling, the more efficient the stove (Mercy Corps, 2010). The Water Boiling Test is able to control for confounding factors and provides a high degree of replication, but it does not reflect actual cooking performance (Adkins, 2010), and is therefore mostly suited to lab-based screening of stove efficiency (Bailis *et al*., 2007). The CCT involves simulation of the real cooking practice by controlling variables like quantity of food prepared, quantity of fuel used and the behaviors of the cook (Bailis *et al*., 2007; Mercy Corps, 2010). It is less standardized and more realistic than the Water Boiling Test, but still does not reflect the actual cooking practice in the field. The KPT involves assessment of fuel consumption by households under a normal cooking practice (Granderson *et al*., 2008). It is preferred over both the Water Boiling Test and CCT for actual in situ stove performance assessment (Granderson *et al*., 2008), as the results reflect the real cooking situation in a kitchen hence and so reflect actual cooking practice (Bailis *et al.*, 2007). Therefore, in this study, KPT was selected and used to monitor field-based biomass fuel consumption rates of the different stove types in Kumbursa Village.

The KPT has been applied using the protocol set out by Bailis *et al.* (2004). The KPT was supported by the CCT and short-term participant observation survey, following the approach used by Granderson *et al*. (2008). The results obtained using both CCT and participant observation survey methods were then compared and triangulated with those of the KPT in order to strengthen the reliability of the findings. The average specific fuel consumption was calculated by dividing the amount of biomass fuel consumed in kg (air dried) by the amount of *injera* baked in kg. Percentage of biomass fuel saving was calculated by subtracting the specific fuel consumption measured with a three-stone open fire from that measured with a mud-stove or mirt stove.

3.3.2.3. The Kitchen Performance Test and selection of households and cooks

The KPT was done in the same household to measure fuel consumption rates before and after installation and conversion to biogas, mud-stoves and mirt stoves as well as parallel utilization of mud-stove + biogas stove and mirt stove + biogas stove. Before and after comparisons yield more accurate results than testing of paired households with and without the intervention (Granderson *et al.*, 2008). Therefore, the KPT was longitudinally designed based on pre-intervention and post-intervention of within-subjects experimental observations. The KPT was carried out under natural conditions in a way that reflects the usual cooking activity in households. The participant households were selected to have similar kitchen dimensions, typically thatched huts with plastered walls having size of $6m^2$ to $10m^2$. The study was limited to only one season, but was supplemented by householder interviews to compensate for this limitation.

The same types of biomass fuels were supplied to each participant household. The biomass fuel used in this study was composed of the mixture of crop residues, dung cakes and firewood as is normal practice in the study Village. Each participant household was asked to report the approximate amount of their daily fuel requirement and the amounts delivered to them were increased over the estimates by 50%. The participants were told to use only the fuel measured and given to them. In this experimental design, 42 sampled households were involved. The participant households were selected based on recommendations given by the local development agent and Village leader. Willingness to participate in the study was also taken into account in the selection process. Cooking food for the family is mainly done by the mother, so mothers were selected to participate in both the KPT and CCT. Initially all of the 42 selected participant households were instructed to cook their food using the traditional three-stone open fire stoves (Figures 3.1a & b) for seven days.

After every cooking activity, the participants were asked to immediately extinguish the fire and keep the remaining fuel from the first to the seventh day. Then on the last day, the remaining fuel was measured to quantify the amounts of fuel consumption using traditional three-stone open fire stove by each participant household.

The households were then divided into four sub-groups randomly by lottery method and the technologies were provided to the groups as follows: constituting 11 members using only mud-stoves (Figure 3.1c) (group 1), 11 members using only mirt stoves (Figure 3.3d) (group 2), 10 member using mud-stoves + biogas stoves (group 3), and another 10 members using mirt + biogas stoves (group 4).

Figure 3.1. Traditional three-stone open fire stoves (a) and (b), mud-stove (c) and mirt stove (d).

3.3.2.4. The Controlled Cooking Test

The CCT, also called the standard meal test, was undertaken for baking *injera*. Triplet replications over seven days and for treatments (traditional three-stone open fire which served as control, mud-stoves and mirt stoves) were used. Three experienced cooks (women who have been cooking for their families for fifteen years and more) were selected to bake *injera* for a week each, using a three-stone open fire, a mud-stove and a mirt stove.

The CCT was undertaken in the household kitchens so as to simulate normal cooking conditions (Adkins *et al.*, 2010; Abebe *et al.*, 2015). Baking was done by the same people (the cook and her assistant), at a similar time and place using similar biomass fuels, “mitads” and teff dough in order to control variations in fuel consumption rates due to factors other than stove type.

Fuels and dough were weighed using a weight balance before starting to cook, and the amount of fuel remaining after cooking was weighed in order to determine fuel consumption for each stove type. Immediately after cooking was completed, the unburnt fuel was removed by extinguishing the fire. The baked *injera* was weighed together with the container (locally known as the *sefed*) and the weight of the *sefed* was subtracted from the total weight to obtain the net weight of the baked *injera*. A cold start was used and cooking was started at 10:00 am for all the three stove types tested to control for the effects of local weather variation.

3.3.2.5. Calculation of the nutrient content of dung cakes, crop residues and bioslurry

The average amounts of dung cakes and crop residues saved in the post-intervention KPT were converted into an annual average. The dry weight of bioslurry produced by the biogas users was measured over a period of two weeks and also converted into an annual average. Dung cakes, crop residues and bioslurry samples were analyzed in the laboratory to determine the percent nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC) contents. The amount of nutrients or OC saved by the household, M_X (kg week$^{-1`}$), was then calculated from the weight of the organic waste saved (dung cakes, crop residues or bioslurry), M_{OW} (kg week^{-1}), as

$$Mx = Mow \times {}^{Px}\!/_{100} \qquad (4)$$

Where PX is the percentage of X (N, P, K or OC) in the dry organic waste.

3.3.2.6. Calculation of greenhouse gas emissions

The three most important GHGs; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have global warming potentials of 1, 25 and 298 carbon dioxide equivalents (CO_2e), respectively (IPCC, 2007), were considered in this study. The IPCC (2007) default thermal values (MJ kg^{-1} fuel) and emission factors (CO_2e in milligram (mg) MJ^{-1}) (Table 3.3) were used to estimate the likely GHG emissions. In order to convert the weight of biogas in kg a conversion factor of $1m^3$ of biogas with a thermal value of 23 MJ and a weight of 0.7 kg was considered (Mulu *et al.,* 2016). The replacement potential of biogas for firewood was determined following the method provided by Pathank *et al.* (2009), which assumed that $1m^3$ of biogas provided equivalent heating energy to 5.5 kg of firewood. The GHG reduction potential of the biogas digester having average volumes of $6m^3$ and $8m^3$ was assumed 1.9 t CO_2e per digester per year (Mulu, 2016).

Table 3.3.Thermal values (MJ kg-1) of fuels (biomass, biogas & Kerosene) and greenhouse gas emission factors (mg MJ-1) (IPCC, 2007)

Fuel type	Thermal values ($MJ\ kg^{-1}$)	CO_2 ($mg\ MJ^{-1}$)	CH_4 ($mg\ MJ^{-1}$)	N_2O ($mg\ MJ^{-1}$)
Air dried fuel wood, branches, leaves and twigs	15.5	112,000	300	4
Air dried dung fuels	15	100,000	300	4
Air dried crop residues	13.8	100,000	300	4
Biogas	33	54,000	5	0.1
Kerosene	36	71,900	10	0.6

To quantify the amounts of biogas consumed, households were asked to report the duration of daily biogas utilization for cooking and lighting (Mulu *et al.*, 2016).

The annual mass of GHGs emission in kg per household from the combustion of fuel type ‘a’ (Ea) was calculated for each fuel type in terms of carbon dioxide equivalent (CO_2e) as follows:

$$Ea = \frac{((a \times EFCO_2 + (a \times EFCH_4) + (a \times EFN_2O))}{1{,}000{,}000} \qquad (5)$$

Where ‘a’ is annual thermal value of combustion fuel in MJ per household, $EFCO_2$ is emission factor of Carbon dioxide (CO_2), $EFCH_4$ is emission factor for Methane (CH_4) and EFN_2O is emission factor for Nitrous oxide (N_20) in milligram MJ^{-1}.

Annual thermal value of a given fuel of a household (a) is computed by multiplying the weight of a fuel by its thermal value (MJ kg^{-1}) (Table 3.3).

The total annual mass of GHG emission (TAG) in kg of CO_2e per household in the study area was computed as:

$$TAG = Ea_1 + Ea_2 + Ea_3 + Ea_4 + Ea_5 \qquad (6)$$

Where, Ea_1, Ea_2, Ea_3, Ea_4 and Ea_5 are the annual mass of GHGs emission in kg per household from the combustion of wood, dung, crop residue, biogas and kerosene, respectively. The GHG emissions were calculated for each stove type and fuel type based on the mass of fuel consumed during KPT and the corresponding emission factors (Table 3.3). Emission reductions were then quantified by subtracting fuel consumed in post improved cookstoves intervention from pre-improved cookstoves intervention and then converting into amount of GHGs using their corresponding emission factors for each fuel type.

The amount of methane leakage to the atmosphere was assumed to be 10% for this study (Mulu *et al.*, 2016). The minimum daily average biogas production for 6 m^3 and 8 m^3 (1.2 m^3) was used for this study since there is probable failure to exploit the full potential of the biogas digesters due to reasons such as improper functioning of biogas stoves or lamps and inadequate feedstock.

The average annual leakage emission of methane was computed based on Mulu *et al.* (2016) as follows:

$$E_{CO_2}e = YC \times P_{CH_4} + GWP_{CH_4} \times R \qquad (7)$$

where, $E_{CO2}e$ is the average annual emission of methane from the biogas digester in kg of $_{CO2}e$; YC = yearly average biogas generation value of a biogas digester (NBPE, 2008); P_{CH4} stands for the proportion of methane in biogas (0.6); GWP_{CH4}= Global warming potential of methane (25 over carbon dioxide (Mulu *et al.*, 2016); R = average rate of methane emission through leakage was assumed to be 0.1 (IPCC, 2007).

3.3.2.7. Replacement cost analysis

The average annual saving of nutrients (N and P in bioslurry) and fuels (woodfuel, crop residues, dung cakes and kerosene) due to substituting a three-stone open fire with a mud-stove or mirt stove, without or with a biogas stoves, was calculated and valued using the monetary value of fertilizers and fuels. For fertilizers, the farm gate price in Kumbursa in 2016 for diammonium phosphate fertilizer (DAP) was used; 15 Ethiopian Birr (ETB) kg^{-1} (0.72 US\$ kg^{-1}). For fuels, local market prices in 2016 were used; for firewood =1.8 ETB kg^{-1} (0.09 US\$ kg^{-1}), for crop residues = 2.1 ETB kg^{-1} (0.1US\$ kg^{-1}), for dung cakes = 2.0 ETB kg^{-1} (0.1US\$ kg^{-1}) and for kerosene = 16.0 ETB dm^{-3} (0.76US\$ dm^{-3}).

The carbon financing potential from GHG emission reduction was estimated as 16.4US\$ or 360.8 ETB per 1 t CO_2e, based on offset price of the Gold Standard Verified Emission Reduction (VER) of Clean Development Mechanisms (SEI, 2013).

3.3.3. On-farm trial experiment methods

3.3.3.1. Establishment of the on-farm field trials

The trials were established using teff and wheat crops due to the importance of these crops in the Highlands of Ethiopia. Fertilizer was applied using the national blanket recommendation rate as the baseline; for all the fertilizer types, three rates were selected, 50%, 100% and 150% of the recommended rate.

The N and P contents of bioslurry and bioslurry compost were determined before application to the field in order to determine the rate of application, based on N content, and using triple superphosphate to ensure equivalent rates of P. A Complete Randomized Block Design (CRBD) was used to allocate different types and rates of fertilizer to the different plots in the trial.

3.3.3.2. Soil sampling

Soil samples were collected before and after treatment from the plough layer (from a depth of 0-20 cm), carefully removing surface plant litter before taking the soil samples. The soil samples were collected in plastic bags and labeled in the field. For pre-treatment characterization of the soil, five composite soil samples (each containing seven sub-samples bulked together) were collected for each of the experimental fields and analyzed for N, P, K, organic C, pH, texture, cation exchange capacity (CEC) and percent base saturation. Fifteen undisturbed core samples were collected for laboratory analysis of bulk densities. The coring cylinder was driven into the soil, which was then carefully dug out; the top and base were fitted with caps, and immediately taken to the laboratory for bulk density determination. The pre-treatment soil analysis provided baseline data for the plots as well as for assessing the status of the considered soil parameters compared to standardized values from literature.

After crop harvest during the second cropping season (2015 cropping season), three soil samples, each constituting seven sub-samples bulked together, were collected from each treatment and analyzed for N, P, K, organic C, pH, CEC and percent base saturation in order to capture the impact of the treatments. The effect of different types and rates of fertilizer application was assessed by comparing pre-treatment and post-treatment data for all of the soil parameters considered in the study.

3.3.3.3. Sampling bioslurry and bioslurry compost

The bioslurry in the digester tank (temporary storage of bioslurry) was mixed thoroughly just before taking the samples. Two sub-samples were taken from the upper part, three sub-samples from the middle and two sub-samples from the bottom of the tank and bulked together to produce a composite sample.

Similarly, two, three and two sub-samples of bioslurry compost were taken from the upper, middle and bottom part of the compost pit and bulked together. Greater numbers of sub-samples (three sub-samples) were taken from the middle part because it shares average characteristics between the top and bottom part. The five composite samples from bioslurry and also five composite samples from bioslurry compost were collected and taken to Debre Zeit Agricultural Research Institute for laboratory analysis of nitrogen and phosphorus contents.

3.3.3.4. The design of the on-farm trials

The experiment was undertaken in randomized plots for two successive main cropping seasons (2014 and 2015 cropping seasons). The size of each plot was 3m × 3m = $9m^2$; spacing between blocks and plots respectively were 1m and 0.5m, with a buffer of 3m on all sides of the fields. The on-farm trials were laid out in a factorial fashion, constituting 15 treatments from different types of fertilizer with varying levels of N and P as well as a control with zero N and P addition. The fertilizers used included bioslurry, bioslurry compost, inorganic fertilizer in the form of DAP and urea, combined bioslurry and inorganic fertilizer, bioslurry compost and inorganic fertilizer. Each treatment was applied at three different levels; 32 kg N ha^{-1} and 23 kg P ha^{-1} (50% of the blanket recommendation), 64 kg N ha^{-1} and 46 kg P ha^{-1} (100% of the blanket recommendation); and 96 kg N ha^{-1} and 69 kg P ha^{-1} (150% of the blanket recommendation). The trial plots were laid out in a randomized complete block design with three replicates.

3.3.3.5. Land preparation and management for the on-farm trials

For the first cropping season, land preparation was carried out using oxen following the local practices at the experimental sites; the experimental fields were plowed six times at Doliyo and four times at Kumbursa before sowing. Sowing time was also set in line with the local practices of farmers at the study sites. Preparation of land for both teff and wheat production normally begins just after the ground is adequately wet at the beginning of the Ethiopian summer season (Sowing dates for both wheat and teff are demonstrated in Table 3.4).

Based on the nutrient contents of bioslurry and bioslurry compost (analyzed in the laboratory), the inorganic fertilizer (DAP and urea) equivalent amounts of both bioslurry and bioslurry compost were determined before application to the field. Both bioslurry and bioslurry compost were applied three days before sowing. Seedbed preparation was undertaken in rows (Figure 3.2a-d) of 30cm and 25cm intervals for wheat and teff respectively, following recommendation by ATA (2013). Seed sowing and fertilizer application were undertaken in rows, because it has been shown to be a more productive sowing method, as witnessed by the local Development Agents and model farmers (Figure 3.2d). Seed rates for wheat and teff were 100kg ha^{-1} and 15kg ha^{-1}, respectively. Improved varieties of wheat and teff were sown on both experimental sites. An improved teff variety (DZ-cr-387), locally referred to as *Quncho*, and an improved wheat variety, *Qaqqabaa*, which thrives at mid altitude agroecology, were used for the Kumbursa trial fields. The improved wheat variety, *Danda'aa*, which suits to higher altitudes of Dega/Baddaa was used for Doliyo site. The germination efficiencies were tested for both wheat and teff before sowing and the results were 96% and 98%, respectively. Weeds were controlled by hand weeding; chemicals were not used for weed and pest control as this is not common local practice. The bioslurry and bioslurry compost were applied within the plough layer (20cm) depth.

Figure 3.2. Designing the trial plots for Doliyo site (3.2a); Kumbursa site (3.2b), and preparation of rows for sowing at Doliyo (3.2c); Kumbursa (3.2d).

For the second cropping season (2015), the design of the trial experiment, fertilizer, seed doses and crop varieties were all the same as in the previous year. The difference in this year's experiment was that land preparation was undertaken using a hoe so as to avoid soil mixing between adjacent trial plots (Figure 3.3a & 3.3b).

Table 3.4. Rates of nitrogen and phosphorus applied from the different types of fertilizer

Rep	Treatments/amendment inputs(Kg ha^{-1})	Rep	Treatments/amendment inputs (Kg ha^{-1})
T1	$N_{64}P_{46}$ from sole bioslurry	T9	$N_{96}P_{69}$ from sole inorganic fertilizer
T2	$N_{32}P_{23}$ from sole bioslurry	T10	$N_{32}P_{23}$ from bioslurry and inorganic fertilizer
T3	$N_{96}P_{69}$ from sole bioslurry	T11	$N_{64}P_{46}$ from bioslurry and inorganic fertilizer
T4	$N_{64}P_{46}$ from sole bioslurry compost	T12	$N_{96}P_{69}$ from bioslurry and inorganic fertilizer
T5	$N_{32}P_{23}$ from sole bioslurry compost	T13	$N_{32}P_{23}$ from bioslurry compost and inorganic fertilizer
T6	$N_{96}P_{69}$ from sole bioslurry compost	T14	$N_{64}P_{46}$ from bioslurry compost and inorganic fertilizer
T7	$N_{64}P_{46}$ from sole inorganic fertilizer	T15	N_{96} P_{69} from bioslurry compost and inorganic fertilizer
T8	$N_{32}P_{23}$ from sole inorganic fertilizer	T16	N_0P_0 (control)

Figure 3.3. Field preparation using hoe for the second season trial experiment (3.3a & 3.3b); application of bioslurry (3.3c) and compost (3.3d); sowing wheat (3.3e) and wheat field after two weeks of sowing (3.3f).

Days to physiological maturity for wheat was generally longer at Doliyo (140 for 2014 cropping year and 129 for 2015 cropping year) compared to Kumbursa Village (109 for 2014 cropping year and 82 for 2015 cropping year).

The reason for the late maturity in Doliyo can be ascribed to the cooler Dega/Baddaa climatic condition compared to that of Kumbursa, which is characterized by warmer Woina Dega/Badda Daree agroecology. The time to physiological maturity was generally shorter for 2015 cropping season than the 2014 cropping season due to the occurrence of drought in 2015.

Table 3.5. Experimental fields, crop types, sowing and harvesting dates and days to physiological maturity

Field Name	Crop Type	Sowing Date		Harvesting		Days to physiological maturity	
		Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Doliyo	Wheat	16/07/2014	12/07/2015	05/12/2014	17/11/2015	140	129
Kumbursa	Wheat	20/07/2014	18/07/2015	12/11/2014	22/10/2015	122	97
Kumbursa	Teff	27/07/2014	24/07/2015	11/11/2014	13/10/2015	109	82

3.3.3.6. Determination of the total above ground biomass and grain yields

The samples were taken from the centre of each plot using a 1m × 1m metal quadrant (Figure 3.4a & 3.4b) and carefully put into labeled sacks (Figure 3.4d) to be dried and threshed (Figure 3.4e). The samples were sun dried and weighed to determine the total above ground biomass, and were then carefully threshed to separate the grain from the straw and weighing. The remaining crop on each plot was again harvested without leaving any crop at the border; this was then separately threshed to compare the results with that of samples taken using square metal quadrant. Residue yield was determined by subtracting the weight of the grain yield from the weight of the total above ground biomass.

Figure 3.4. Putting 1mx1m metal quadrant in wheat plot (3.4a), harvesting teff from the inside the quadrant (3.4b), labeling the sack for samples (3.4c), putting the harvested crop sample in a labeled sack(3.4d), threshing (3.4e) and labeling wheat grain samples (3.4f)

3.3.3.7. Straw and grain sampling

After threshing, seven sub-samples of straw were collected and bulked together to provide a composite sample. Grain samples were also taken from the different treatments. Both straw and grain samples were carefully labeled in the field and taken to Debre Zeit Agricultural Research Institute for the analysis of N and P contents. Grain and straw samples of both the wheat and teff treated with different types and rates of fertilizer were also analyzed for their N and P contents in order to evaluate nutrient uptake, nutrient use efficiencies and apparent nutrient recoveries.

3.3.3.8. Estimation of nutrient use efficiencies and apparent nutrient recoveries

Assessment of nutrient use efficiency is vital for proper management of crop production (Dobermann, 2005). Nutrient use efficiency can be influenced by several factors, including fertilizer management, soil quality, crop type and variety, and water available to the crop (Dobermann, 2005; Roberts, 2008).

There are several ways of evaluating nutrient use efficiency and the preference among the different approaches is influenced by the objective of the study. For this study, nutrient use efficiency is expressed as kg grain per kg of nutrient applied and apparent recovery is defined as the proportion of nutrient used by a crop relative to the total amount applied. The nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) as well as apparent nitrogen recovery (ANR) and apparent phosphorus recovery (APR) were calculated using the formulae provided by Husan *et al.* (2014) as follows:

$$NUE = \frac{YF - YC}{FN} \qquad (8)$$

where YF is the yield of fertilized plot (kg ha^{-1}),YC is the yield of the control plot (kg ha^{-1}), and FN is the fertilizer N applied (kilograms ha^{-1})

$$PUE = \frac{YF - YC}{FP} \qquad (9)$$

Where YF= yield of fertilized plot (kg ha^{-1}); YC= yield of control plot (Kg ha^{-1}); FP = fertilizer P applied (kilograms ha^{-1})

$$ANR(\%) = \frac{NUF - NUC}{FN} \times 100 \qquad (10)$$

Where, NUF = Total N uptake in fertilized plot; NUC= Total N uptake in control plot and FN = Fertilizer N applied (Kg ha^{-1})

$$APR(\%) = \frac{PUF - PUC}{FP} \times 100 \qquad (11)$$

Where, PUF = Total P uptake in fertilized plot; PUC= Total P uptake in control plot and FP = Fertilizer P applied (kilograms ha^{-1})

3.3.4. Laboratory analysis of samples

3.3.4.1. Crop residue and dung cake samples laboratory analysis

The collected crop residues and dung cake samples were analyzed in the soil and plant analysis laboratory of Debre Zeit Agricultural Research Center, Ethiopia, to quantify total nitrogen (TN), available phosphorus (Av.P), exchangeable potassium (EK) and organic carbon (OC) contents. The Kjeldahl method, which involves wet digestion, distillation and titration, was used for analysis of total N (Anderson & Ingram, 1993).

Following the dry-ashing method (Sahlemedhin &Taye, 2000), P and K contents of crop residues and dung cakes were determined by spectrophotometer and atomic absorption. Organic carbon was determined from the ash by comparing weight before and after oxidation (Sahlemedhin &Taye, 2000).

3.3.4.2. Laboratory analyses of the soil samples

Pretreatment and post-treatment soil total nitrogen, available phosphorus, exchangeable potassium, organic carbon, pH, cation exchange capacity, percent base saturation, and bulk density and texture were analyzed to determine the effects of different types and rates of fertilizers. Total nitrogen was analyzed using Keldahl digestion and distillation method (Carter and Gregorich, 2008). The method presented by Bray (1945) was used to determine available phosphorus.

The Walkley and Black oxidation method was used for determining amounts of organic carbon content (Landon, 1991). Cation exchange capacity and exchangeable bases were quantified using the ammonium acetate extraction method (Carter and Gregorich, 2008). Measurements of exchangeable K and sodium were undertaken using a flame photometer and an atomic absorption spectrometer was used for quantifying exchangeable magnesium and calcium (Carter and Gregorich, 2008). Percentage base saturation was calculated by summing up exchangeable bases (K^+, Mg^{2+}, Ca^{2+} and Na^+) and dividing by CEC and then multiplying by 100 (Landon, 1991). Bulk density was measured by oven-drying the soil cores at 105 ºC (Landon, 1991). Particle size distribution was assessed using the hydrometer technique (Van-Reeuwijk, 1993), and soil bulk density was measured by dividing weight of oven dried soil core to its corresponding volume (Carter and Gregorich, 2008). Soil pH was measured in 1:2.5 soil water suspension using KCl (Landon, 1991).

The study of soil nutrient input, output and balance is one of the mechanisms through which farming system sustainability is evaluated (Amare *et al.*, 2006). The assessment of soil nutrient balance can be undertaken at different spatial scales that range from global to plot level. In this study, the N and P balances were assessed for the different types and rates of fertilizer at plot level.

3.3.4.3. Laboratory analyses of bioslurry, bioslurry compost, straw and grain samples

The bioslurry, bioslurry compost, straw and grain samples were analyzed at the Soil and Plant Analysis Laboratory of Debre Zeit Agricultural Research Institute and their nitrogen and phosphorus contents were determined following Kjeldhal method (Anderson and Ingram, 1993), and dry ashing method (Sahlemedhin & Taye, 2000) respectively.

3.4. Statistical analysis

The generated household survey, stove efficiency test, soil and agronomic data were analyzed using Statistical Package for Social Sciences (SPSS) version 20 and Microsoft word Excel (2007). Quantitative data obtained from the farm household survey, field observations and measurements, and laboratory analyses were averaged and summarized in tables and graphs. One way analysis of variance (ANOVA) was used to compare mean energy consumptions of the three farm wealth groups, while Pearson correlation coefficient was used to analyze the relationships between energy consumption and farm household resource endowment, as well as the relative consumption rates of different biomass fuels. Qualitative data generated from key informant interviews, focus group discussions and personal observations were used as supplementary for household survey data and analyzed using narration under different themes. Data of pre-intervention stage were compared with that of post intervention stage fuel saving using paired sample *t*-test. The confidence interval used for comparing significances of mean variation was 95% with p-values less than 0.05.

Mean values were used for quantifying GHG emission and analyzing the replacement costs of the biomass fuels, biogas and the nutrients saved due to reduced use of wood, dung and crop residues in the post-intervention KPTs. Correlation analysis was carried out in order to triangulate outcomes from KPTs with CCTs.

The average pretreatment soil parameters were used to evaluate the status of the soils in comparison with standard values in literature used to categorize the soils as low, medium or high fertility. One way analysis of variance (ANOVA) was used to assess variations in the different soil parameters in the trial plots treated after the different types and rates of fertilizer. Linear regression model was used to determine the effects of different types and rates of fertilizer on total above-ground biomasses, grain yield, nutrient use efficiency and apparent nutrient recovery of wheat and teff. The variations in different agronomic parameters for the plots treated with different types of fertilizer were analyzed using one way ANOVA.

The different agronomic parameters of the two cropping seasons were aggregated and averaged since the general patterns of agronomic responses for both cropping seasons were similar. The generated agronomic data were analyzed using SPSS version 20 and Microsoft Excel (2007). One way analysis of variance (One way ANOVA) was used for assessing variations in total above ground biomass and grain yields as a result of applying the different types of fertilizer. A linear regression model was used to determine the effects of different types and rates of fertilizer on total above-ground biomass, grain yields, nutrient use efficiencies and apparent nutrient recoveries for wheat and teff.

Chapter 4

Description of the study sites

4.1. Location of Walmara and Ada'a Districts

Walmara and Ada'a Districts are located to the west and southeast of Addis Ababa respectively. Walmara District is located in the central Highlands of Ethiopia on the western side of the Great East African Rift Valley extending from $8^0$52'45" to $9^0$15'30" N latitude and $38^0$25'24" to $38^0$42'45" E longitude. Ada'a District is also situated in the Central Highlands of Ethiopia very close to the western escarpment of the Great East African Rift Valley. Astronomically, the District extends from $8^0$40'00" to $8^0$42'30" N latitude and $39^0$00'00" to $39^0$02'30" E longitude. The administrative center of Walmara District, Holata town, is located at about 35 km from Addis Ababa while that of Ada'a District is Bishoftu which is situated at about 47 km from the national capital, Addis Ababa.
In terms of the administrative structure, Walmara and Ada'a Districts are respectively found in *Finfinnee* Surrounding Special Zone, and East Shewa Zone of Oromia National Regional State.

On three fields, on-farm trials were undertaken during the 2014 and 2015 main cropping (summer) seasons. One On-farm wheat trial field was established at Doliyo Village of Nano Genete Kebele in Walmara District; and two trial fields (one wheat field and one teff field) were established at Kumbursa Village of Ude kebele, Ada’a District.

Kumbursa and Doliyo Villages are respectively located at about 55 km in the southeast from Addis Ababa (8^0 10’ 45’’ N and 390 44’ 12’’ E); and 34 km (9^0 07’ 15” N & 38^0 32’ 27’’ E) in the western direction from Addis Ababa.

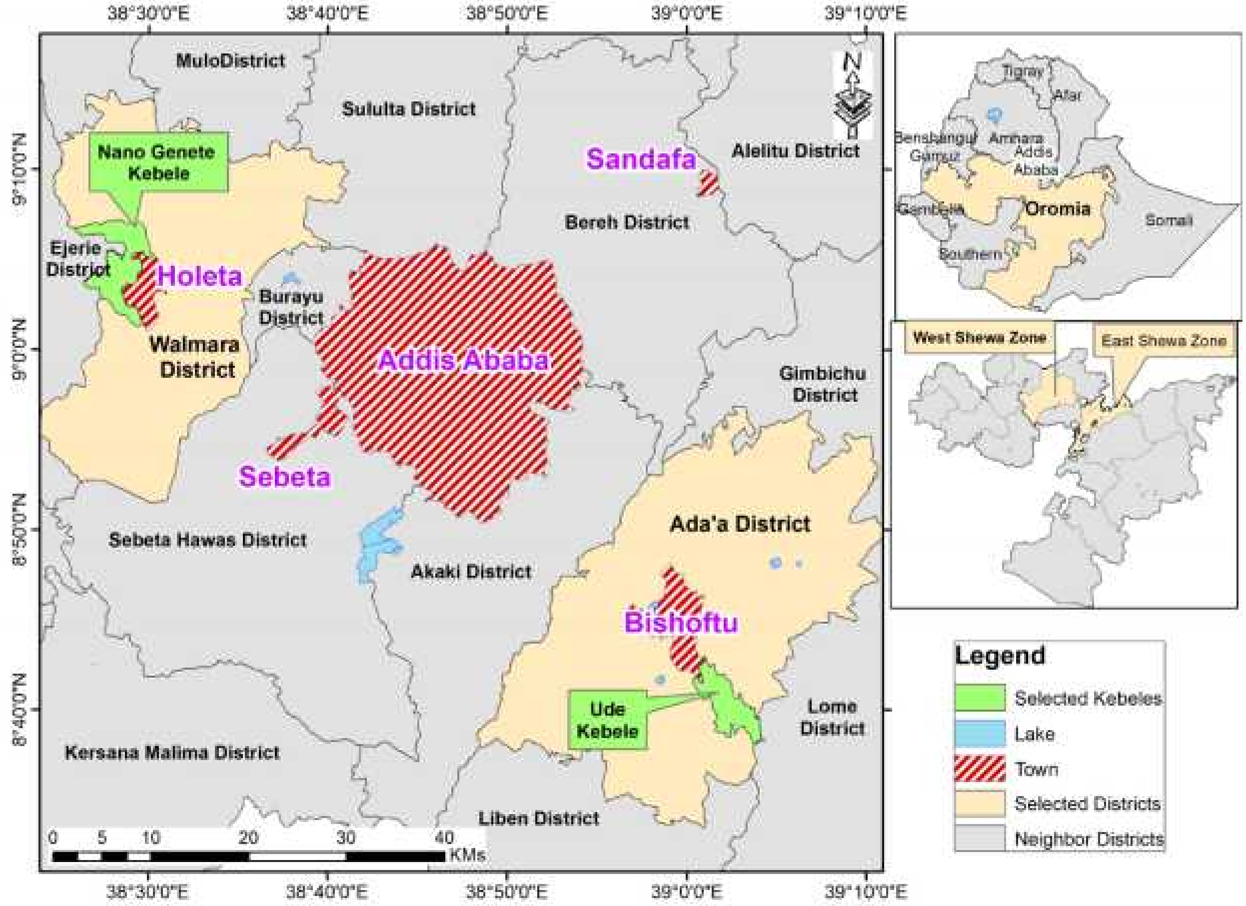

Figure 4.1. Location map of Nano Genete Kebele in Walmara District and Ude Kebele in Ada'a District (Source: Erdas Imagine and Arc GIS 10)

4.2. Relief and climate

Walmara District is characterized by dissected topography with plateau and mountains which are geologically young trachyite basalt that belong to the Wachacha mountain range (Attah & Melkamu, 2013). The geological history of Ada'a District belongs to the Bishoftu formation of the Cenozoic Era that contains alkaline basalt and trachiyte (Mesfin *et al.*, 2010).

Kumbursa Village, which is one of the three Villages in Ude Kebele (the smallest administration unit in Ethiopia) of Ada’a District in East Shoa Zone, has altitude ranging between 1878m and 1892m above sea level with flat to slightly undulating topography covering the total area of nearly 1000 ha.

The altitude of Walmara District ranges from 2060 m above sea level (a.s.l.) to 3380 m above sea level; about 41% of the District is characterized by a cool temperate climate, locally referred to as Dega (Baddaa), while 59% is categorized as warm temperate, Woina-Dega (Badda-Daree) (Walmara Agriculture Office, 2014).

The rainfall distribution pattern of Ada'a District in general and Kumbursa Village in particular is unimodal with 74% of the mean annual precipitation occurring between June and September and a total annual average of 839 mm (Minase *et al*., 2015). The average monthly temperatures range from 17.2 °C (in December) to 20.7 °C (in May), with a mean annual record of 18.9 °C (Minase *et al*., 2015).

Ada'a District, in which Kumbursa site where wheat field established is characterized by dominantly Woina-Dega (Badda-Daree) type of agroecology while smaller proportion of the District has Dega (Baddaa) type of agroecology. So with altitude ranging between 1888 m and 1992 m, Kumbursa Village is dominantly characterized by warmer temperate-like climate called Woina-Dega (Badda-Daree) type of agroecology. The climatic conditions in Kumbursa Village are suitable for teff production which is the dominant cereal crop produced in the area.

Walmara District is characterized by bimodal rainfall with minor rain occurring in the spring and major rain falling during summer. Annual rainfall of Walmara District is 1063 mm with mean monthly maximum temperature of 24.6C^0 in May and minimum temperature of 2.3C^0 in November and December (Figure 4.2). For Kumbursa, the highest maximum temperature occurs in May (29C^0) minimum in November (8C^0) and the annual rainfall for Kumbursa is 818 mm (Figure 4.3).

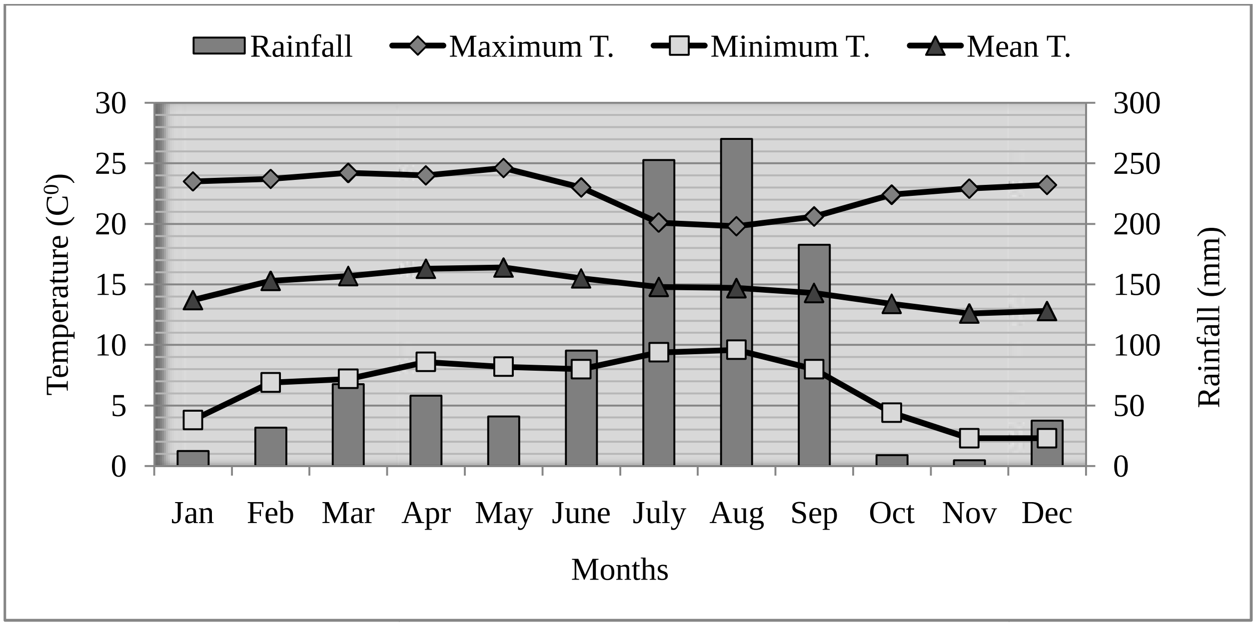

Figure 4.2. Monthly temperature and rainfall distributions of Doliyo Village (27 years average i.e. 1986 - 2013); results from Holata Agricultural Research Center meteorological station 3.5 km from the study village (Source: Office of National Metrological Agency, 2016).

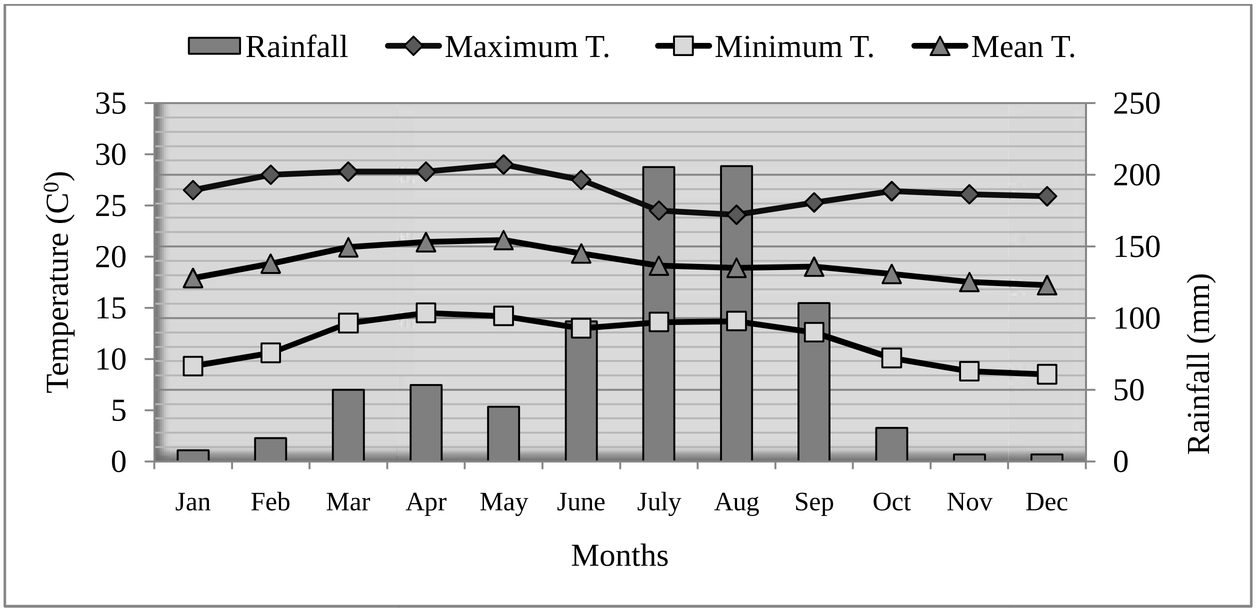

Figure 4.3. Monthly temperature and rainfall distributions of Kumbursa Village; (27 years average i.e. 1986 - 2013), results from meteorological station of Debrezeit Agricultural Research Institute located at 3 km from the study village (Source: National Mereological Agency, 2016)

4.3. Soils of the study sites

The dominant soil type in Ada'a District in general and Kumbursa Village in particular is black cotton soil (Yimenu & Chemeda, 2010). The vertisol soils of the Kumbursa site wheat and teff fields have been derived from alkaline basalt and trachyte which belong to the Bishoftu formation of Cenozoic volcanic eruption (Mesfin *et al.*, 2012). Soils of Walmara District in general and Doliyo Village in particular are made up of highly weathered acidic rocks resulting in acidic soil which is found to pose challenge to crop production (Woubshet *et al.*, 2017).

Well drained friable reddish brown soils with clay to clay loam texture are dominant in Doliyo Village (Getachew, 2017) while chromic vertisols are the single dominant soils in Kumbursa Village (Mesfin *et al.*, 2010). As also reported by Bogale (2014), the dominant soil type of Ude *kebele,* in which Kumbursa Village is found is vertisol, and this type of soil is characterized by high water holding capacity but creates challenge of water logging while showing cracking behavior during the dry season.

The soil of the trial field of Doliyo site was acidic reddish brown nitosol while that of the Kumbursa is chromic vertisol with near neutral pH. Soils in the Walmara District, where Doliyo is located, are characterized by low fertility, and the only traditional soil fertility improvement practice used is crop rotation (teff-wheat-food legumes) (Getachew *et al.*, 2014). Both the soil and climatic conditions of Kumbursa Village are suitable for teff production, which is the dominant cereal crop in the area.

4.4. The characterizing features of the farming systems in the study sites

The farming systems in the study sites (Walmara & Ada'a Districts) are denoted by close interdependence and integration of crop cultivation and animal husbandry, where the production and productivity of one is inextricably related to the other. There is no communal land for livestock grazing or firewood collection in Kumbursa Village.

Therefore, farm households of the Village almost entirely depend on resources collected from their farmlands and homesteads for food, feed, fuel and cash.

Both Doliyo and Kumbursa Villages are characterized by very high human and livestock population; and where intensive crop-livestock mixed farming is practiced. Many urban centers are found in both Walmara and Ada'a Districts and their close proximity to different urban centers including Addis Ababa has been resulting in extremely high human and animal population pressure on the land. Both in Walmara and Ada'a Districts; there are high competitions on the land resources for industries, floriculture, settlement and agriculture (Getachew, 2014).

The crop production systems in both study sites are dominantly reliant on cereal production with the use of legumes for rotation. The wheat based farming is common for Doliyo (Getachew, 2014) while teff is the dominant crop for Kumbursa Village (Bogale, 2014). In Walmara District, teff (Eragrostis tef) and wheat (Triticum aestivum L.) are the two cereal crops dominantly grown as mono crop usually rotated with leguminous crops in the order of teff-wheat-food legumes (Getachew, 2014). Ada'a District is one of the most agriculturally important Districts in Ethiopia which is known for production of best quality teff locally called *magna* that is sold at premium price (Yimenu and Chemeda, 2010).

Both Doliyo and Kumbursa Villages are characterized by intensive integrated crop-livestock mixed agriculture with dominantly cereal crop production. Wheat is the most important cereal crop for Doliyo Village while teff covers the largest proportion of crop land at the Kumbursa site. The main traditional soil fertility improvement mechanism predominantly practiced in the study Villages was rotation of cereal crops with leguminous crops. As reported by Getachew *et al.* (2014), the soils in the Walmara District including that of the Doliyo Village are characterized by low fertility, and the only traditional soil fertility improvement practice nowadays practiced in this area is crop rotation (teff-wheat-food legumes).

One-to-one rotation between cereal and legume crops is rare due to more inclination of farmers towards production of cereals. The common pattern of rotations in both experimental sites is therefore two cereals followed by a legume crop.

The major crop rotation sequences in Kumbursa Village are mostly in the order of:

- wheat (Triticum aestivum) – wheat (Triticum aestivum) - chickpeas (*Cicer arietinum*),
- wheat – teff (Eragrostis tef) - chickpeas,
- teff - wheat -chickpeas, or
- teff - teff - chickpeas.

In Doliyo Village, the rotation sequences are mainly:

- barley (*Hordeum vulgare*) - wheat (Triticum aestivum) - beans (*Phaseolus vulgaris*),
- barley - barley - beans or peas (*Pisum sativum*), or
- wheat - wheat - beans/peas.

The most dominantly grown cereal crops in the study sites, i.e. wheat and teff in Kumbursa, and wheat in Doliyo, were deliberately selected for the on-farm trial experiments. Wheat and teff together account for about 90% of cultivated land in Kumbursa Village (Dugassa *et al.*, 2017).

Teff production is most suited to medium altitudes locally referred as 'Badda Daree/Woina Dega' agroecological zones (Haftamu *et al.*, 2009), and it is generally the most dominantly grown cereal crop in the Highlands of Ethiopia (Abay *et al.*, 2011). Kumbursa Village, with its altitude ranging between 1878 and 1892m above sea level (a.s.l.), and annual rainfall (839mm), average temperature (18.9 ºC) and dominantly clay textured vertisol is highly suitable for teff production (Bogale, 2014; Dugassa *et al.*, 2017).

4.5. Household energy use characteristics

Ada'a District, where Kumbursa Village is situated, is largely characterized by a cycle of energy-driven deforestation and soil fertility loss, with cattle dung and crop residues constituting 61% and 18% of the total household energy demand, respectively (Campbell, 2005). Fuel sources are mainly from household owned woodlot plantation, and dung and crop residues from household owned livestock and fields. The urban centers found in and around the Districts largely rely on the surrounding rural areas not only for agricultural produce but also for biomass energy.

As elsewhere in Ada'a District, in Kumbursa Village, dung cakes and crop residues are the dominant fuels and cooking is usually done using a traditional three-stone open fire (Dugassa *et al.*, 2017).

All of the households in Kumbursa use separate kitchens in thatched huts with poor ventilation for cooking. Cooking hearths are located at the corner of a kitchen and they are mostly constructed on a raised level of approximately 1m height, locally referred to as a *madab*. The walls of the kitchens are plastered with mud and the air quality during cooking is poor as the kitchens lack chimneys and windows.

4.6. Land use/cover types of Nano Genete and Ude Kebeles

It is possible to understand the farming systems and household energy utilization characteristics through careful analysis of Land Use/Land Cover Changes (LULCC). As shown in Figures 4.4 and 4.5 as well as Table 4.1, quite large proportions of land (4146.5 ha (44.0%) for Nano Genete Kebele and 4134.4 ha (67.3%) for Ude Kebele) were under crop production. The built up area was the smallest land use type covering 52.1 ha accounting for only 0.8% in Ude Kebele while in Nano Genete, bare land with area coverage of 654.1 ha (6.9%) was found the least in area coverage.

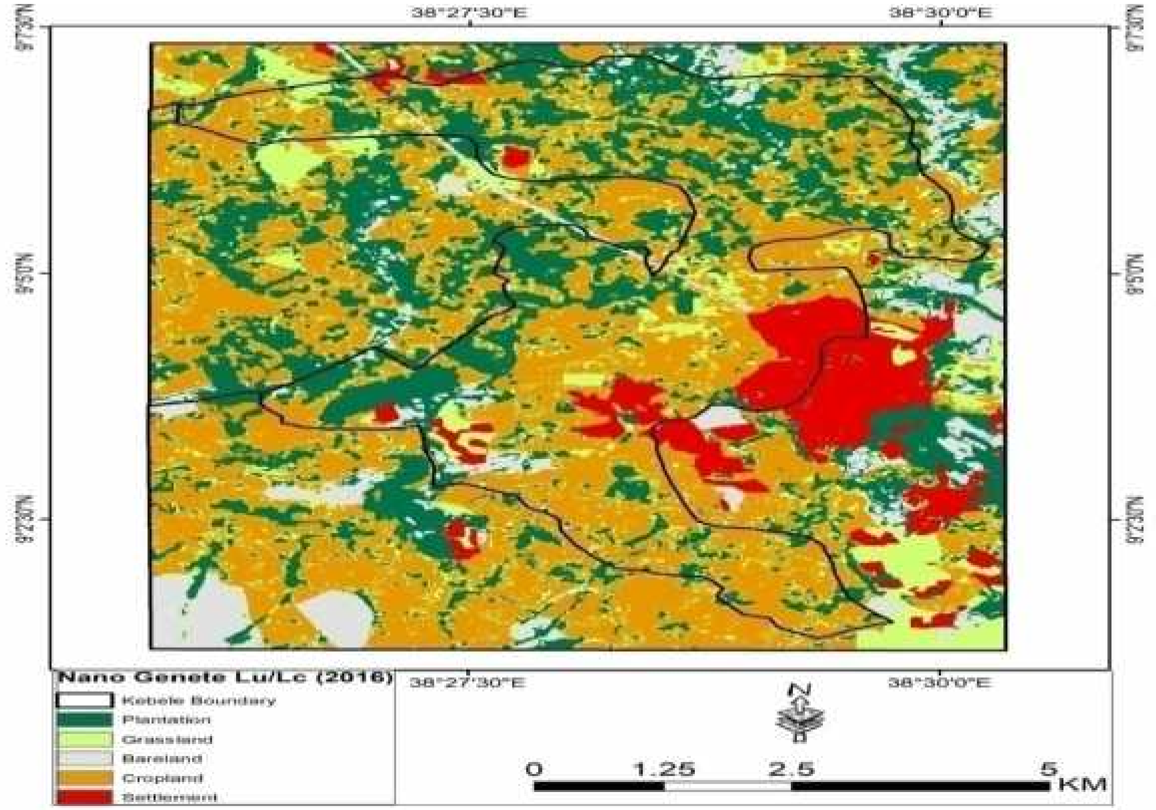

Figure 4.4. Land use/cover map of Nano Genete Kebele (Source: Erdas Imagine and Arc GIS 10)

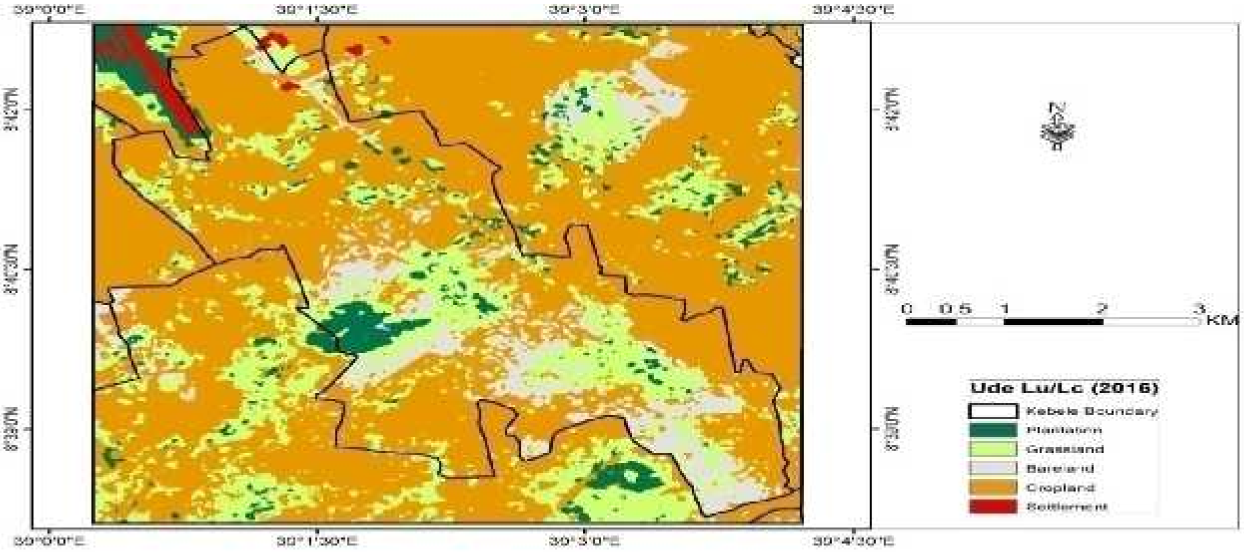

Figure 4.5. Land use/cover map of Ude Kebele (Source: Erdas Imagine and Arc GIS 10)

As depicted in Figures 4.4 & 4.5 as well as Table 4.1, quite large areas were covered by plantations (predominantly eucalyptus trees) in Nano Genete kebele while only very small areas were found to be under forest/plantation in the case of Ude kebele. This implies that there is more serious fuel wood scarcity in Ude kebele than Nano Genete kebele.

Table 4.1. Land use/cover types of Nano Genete and Ude Kebeles in 2016

LULC Type	Nano Genete Kebele		Ude Kebele	
	Ha	%	Ha	%
Forest/plantation	2595.9	27.5	292.7	4.8
Grassland	1351.7	14.3	1208.7	19.7
Bareland	654.1	6.9	452.9	7.4
Cropland	4146.5	44.0	4134.4	67.3
Built-up area	678.6	7.2	52.1	0.8
Total	9426.9	100.0	6140.9	100.0

Results, Discussion and Conclusion

Chapter 5

Household energy and recycling of nutrients and carbon to the soil in integrated crop-livestock farming systems

In this unit, results and discussions on types and sources of household energy, amounts of biomass fuel consumptions and loss of nutrients and carbon due to burning as fuel are presented. So the first part of this unit focuses on identification of household energy sources and analysis of their consumption patterns among different farmer wealth groups using the fuel stacking model. The second part is devoted to the quantification of losses of nutrients and carbon from farming systems with removal of crop residues and dung cakes for household energy. The third part is primarily concerned with the assessment of the implications of the switch from fuel wood to agricultural wastes for soil nutrients and carbon recycling in integrated crop-livestock farming systems in the different wealth groups. Finally, possible recommendations were given on how to increase availability of organic resources for soil fertility amendment.

5.1. Major sources of household energy in Kumbursa Village

The major biomass fuel sources in decreasing order of local use for all the three farm household wealth groups were dung cakes, crop residues, firewood and charcoal with corresponding mean consumption rates per household of 4300(±150) kg yr^{-1} (46000(±1600) MJ yr^{-1}), 1800(±70) kg yr^{-1} (26000 (±1000) MJ yr^{-1}), 920(±30) kg yr^{-1} (14800 (±500) MJ yr^{-1}) and 150(±4) kg yr^{-1} (3700(±100) MJ yr^{-1}) respectively (Table 5.1). Kerosene is used for lighting and its mean consumption rate per household was 40(±1) dm^3 yr^{-1} (1500 (±40) MJ yr^{-1}) (Table 5.1).

In terms of consumption by energy content, dung cakes and crop residues together provided 80(±3) % of the total energy used for cooking, while the share of firewood and tree-litter was 15.9(±0.6) %, and that of charcoal was only 4.1(±0.4) % (Figure 5.1).

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5.2. Biomass fuel production and consumption patterns among the three farm wealth groups

Both biomass fuel production and consumption were directly related to the size of landholding, livestock number and family size, and significantly varied among the three farm wealth groups ($p<0.001$; Table 5.1). This suggests that rich farm households were producers of higher amounts of biomass fuels since they had larger landholdings (3.3 ± 0.2ha) compared to the medium (1.5± 0.1 ha) and poor (1.1± 0.1 ha) wealth groups (Table 5.1).

Rich farm households also had a higher number of livestock (8.4 ± 0.3TLU) compared to the medium (4.1 ± 0.2TLU) and poor (2.5±0.1 TLU) households (Table 5.1), and this implies higher availability of cattle dung for dung cake preparation.

It was observed that rich households had also more eucalyptus trees for firewood production in their homesteads and more acacia trees scattered in their farmland for charcoal production compared to the medium and poor households. Consumption of a given biomass fuel was also found to be related to consumption of the other biomass fuels, availability of biomass resources and family size (Tables 5.2).

Rich farm households had larger families (7.2±0.3 people per household) compared to the medium (5.9±0.4 people per household) and poor farm households (5.5±0.3 people per household). Per capita biomass fuel consumption also significantly varied among the three farm wealth groups ($p<0.001$; Table 5.1); this was higher for the rich ($63 \pm 4 \text{MJ d}^{-1}$) compared to the medium and poor wealth groups, which respectively consumed ($33 \pm 2 \text{MJ d}^{-1}$) and ($26 \pm 2 \text{MJ d}^{-1}$) (Table 5.1).

Among the 120 households, 82 (68.3%) were using three-stone open fires, 21 (17.5%) mud-stoves, 10 (8.3%) improved solid biomass stoves, 3 (2.5%) both biogas stoves and mud-stoves, and 4 (3.3%) both biogas stoves and improved solid biomass stoves (Table 5.3).

As shown in Table 5.2, consumption rates of the different biomass fuel sources (dung cakes, charcoal, firewood and crop residues) were positively and significantly correlated ($p < 0.01$). This is because different biomass fuel sources were used as complementary and not as substitutes for each other. For instance, it was observed during the field survey that both dung cakes and crop residues were used together for *‘injera’* (traditional pancake-like bread) baking for increasing burning efficiency and as mechanism of adapting to fuel scarcity. There was also a tendency to use specific biomass fuels for specific cooking purposes and hence higher consumption rates of one biomass fuel source led to corresponding higher consumption rates of other biomass fuel source (Table 5.2).

For instance, baking more *‘injera’* required more dung cakes and crop residues which obliged farm households to prepare more ‘wot’ (traditional sauce eaten with *‘injera’*) which in turn required more firewood. Kerosene consumption rates also significantly varied among wealth groups (Table 5.2); this was highest for the rich (58(±1) dm^3 yr^{-1} per household) followed by the medium (38 (±0.8) dm^3 yr^{-1} per household) and the poor (31(±0.7) dm^3 yr^{-1} per household). It was determined from focus group discussions and key informant interviews that families with alternative sources of energy for lighting, such as biogas, battery and solar energy consumed lower amounts of kerosene compared to families without alternative light sources.

5.3. Amounts of nutrients and organic carbon loss with use of dung cakes and crop residues for fuel

Using the measured nutrient contents, the mean loss across all wealth groups of nutrients and OC due to using dung cakes and crop residues for fuel was 59(±2) kg N ha^{-1} yr^{-1}, 14(±0.5) kg P ha^{-1} yr^{-1} , 79(±2) kg K ha^{-1} yr^{-1} and 1540(±20) kg OC ha^{-1} yr^{-1} (Figures 5.2 and 5.3).

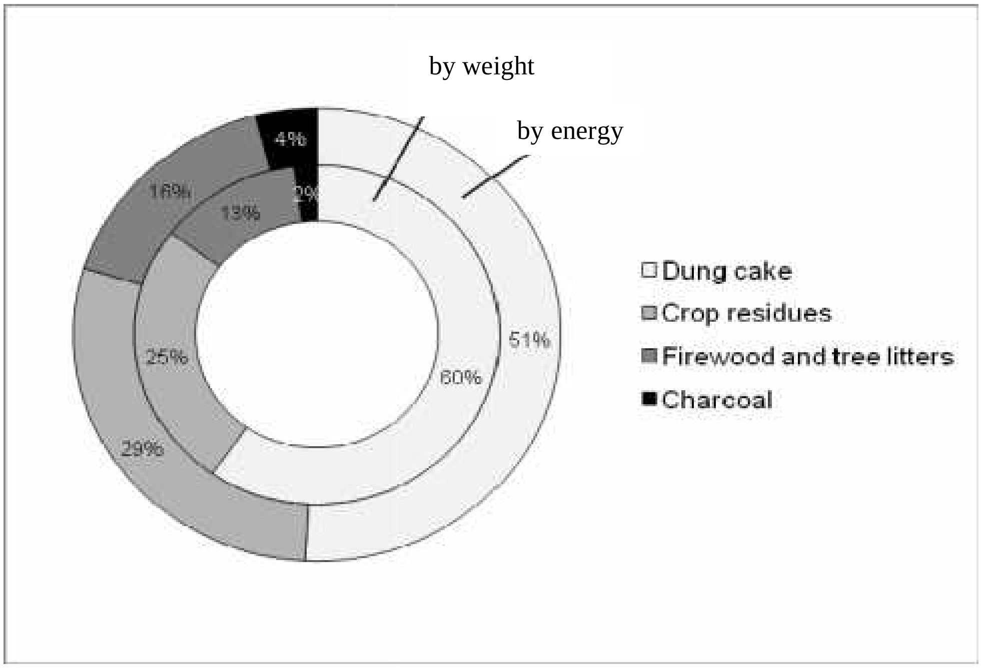

Figure 5.1. Proportion on dry base weight (inner circle) and by energy content (outer circle) of different biomass fuels used in Kumbursa Village

Table 5.1. Farm households' energy consumption rates and resources endowment by wealth group

Wealth groups (N=120)	Dung cakes ($kg\ yr^{-1}$)	Crop residues ($kg\ yr^{-1}$)	Firewood ($kg\ yr^{-1}$)	Charcoal ($kg\ yr^{-1}$)	Kerosene ($dm^3\ yr^{-1}$)	Land holding size (ha)	Livestock number (TLU)	Dung cake huts (number)	Fuel consumption rate (MJ ($capita^{-1}\ d^{-1}$))
Rich (n = 22)	7700 (±300)	2500 (±100)	1520 (±50)	190 (±5)	58 (±1)	3.3 (±0.2)	8.4 (±0.3)	4.4 (±0.2)	63 (±4)
Medium (n = 73)	3800 (±100)	1800 (±70)	810 (±30)	150 (±4)	38 (±0.8)	1.5 (±0.1)	4.1 (±0.2)	2.5 (±0.1)	33 (±2)
Poor (n = 25)	2800 (±100)	1240 (±50)	690 (±20)	90 (±3)	31 (±0.7)	1.1 (±0.1)	2.5 (±0.1)	1.3 (±0.1)	26 (±2)
Mean (n= 120)	4300	1800	920	150	40	1.9	5.0	2.7	41
Standard deviation	1677	409	292	42	1.2	1.2	2.5	1.5	19
Coeff.of variation (%)	39	22	32	29	34.9	67.8	57.3	53.1	47
Standard error	150	70	30	4	1	0.1	0.2	0.1	2.5
p-value	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**

Notes: kg $capita^{-1}\ d^{-1}$ includes only dung cakes, crop residues and firewood; ** significant at 0.001 level; TLU = Tropical Livestock Unit; n= the number of samples; standard errors are given in brackets

Table 5.2. Bivariate correlation coefficients between different biomass fuel consumption rates and resource endowment of the farm household

	Dung cakes (kg)	Charcoal (kg)	Firewood (kg)	Crop residues (kg)	Land holding size (ha)	Family size (capita)	Livestock number (TLU)
Dung cakes(kg)	1.00						
Charcoal (kg)	.654**	1.00					
Firewood (kg)	.994**	.628**	1.00				
Crop residues (kg)	.936**	.764**	.910**	1.00			
Land holding size (ha)	.651**	.461**	.652**	.597**	1.00		
Family size (capita)	.197*	.160*	.211*	.189*	.194*	1.00	
Livestock number (TLU)	.792**	.593**	.789**	.782**	.508**	.155*	1.00

Notes: $kgcapita^{-1}d^{-1}$ includes only dung cake, crop residues, and firewood; **significant at 0.001 level; TLU=Tropical Livestock Unit; n= number of samples; standard errors are given brackets.

Table 5.3. The surveyed farm households of Kumbursa Village by stove types

Stove type	Number of households	Percentage
Three stone open fires	82	68.3%
Mud-stoves	21	17.5%
Improved solid biomass stoves	10	8.3%
Biogas stoves and mud-stoves	3	2.5%
Biogas stoves and improved solid biomass stoves	4	3.4%
Total	120	100%

Note: improved solid biomass stoves include those stoves that can be bought from local markets such as Lakech, Mirt and Gonziye stoves * significant at 0.01level; ** significant at 0.001 level

These losses of nutrients are higher than has been measured by other researchers working in the Central Highlands of Ethiopia; Aklilu (2006) measured nutrient losses of 21 kg ha^{-1} yr^{-1} N, 4.5 kg ha^{-1} yr^{-1} P and 20.7 kg ha^{-1} yr^{-1} K due to the use of dung cakes as fuels, and Kassahun *et al*. (2013) measured nutrient losses of only 13.2 kg ha^{-1} yr^{-1} N, 3.3 kg ha^{-1} yr^{-1} P and 15.8 kg ha^{-1} yr^{-1} K due to the use of both dung cakes and crop residues for fuel. The differences in the observations may be due to larger areas of landholding per household in the areas selected in the earlier studies, resulting in the same household fuel use causing smaller nutrient losses per area of land. This is reflected in the losses of nutrients and OC observed for the different wealth categories, with the losses per area of land from the rich wealth group being significantly lower than from the medium or poor wealth categories.

If the losses are considered across the whole households, the mean losses across all wealth groups of nutrients and OC through the use of dung cakes for fuel are estimated to be 90 (±7) kg yr^{-1} N, 24 (±2) kg yr^{-1} P,120(±10) kg yr^{-1} K and 2000(±200) kg yr^{-1} OC per household, and due to use of crop residues as fuels to be19 (±1) kg yr^{-1} N, 2.4 (±0.2) kg yr^{-1} P, 30 (±1) kg yr^{-1} K and 980(±50) kg yr^{-1} OC per household (Figures 5.2 and 5.3). This gives a total nutrient loss due to using dung and crops residues as fuels of 110(±8) kg yr^{-1} N, 26(±2) kg yr^{-1} P, 150(±10) kg yr^{-1} K and 3000(±300) kg yr^{-1} OC per household.

Contrary to the result per area of land holding, the rich farm wealth group was found to use significantly more dung and crop residues for fuel than the medium and the poor farm wealth groups (Figure 5.1).

The mean consumption of OC in dung cakes and crop residues per household was 2000(±200) kg yr^{-1} and1000 (±60) kg yr^{-1}. The highest loss of OC with the dung cakes was recorded for the rich farm wealth group (162% of the losses from the medium farm wealth group and 223% of the loss from the poor farm wealth group) (Figure 5.3). The nutrient loss due to use of dung cakes for fuel was significantly higher (90 (±7) kg yr^{-1} N, 24 (±2) kg yr^{-1} P, 120(±10) kg yr^{-1} K) than that of the crop residues (19 (±1) kg yr^{-1} N, 2.4 (±0.2) kg yr^{-1} P, 30(±2) kg yr^{-1} K) (Figure 5.2). This is because crop residues are mostly used for feeding to the livestock.

It was reported by key informants that there had been a general switch to dung cakes and crop residues due to fuel wood scarcity, not only for domestic consumption, but also for sale. Apart from dung cakes, farm households of Kumbursa do not usually have surplus fuel to sell. The average value of dung cakes sold by a household was 2686 (±127) ETB yr^{-1} (128 (±6.1) US\$ yr^{-1}) per household.

5.4. The study in Kumbursa in the context of Ethiopia

Typical of rural Villages in Ethiopia, farm households in Kumbursa were almost entirely dependent on biomass fuels for all household energy requirements (Figure 5.1), with the exception of lighting. However, unlike many rural farm households in the Ethiopian Highlands, which often at least partly depend on community forests for fuel wood (Abebe *et al*., 2011; Badege, 2001; Dawit, 2012; Fekadu, 2015), almost every farm household surveyed in Kumbursa was dependent on dung and crop residues collected from their own holdings (cropland and homestead) for fuel. There was neither a community forest for firewood nor communal grazing lands for dung collection. As such, Kumbursa represents the situation in an Ethiopian Highland Village after the community forest has been depleted; a situation that will become more common as community forests become increasingly deforested due to population growth and overuse. Kumbursa Villagers now only obtain 16(±0.6)% and 4.1(±0.2)% of their energy requirements from fuel wood and charcoal respectively, the remainder being obtained from dung and crop residues (Figure 5.1; Table 5.1) which formerly had been applied to farmland for soil fertility amendment. This has seriously threatened a generations old practice of carbon and nutrient recycling within the farming systems through application of animal manures and crop residues in the smallholder crop-livestock integrated farming systems of the Ethiopian Highlands in general and in Kumbursa Village in particular.

Field observations at the study site showed that almost all of the crop residues were used to feed livestock, while dung produced by cattle was a major source of fuel. Dung cakes and crop residues together made up 80(±4) % of the total biomass fuel consumption by energy content and 85(±4) % by dry mass weight (Figure 5.1).

As determined by key informant interviews and focus groups discussions, all the available dung was collected and made into dung cakes, while crop residues were largely used as feed for livestock. It was also observed during the field survey that the partially decomposed crop residues that are not suitable for feeding to livestock and any residues left over from livestock feed were almost exhaustively collected to either mix with the dung for dung cake preparation or to use directly as a fuel for cooking. In line with this finding, Aklilu (2006) observed that farm households in Beressa Watershed of the Central Highlands of Ethiopia prepared about 90% of their cattle manure into dung cake.

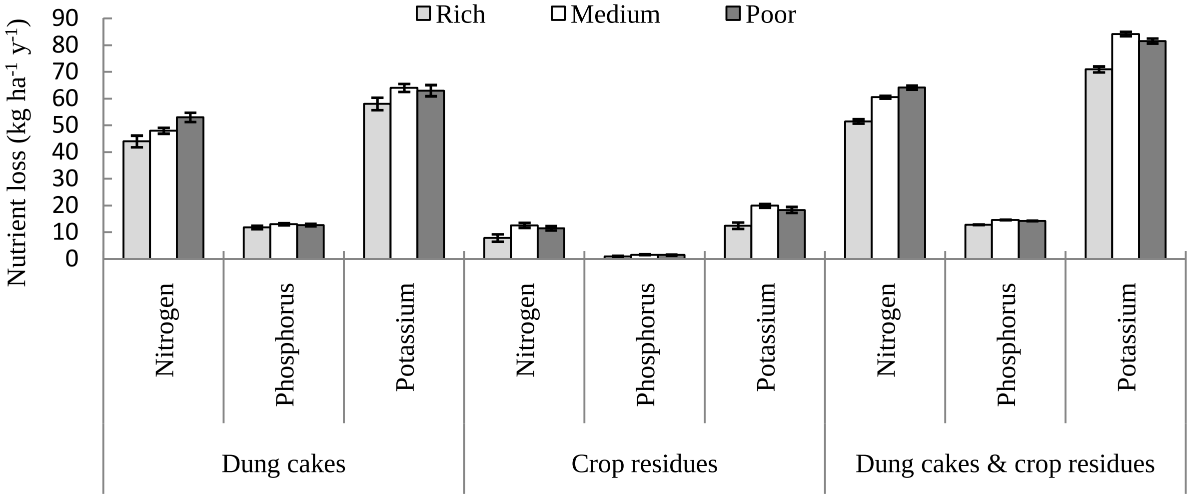

Figure 5.2. Mean loss of nutrients by area of landholding due to use of dung cakes and crop residues for fuel separately as well as in combination.

Note: nutrient losses both through consumption by the households and sale were included; error bars show standard errors

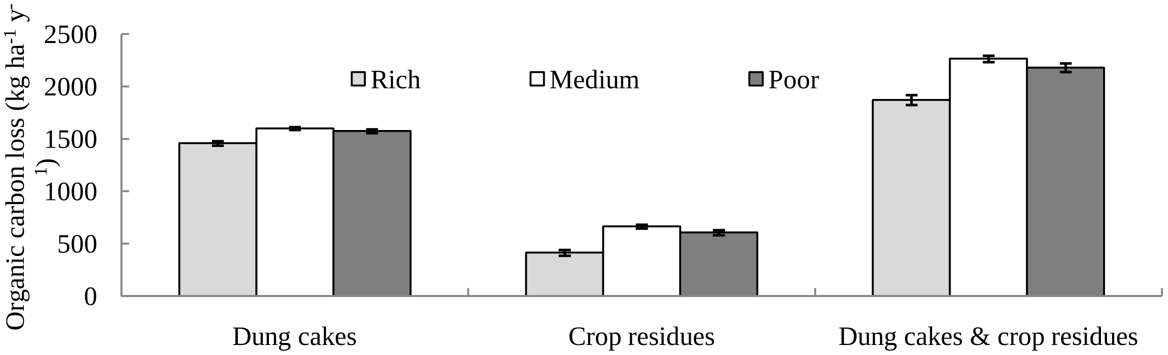

Figure 5.3. Mean loss of organic carbon by area of landholding with use of dung cake compared to crop residues for fuel for farm wealth groups.

Note: Organic carbon loss both through consumption by farm households and sale were included. Error bars show standard errors.

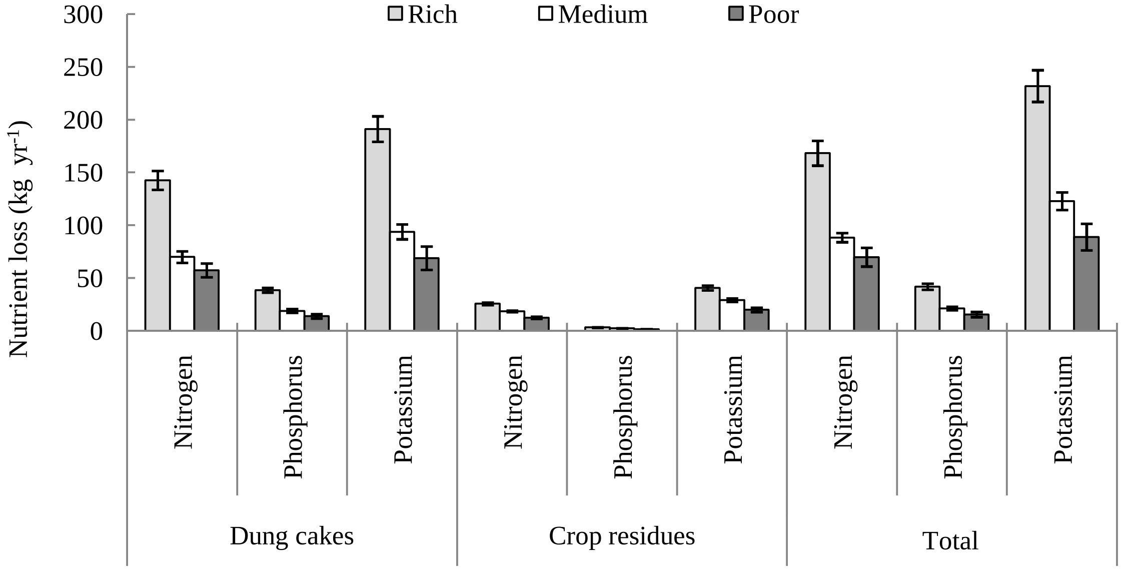

Figure 5.4. Mean loss of nutrients for the household by wealth group due to the use of dung cakes and/or crop residues as fuel.

Note: Nutrient losses both through consumption by the households and sale were included. Error bars show standard errors.

EUEI (2013) also suggested that ~60% of dung and crop residues are used for household energy in the Highlands of Ethiopia. This suggests that the use of both animal manure and crop residues for improving soil fertility in Kumbursa, and Ethiopia as a whole, is very low, resulting in high loss of nutrients and carbon from the farming systems.

5.5. The situation today compared to the situation in the past

Interviews conducted with key informants also indicated that, in the past, firewood was abundant and large tracts of communal lands were available for livestock grazing. As a result, crop residues were left on farmland and animal manure was recycled into the farming system; this provided a significant contribution to soil fertility improvement. In the past, application of chemical fertilizers to cropland was rarely practiced by farmers of Kumbursa. However, farm households have now changed their practices to use dung cakes and crop residues for household energy instead of applying them to farmlands.

As a result, it is suggested here that farmlands have become increasingly infertile and crop production without chemical fertilizer has become difficult.

5.6. Relationship between wealth status and tendency to use multiple fuels

In an effort to reduce the gap in the empirical literature on household energy and its interaction with carbon and nutrient recycling within the farming systems, this study has assessed biomass fuel production and consumption patterns among the different farm wealth groups. More specifically, the study has quantified the loss of nutrients and organic carbon from the farming systems with removal of crop residues and dung cakes for fuel, and explored its implications for sustainability of agricultural productivity.

There tends to be a positive relationship between resource endowment and fuel stacking. However, sometimes this relationship becomes unclear because non-economic factors, which could be socio-cultural and/or geographical, can also influence the tendency to use multiple fuels, so it is important to clarify the degree of relationship.

Wealth status, which is based on resource endowment, had little or no impact on farm households' energy choice in Kumbursa Village as all of the three wealth groups (rich, medium and poor) were dependent on biomass fuel for cooking (Table 5.1). In other words, higher wealth status/resource endowment did not lead to energy stacking or partial energy switching. The focus group discussions suggested that some farm households were not willing to pay for alternative energy sources for cooking as long as dung cakes and crop residues were available, while others mentioned lack of access to alternative fuel sources as an underlying constraint to energy stacking. There also seemed to be little awareness or promotion of the benefits of modern cooking fuels over traditional biomass fuels in the area.

Overall, the impact of household resource endowment in dictating fuel choice and energy stacking was found to be insignificant. Based on focus group discussions and key informant interviews, multiple fuel use appeared to be curtailed by (1) inadequate awareness of the benefits of alternative fuel sources, and (2) limited access to the clean and safe energy alternatives which can serve to substitute or supplement biomass fuels.

Therefore, under the present situation, the finding of this study does not follow the ‘Energy Stacking’ model since it fails to establish positive correlation between resource endowment and multiple fuel use.

5.7. Implications of large scale removal of agricultural wastes for fuel

The loss of nutrients (N, P and K) from croplands through removal of crop residues was very high. Only small amounts of crop residues from stubble (approximately 10% based on a rough visual estimate) were left in situ for recycling back to the soil and this was further exposed to losses by livestock grazing after crop harvest. In the case of chickpeas, even the underground plant biomass was removed as harvesting was usually undertaken by uprooting. Abebe *et al.* (2015) also reported that less than10% of manure and crop residues produced by smallholder farmers in Ethiopia were recycled into croplands for soil fertility amendment. Other studies have reported a shift to using animal manure and crop residues for household energy at the expense of applying them to croplands (Assefa *et al.*, 2007; EUEI, 2013; Woldeamlak, 2003). Studies undertaken in several Ethiopian Highlands show high loss of organic matter from farming systems due to widespread conversion of households to dung cakes and crop residues for fuel in response to dwindling firewood supply (Aklilu, 2006; Dawit, 2012; Getamesay *et al.*, 2015; Gwavuya *et al.*, 2012; Kassahun *et al.*, 2013).

There were large differences among the three wealth groups in the total amount of nutrients and carbon lost due to use of organic resources as fuel. Although the total household loss of nutrients and OC was higher for the rich than the medium or poor farmers (Figures 5.4 & 5.5), when the loss was calculated per area of landholding, the losses were higher for the poor and the medium wealth groups than for the rich farmers (Figures 5.2 & 5.3). This suggests that depletion of soil, due to not incorporating dung and crop residues, will have a greater impact on the land belonging to poor and medium wealth class farmers than on land belonging to rich farmers, resulting in a cycle of decreasing soil fertility that increased poverty levels particularly in the famers who are already poor.

The mean annual loss of N and P with use of crop residues and dung cakes for fuel was equivalent to 156 (±7) kg diammonium phosphates and 80(±3) kg urea per household.

In financial terms, the average loss for all the three farm wealth groups was estimated to be 3380 (±160) ETB yr^{-1} (162 (±7.6) US$ yr^{-1}). However, this is less than their value as fuels, which was 10297 (±483) ETB yr^{-1} (490 (±23) US$ yr^{-1}). Therefore, farmers will only be persuaded to use these valuable assets as soil improvers if an alternative, cheaper fuel source can be found. Of course it is worth noting that the value of organic fertilizers can be far higher than this if the value of all the nutrients (both macro and micro), and the effects of increasing soil organic matter and water holding capacity are taken into account.

The sale of dung cakes to provide household cash income also contributed to the removal of OC and nutrients from the farming system. Because Kumbursa is close to the capital city (Addis Ababa) and several small urban centers, such as Bishoftu, Dukam and Galan, there is an increased market demand for dung cakes; and this has caused farm households to collect almost all the available dung for dung cake preparation leaving little for application to farmland for soil fertility amendment. Aklilu (2006) also suggested that the farm households in the Central Ethiopian Highlands obtain cash income from the sale of dung cakes in the nearby towns. A study undertaken by Abebe *et al.* (2015) in the suburbs of Addis Ababa reported that up to 10% of household income is generated from the sale of dung cakes.

Generally, the prevailing switch to the widespread use of agricultural wastes both for domestic consumption and sale as fuel was identified as serious hurdle to the recycling of carbon and nutrients back to soils. This suggests that the already inadequate application of inorganic fertilizers (typically 49 kg ha^{-1} N and 46 kg ha^{-1} P) is rarely supported by recycling of nutrients from agricultural wastes; this jeopardizes the long term sustainability of agricultural production.

5.8. What can be done?

The availability of cattle dung and crop residues for soil amendment could be increased through use of fuel-efficient improved cookstoves or increased use of multiple energy alternatives, such as small scale biogas digesters or solar energy; these have the added advantage of being clean and sustainable.

Chemical fertilizer should be used to complement, not as a substitute for, organic fertilizers; organic fertilizers provide organic matter as well as nutrients to the soil, improving soil structure and increasing the water holding capacity.

Therefore, policy makers should work towards encouraging farmers to use chemical fertilizers in combination with organic fertilizers instead of using chemical fertilizer alone.

5.9. Further work

Although this study was conducted in only one Village, the findings and recommendations are likely to be representative of wider rural areas of Ethiopian Highlands that have switched to agricultural wastes for fuel in response to dwindling woody biomass supply, shrinking communal lands for livestock grazing and firewood collection. We recommend further studies to evaluate the long term changes in soil nutrient status in Ethiopia, and the sustainable limit to the amounts of dung cakes and crop residues that can be removed for fuel. We also suggest the need for studies on the challenges and opportunities for improving biomass fuel use efficiency, non-economic factors constraining the uptake of multiple fuels and the actions needed to make fuel use sustainable in Ethiopia.

Chapter 6

The contribution of improved cookstoves and biogas to the availability of organic fertilizer, improvement of household finances and mitigation of greenhouse gas emissions

This chapter tries to present results and discussion on the relevance of improved cookstoves and biogas stoves in enhancing the availability of agricultural wastes for soil amendment, improvement of household finances and mitigation of greenhouse gases emissions as compared to the three stone open fires. Field–based empirical evidence on potential environmental and socio-economic implications of improved cookstoves and biogas digesters are generally sparse, and field-based evaluation of end-use biomass fuel efficiency is lacking (Adkins *et al*., 2010; Mercy Corps, 2010). Therefore, the aim of this work was to assess the potential impact of mud-stoves and mirt stoves, with-and-without biogas stoves, on the biomass fuel saving of farm households, and to determine the implications for availability of agricultural residues for soil improvement, mitigation of GHGs emissions and improvement of household finances. This was done for the case study of Kumbursa Village in the central Highlands of Ethiopia using the Kitchen Performance Test (KPT), the Controlled Cooking Test (CCT) and household survey.

6.1. Biomass fuel saving

Results from KPT showed that the mean per household biomass fuel saving was 32% (2842(±21) kg yr^{-1}) per household for mud-stoves (group 1), 45% (3997(±27) kg yr^{-1}) for *mirt* stoves (group 2), 49% (4352(±33) kg yr^{-1}) for combined use of mud and biogas stoves (group 3), and 54% (4796±27 kg yr^{-1}) for combined use of *mirt* and biogas stoves (group 4) (Table 6.1). The biomass fuel saving was statistically significant for all the four groups (Table 6.1; $p<0.001$) with the highest fuel saving for the households using *mirt* strove + biogas stove.

The greater efficiency of the *mirt* stoves compared to the mud-stoves was attributed to the better design and construction of the former. In addition to preparing *injera*, *mirt* stoves were used for drying and refreshing stale *injera*, and preparing *firfir* (made by mixing dried *injera* with hot sauce) using the heat remaining after baking *injera*. The mirt stove was also used for preparation of sauce/*wot* on the chimney during *injera* baking, which as reported by the participants further saved biomass fuel and reduced cooking time.

The biomass fuel saving of the *mirt* stove over the traditional three-stone open fire was in agreement with the findings of Yosef (2007), who reported a 45% fuel saving for an *injera mirt* stove compared to a traditional open fire system. However, the result of this study was higher than the findings of Elisabeth *et al.* (2014), Abera (2015) and Dagninet *et al.* (2015), who reported savings of 40%, 22% and 33%, respectively. Further savings were observed when stoves were used in combination with biogas stoves. This is because biogas was used for cooking activities other than *injera* baking, such as for *wot* preparation, making coffee and tea and boiling water. This further reduced the use of solid biomass fuels.

From the household survey, it was observed that 173 (67%) out of the total 258 households in Kumbursa village have enough feedstock, good access to water and adequate financial capacity to install biogas digesters. If the full potential of biogas is exploited and used together with mud-stoves, there would be biomass fuel saving of 4352(±33)kg yr^{-1} per household and 4796(±27) kg yr^{-1} per household respectively while the respective possible biomass fuel savings across all potential users in Kumbursa would be 752.9±5.7 t yr^{-1}, and 829.7 ±4.6t yr^{-1}).

Table 6.1. Biomass fuel saving efficiencies of mud-stoves and *mirt* stoves with and without biogas stoves as compared to three-stone open fire stoves (average biomass fuel consumption for three stone open fires = 8891 kg yr^{-1} per household)

Stove types	Mean biomass fuel saving per household		Standard deviation	*t*-value	Df	p-value (2-tailed)
	Absolute (kg yr-1)	Relative				
Group 1: Mud-stove	2842±21	32%	350	19.4	10	.000**
Group 2: Mirt stove	3997±27	45%	441	20.6	10	.000**
Group 3: Mud and biogas stove	4352±33	49%	735	13.7	9	.000**
Group 4: Mirt and biogas stove	4796±27	54%	816	13.8	9	.000**

6.2. Enhancement of nutrient availability

A farm household on average saves 43.1(±0.32) kg yr^{-1} N, 10.5(±0.07) kg yr^{-1} P, 54.2(±0.39) kg yr^{-1} K and 1177.9(±8.5) kg yr^{-1} OC when a three-stone open fire is substituted by a mud-stove with a further higher savings for a *mirt* stove, a mud-stove with biogas, and a mirt stove with biogas (Table 6.2). This implies that if saved fuels are used as organic fertilizers, using improved cookstoves together with biogas stoves can substantially increase the availability of nutrients for field application relative to the use of improved cookstoves without biogas stoves. Average landholding size for Kumbursa Village is 1.9 ha (Dugassa *et al.*, 2017) which requires nearly 190 kg DAP and 190 kg urea based on blanket recommendation. So the amounts of N (117 kg) and P (34 kg) saved when *mirt* stoves and biogas stoves are used in combination are almost equivalent to the amounts recommended from inorganic fertilizer i.e. 121.6 kg N and 34.2 kg P.

Assuming that the saved cattle dung and crop residues are properly and exhaustively recycled to farmland, the amounts of nutrients saved due to substituting three-stone open fire with *mirt* and biogas stoves can almost entirely replace inorganic fertilizer. However, the use of bioslurry as fertilizer in the predominantly cereal cropping areas of the Central Highland of Ethiopia including Kumbursa Village is very rare. Farm households also prefer to sell the surplus cattle dung as dung cakes instead of applying it to farmland since dung cake demand as fuels is very high near to urban markets.

The exhaustive exploitation of the available biogas potential together with use of mud-stoves for the entire 258 households of Kumbursa Village can result in potential nutrient saving of 25.2(±0.13) t N yr^{-1}, 7.5(±0.03) t P yr^{-1} , 25.9(±0.16) t K yr^{-1} and 573.3(±3.50) t OC yr^{-1}; if biogas is used together with mirt stoves the nutrients saving potential would be 27.9(±0.10) t N yr^{-1}, 7.9(±0.03) t P yr^{-1}, 28.1(±0.13) t K yr^{-1} and 620.7(±2.84) OC t yr^{-1}.

Table 6.2. Nutrient saving of mud-stoves, *mirt* stoves, mud-stove + biogas stoves and *mirt* stove + biogas stove relative to the three-stone open fire

Stove types	Dung and crop residues saving (kg yr^{-1})	Average saving potential (kg yr^{-1}) per household			
		Nitrogen	Phosphorus	Potassium	Organic carbon
Group 1: Mud-stove	2842±21	43.1±0.32	10.5±0.07	54.2±0.39	1177.9±8.5
Group 2: Mirt stove	3997±27	60.6±0.41	14.8±0.10	76.2±0.51	1665.4±9.7
Group 3: Mud-stove +biogas stove	4352±33	62.0±0.51	16.2±0.12	83.0±0.63	1803.8±13.5
	2038 (from bioslurry)	53.0	19.2	26.1	623.6
Group 4: Mirt stove +biogas stove	4796±27	72.7±0.40	17.8±0.09	91.5±0.51	1987.5±11.0
	2038 (from bioslurry)	53.0	19.2	26.1	623.6
P-values	0.000**	0.000**	0.000**	0.000**	0.000**

As depicted in Table 6.2, both the biomass fuel and nutrient savings among the four groups of technologies were statistically significant ($P<0.001$).

Thus, replacement of the existing three stone fires with mud-stoves and *mirt* stoves with-and-without biogas can significantly reduce biomass fuel scarcity, and increase the recycling of nutrients to the soil. The findings imply that though sole utilization of mud-stove and *mirt* stove can significantly reduce biomass fuel consumption and enhance nutrient availability for soil amendment, the use of these stoves with biogas leads to improvement in biomass fuel use efficiencies and nutrient availability by more than twofold (Table 6.2).

6.3. Mitigation of greenhouse gas emissions

The substitution of three-stone open fire with improved cookstoves also significantly contributed to the mitigation of GHG emissions which were reduced per household by 4534 (±32) kg CO$_2$e yr^{-1} for mud stoves, 6370 (±42) kg CO$_2$e yr^{-1} for *mirt* stoves, 6953 (±51) kg CO$_2$e yr^{-1} for mud-stoves plus biogas and 7661 (±43) kg CO$_2$e yr^{-1} for *mirt* stoves plus biogas (Table 6.3).

The biogas digesters prevented 360 m^3 CO_2 and 600 m^3 CH_4 from being emitted to the atmosphere, and saved about 0.562 ha of forest land from being deforested on annual basis (Seid *et al*., 2014). Abera (2016) reported the reduction of CO_2 emission by 2.145 t yr^{-1} per stove as a result of replacing three-stone open fire furnace with a *gonziye* stove (another design of improved *injera* stove).

The GHG abatement potential of using biogas with mud-stoves and *mirt* stoves for the entire 258 households of Kumbursa Village would be 1746.185 t CO_2e yr^{-1} and 2187.868 t CO_2e yr^{-1} respectively.

Table 6.3. Greenhouse gas emission mitigation potentials of mud-stoves and *mirt* stoves with and without biogas stoves relative to the three-stone open fire.

Stove types	Biomass Saving potential (dung and residue) (kg $yr^{-1)}$	GHGs emissions mitigation potential per household (kg CO_2e yr^{-1})			
		CO_2	CH_4	N_2O	Total
Group 1: Mud-stove	2842(±21)	4173(±31)	310(±20)	50(±3)	4534(±32)
Group 2: Mirt stove	3997(±27)	5880(±40)	430(±32)	71(±7)	6370(±42)
Group 3: Mud and biogas stove	4352(±33)	6414(±51)	470(±40)	80(±7)	6953(±51)
	2038 (from bioslurry)	3772	1	-	3773
Group 4: Mirt and biogas stove	4796(±27)	705(±40)	520(±30)	80(±6)	7661(±43)
	2038 (from bioslurry)	3772	1	-	3773
P-value	0.000**	0.000**	0.000**	0.000**	

The GHGs mitigation potentials among technologies were proved to be statistically significant ($P<0.001$) with average values ranging from 4534(±32) kg CO_2e yr^{-1} for the sole use of mud-stove to 11434(±43) kg CO_2e yr^{-1} for the utilization of *mirt* stove with biogas (Table 6.3).

6.4. Improvement of household finances

The average financial savings from the sale of surplus biomass fuel following the replacement of three-stone open fire was 6145(±95) ETB yr^{-1} (279(±4) US$ yr^{-1}) for mud-stoves, 8630 (±115) ETB yr^{-1} (392(±5) US$ yr^{-1}) for mirt stoves, 9406(±139) ETB yr^{-1} (428(±6) US$ yr^{-1}) for mud-stoves + biogas stoves, and 10354(±57) ETB yr^{-1} (471(±2.6) US$ yr^{-1}) for *mirt* stoves + biogas stoves. The combined financial savings per farm household from reducing expenditure on commercial fertilizer and from carbon financing for the mud-stoves and *mirt* stoves without biogas were 3122(±36) ETB yr^{-1} (142(±1.6) US$ yr^{-1}) and 5059 (±45) ETB yr^{-1} (230 (±2) US$ yr^{-1}) respectively, while biogas increased this to 7007(±36) ETB yr^{-1} (318 (±1.6) US$ yr^{-1}) and 8051 (±45) ETB yr^{-1} (366(±2) US$ yr^{-1}). This includes replacement of kerosene by biogas for lighting, which provided a financial saving of 643 ETB yr^{-1}(29 US$ yr^{-1}).

The financial saving from the sale of surplus biomass fuel was found to be higher than the summed financial savings from substituting commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting. This explains why households usually prefer to sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that wide scale adoption of fuel efficient solid biomass stoves can contribute to the financial security of households, and may help to reduce deforestation, but will do little to increase the fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by retaining at least some of the carbon and nutrients in bioslurry that will be applied to the soil.

Table 6.4. Improvement in household finances with mud-stoves and *mirt* stoves with and without biogas stoves relative to three-stone open fire

Stove types	Potential financial saving efficiencies per household in ETB yr^{-1}			
	From sale of saved biomass fuel	From reducing expense on inorganic fertilizer	From carbon financing	From replacement of kerosene for lighting
Group 1: Mud-stove	6145 (±95)	1488 (±12)	1634 (±24)	-
Group 2: Mirt stove	8630 (±115)	2761 (±15)	2298 (±30)	-
Group 3: Mud-stove+biogas stove	9406 (±139)	3308 (±19)	2508 (±35)	643
Group 4: Mirt+biogas stove	10354 (±57)	3450 (±7)	2764 (±168)	643
P-value	0.000**	0.000**	0.000**	

Note:*1USD = 22ETB; dung cakes, crop residues, firewood and charcoal respectively account for 60%, 25%, 13% and 2% of the saved biomass fuel; Local market biomass fuel monetary values were 2ETB* kg^{-1} *for dung cakes, 2.1ETB* kg^{-1} *for crop residues, 1.8 ETB* kg^{-1} *for firewood and 10 ETB* kg^{-1} *for charcoal.*

The average potential financial savings per year for a household from sale of saved biomass fuel, reduction of expense on chemical fertilizer, and carbon financing respectively are given in Table 3.5. Biogas stoves contribute an additional 643 ETB y^{-1} (29 US\$ y^{-1}) for the households using mud-stove + biogas stove, and *mirt* stove + biogas stove. If all households in Kumbursa Village were to use their biogas potential with mud-stoves, there would be financial savings of 2, 149,563(±32,122) ETB yr^{-1} (97,707(±1460) US\$ yr^{-1}), 698,764 (±4,307) ETB yr^{-1} (31,762 (±196) US\$ yr^{-1}), 572,774 (±8095) ETB yr^{-1} (26,035 (±368) US\$ yr^{-1}) respectively from the sale of the saved biomass fuel, substituting commercial fertilizer and carbon financing. From focus group discussions and interviews with participants, it appeared that the time savings and the smokeless nature of the biogas as a fuel were appreciated by the end users, while the benefits of bioslurry as fertilizer were generally ignored and hence undervalued by the farm households.

Abera *et al.* (2016) also reported potential annual financial saving of 3,717 ETB per household as a result of substituting three-stone open fire with *mirt* stoves. With biogas, Zerihun (2015) observed an annual per household savings of ETB 3833, 1243, 129, 266 and 718 from substituting fuel wood, charcoal, dung cake, kerosene and chemical fertilizer respectively with net cash flow of 1530 ETB.

6.5. Biomass fuel saving efficiency assessment of mud-stoves and *mirt* stoves using controlled cooking test

As depicted in Table 6.5, the results are not statistically different within a given technology with (F = 0.679; P = 0.519) for the three stone open fires, ((F = 0.894; P = 0.427) for mud-stoves, and ((F = 2.222; P = 0.137) for the *mirt* stoves. This implies that the efficiency test results are valid, and this has strengthened the findings of the KPT.

Table 6.5. One way ANOVA among stoves and cooks to test biomass fuel consumption by available stove technologies at Kumbursa Village

Code	Mean biomass fuel consumption of 7 days performance (Kg day^{-1})			Mean	Mean square between groups	F-ratio	(P-value)
	Three-stone open fire	Mud-stove	Mirt stove				
Cook 1	19.1±0.31	12.3±0.19	10.2±0.13	13.9±0.86	152.5	433.4	0.000**
Cook 2	18±0.33	11.8±0.14	10.7±0.22	13.5±0.73	107.8	259.3	0.000**
Cook 3	18.4±0.47	12.1±0.32	10.4±0.12	13.6±0.80	125.8	159.5	0.000**
Mean	18.5±0.23	12.1±0.13	10.4±0.10				
Mean square within groups	0.800	0.326	0.409				
F-ratio	0.679	0.894	2.222				
(P-value)	0.519	0.427	0.137				

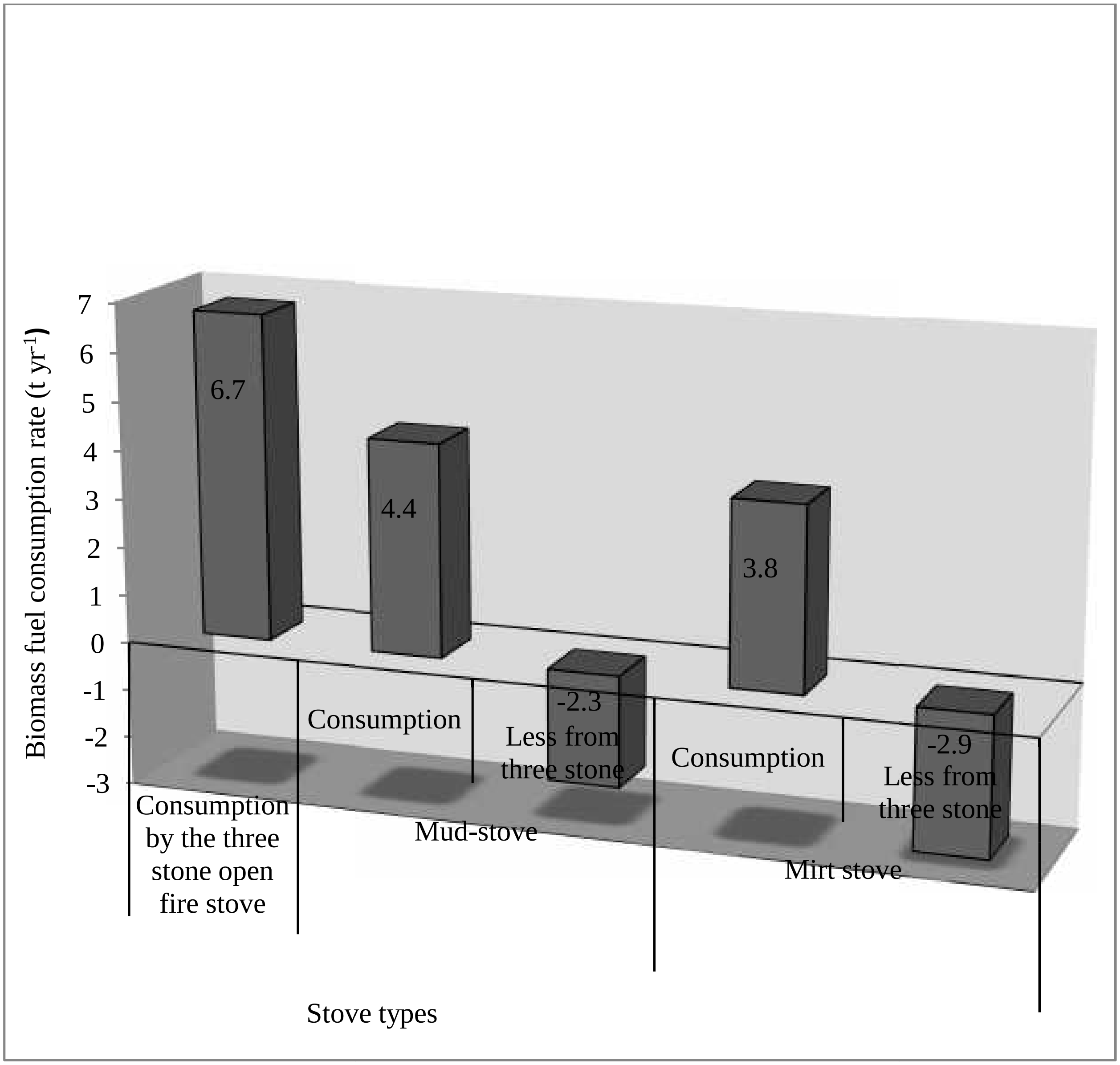

Figure 6.1. Comparative biomass fuel consumption rates by the different stove types

Although the mud-stove was less efficient than the *mirt* stove, and failed to meet the minimum GTZ efficiency requirement of 40% (GTZ, 2007), it significantly increased biomass fuel use efficiency when compared to the traditional three-stone open fire (Figure 6.1). As shown in Figure 6.1, mud-stoves and mirt stoves were found to be 34.7% and 43.5% more efficient than the three-stone open fire respectively with corresponding biomass fuel saving potentials of 2.3 t yr^{-1} and 2.9 t yr^{-1} per stove (Figure 6.1).

Biomass fuel saving efficiencies of mud-stoves compared to the three-stone open fires were higher for CCT than for the KPT results due to stricter control of direct comparison in the case of the former. Moreover, the use of open fire stoves for cooking purposes other than *injera* baking also seemed to account for lower fuel saving efficiency in the case of KPT in the case of mud-stove. On the other hand, the biomass fuel saving efficiency for CCT in the case of mirt stove was found to be slightly lower than that of KPT as the chimney of the *mirt* stove served for preparing sauce, tea and coffee as well as roasting cereals, and boiling water without additional fuel. Thus, the mean biomass fuel saving of mud-stove under CCT was 2.7% higher compared to that of KPT, while fuel saving efficiency of KPT was found 1.3% more than that of CCT.

Studies conducted elsewhere also showed higher biomass fuel saving efficiency of different improved cookstoves under CCT. For instance, for *Gonzie* and *Lakech* stoves, Amogne (2014) measured improved efficiencies of 25% and 47% respectively compared to the three-stone open fire. *Mirt* stoves saved up to 50% of biomass fuel consumption compared to the three-stone open fire stove (GIZ, 2014). Abera (2016) and Elisabeth *et al*. (2014) found 60% and 40% biomass fuel saving efficiency for the *mirt* stove compared to the three-stone open fire system.

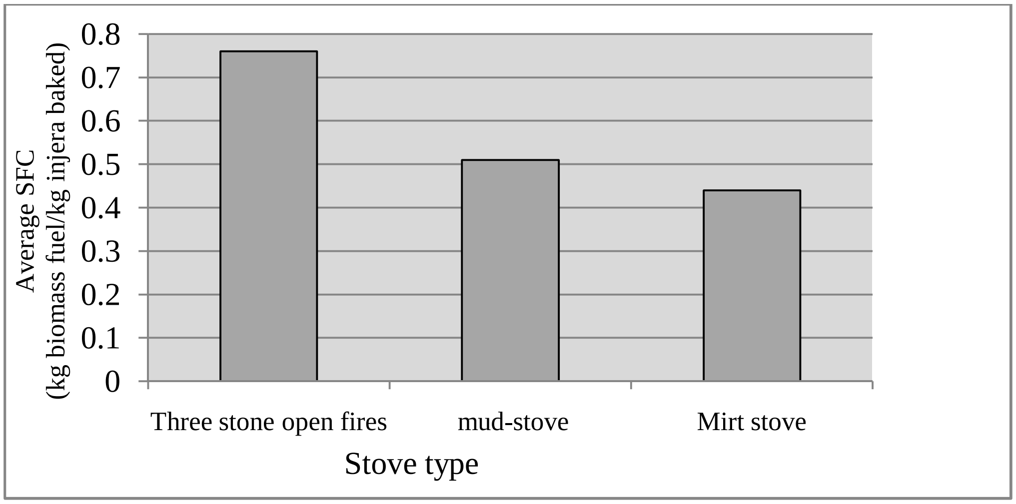

Figure 6.2. Relative average Specific Fuel Consumption (SFC) of the three different stove types

6.6. Triangulation of stove performance results from Kitchen Performance Test with that of Controlled Cooking Test

The result of field based KPT was strongly correlated with that of CCT. These consistencies in fuel efficiency evaluation results provide confidence in the results.

Table 6.6. Pearson correlation coefficients of efficiency evaluation of mud-stoves and *mirt* stove under KPT and CCT.

Pearson correlation (two-tailed)	Mud-stove under KPT	Mud-stove under CCT	Mirt stove under KPT	Mirt stove under CCT
Mud-stove under KPT	1.00	0.935**		
Mud-stove under CCT	0.935**	1.00		
Mirt stove under KPT			1.00	0.887**
Mirt stove under CCT			0.887**	1.00

** correlation is significant at the 0.01 level

The outcomes of fuel efficiency tests from KPT and CCT were strongly correlated (r = 0.935) for the traditional mud-stoves, and (r = 0.887) for the *mirt* stoves.

6.7. End-users' satisfaction survey of alternative stoves

End-users favored many of the different traits of the improved cookstoves compared to a traditional three-stone open fire. Traits of *mirt* and mud-stoves that were particularly appreciated by the end users were fuel saving, reduced frequency needed to tend the fire allowing other household work to be done in parallel with cooking activities, less risk of exposure to burning and cleaner kitchens due to less soot and smoke.

The most commonly favored traits of three-stone open fire were little or no cost incurred to obtain the stoves, easy adjustability for different activities and easy feeding with fuel through the spaces between the stones. The three-stone open fire was reportedly convenient for different cooking purposes as it is easily adjusted to fit cooking utensils of different sizes.

However, the smoky flavor of wot, tea or coffee prepared on a three-stone open fire was disfavored by the observed end users. Households with only an improved stove for *injera* cooking would presumably use three-stone open fire for other cooking purposes.

The main traits disliked about the three-stone open fire were the higher fuel consumption rates relative to both mud-stoves and *mirt* stoves, higher risk of burning and exposure to smoke, and inability of doing other household tasks due to constant tending of the fire.

The longer lifespan of the *mirt* stoves compared to the mud-stove was favored by the end users. Households liked biomass fuel saving provided by both the mud-stoves and *mirt* stoves, while the *mirt* stoves were preferred over the mud-stoves for its durability. Limited biomass fuel supply and consequent higher prices have already prompted many households in Kumbursa to adopt fuel efficient cookstoves.

Chapter 7

Effects of individual and combined applications of organic and inorganic fertilizers on selected soil physical and chemical properties

In this unit, the status of some selected soil physical and chemical properties were evaluated vis-a-vis the requirement for cereal crops production. The effects of the different fertilizer types on the various soil parameters were also discussed by comparing pre-treatment soil data against that of the post-treatment ones. The soil physical properties considered in this study were texture and bulk density while the chemical parameters include total nitrogen, available phosphorus, organic carbon, carbon to nitrogen ratio, exchangeable bases (calcium, magnesium, potassium and sodium), cation exchange capacity, percentage base saturation and soil acidity.

7.1. Pre-treatment status of soil parameters

7.1.1. Pre-treatment soil texture and bulk density

The average sand, silt and clay fractions respectively were 16.3(±0.045)%, 23.6(±0.071)% and 60.0(±0.055)% for Doliyo wheat trial field, 24.3(±0.128%), 24.3(±0.134)%, 51.4±(0.116)% for Kumbursa wheat trial field, and 24.3(±0.154)%, 24.4(±0.134)%, 51.3(±0.093)% for Kumbursa teff trial field (Table 7.1). So in all of the three replicate trial fields at each site and for each crop, soil particle distribution was characterized predominantly by clay with moderate concentrations of sand and silt, and hence fall within textural class range of clay loam to clay soil (Landon, 1991). According to Landon (1991), wheat is best suited to soils of fine texture; and this study confirmed that texture of the soils at both Doliyo and Kumbursa site are suitable for wheat production.

Soil bulk density is used to assess levels of soil compaction and porosity, indicating whether there are problems for root penetration, water infiltration and aeration (Duong, 2013).

The average soil bulk densities were 1.30(±0.004) g cm^{-3}, 1.44(±0.002) g cm^{-3} and 1.45(±0.002) g cm^{-3} for Doliyo wheat trial, Kumbursa wheat trial and Kumbursa teff trial respectively (Table 7.1).

According to Landon (1991), the bulk density of clay and clay loam soils ranges between 1.00 g cm^{-3} and 1.60 g cm^{-3}. So the bulk densities of soils in both of the experimental sites were within the range for the clay and clay loam soils. This would be classified by Landon (1991) as high to very high bulk density. This is likely to be due to low organic inputs due to low application of organic matter and continuous cultivation with grazing on the stubble during the dry season (Dereje and Assefa, 2016).The observed bulk densities are likely to cause reduced root penetration, and the reduced porosity may hinder free movement of air and water in the soil.

7.1.2. Pre-treatment total soil nitrogen, available phosphorus, organic carbon and carbon to nitrogen ratios

The average total N in the Doliyo plots was 0.134(±0.001) % while the average value for both Kumbursa wheat and Kumbursa teff plots was 0.117(±0.002) % (Table 7.1). This would be categorized by Landon (1991) as a very low soil N content. The mean available P was 12.21(±0.003) ppm for Doliyo plots and 3.82(±0.005) ppm for both wheat and teff plots at Kumbursa. Landon (1991) categorizes available P between 6.5 ppm and 13 ppm to be medium while values ranging from 3 ppm to 6.5 ppm are rated as low. So the available P status at Doliyo was medium while that at Kumbursa was low. The mean organic C contents of the wheat plots at Doliyo was 1.44(±0.005) % while the mean values for wheat and teff plots at Kumbursa were 1.33(±0.003) % and 1.32(±0.005) % respectively. Landon (1991) categorizes organic C content as very high (>20%), high (10 - 20%), medium (4 - 10%), low (2 - 4%) and very low (<2%), so the soils at both Doliyo and Kumbursa experimental sites trial fields were very low in organic C. The average C: N ratios were 10.75(±0.048), 11.37(±0.023) and 11.28(±0.060) for the Doliyo plots, Kumbursa wheat plots and Kumbursa teff plots respectively. According to Hazelton & Murphy (2007) the ideal C: N ratio should range between 10 and 25 to avoid excessive release or immobilization of N, so all three experimental fields were within the optimum range.

7.1.3. Pre-treatment exchangeable bases, cation exchange capacity and percentage base saturation

The major exchangeable bases that were measured and evaluated in this study were exchangeable calcium (Ca^{2+}), exchangeable magnesium (Mg^{2+}), exchangeable potassium (K^+) and exchangeable sodium (Na^+). The mean values of Ca^{2+}, Mg^{2+}, K^+ and Na^+ respectively were 12.98(±0.011) millequivalents of charge (meq) per100g, 2.37(±0.004) meq per 100g, 0.29(±0.004) meq per 100g and 0.16(±0.004) meq per 100g for Doliyo wheat trials, while the corresponding average values for both wheat and teff trial plots of Kumbursa site were 12.49 (±0.003) meq per100g, 2.39(±0.004) meq per100g, 0.30(±0.002) meq per100g and 0.17 meq per100g (Table 7.1).

Measurement of cation exchange capacity (CEC) is often undertaken as part of overall evaluation of soil fertility potential and response to fertilizer application (Hartemink, 2006). CEC is defined as the sum of the cations held by clay particles and organic matter present in the soil. The CEC of the soil in all of the three experimental fields at both Doliyo and Kumbursa sites were categorized as high with values of 31.96(±0.007) meq per 100g, 32.00(±0.014) meq per100g and 31.98(±0.009) meq per 100g for Doliyo wheat trial plots, Kumbursa wheat trial plots and Kumbursa teff trial plots respectively (Table 7.1). According to the categorization provided by Landon (1991), CEC values of the soils of both sites of trial fields were high. The observed high soil CEC for both Doliyo and Kumbursa experimental sites may be attributed to the high clay content. The nitisols of Southwestern Highlands of Ethiopia under annual crops were similarly characterized as having high CEC by Dereje & Assefa (2015), with average value of 39.3%.

The percentage base saturation is the share of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) on the cation exchange sites; it indicates the status of soil fertility, without distinguishing between different bases. The mean percentage base saturation was 49.96(±0.047) % for the Doliyo wheat trial field while it was 47.99(±0.018) % for both Kumbursa wheat and teff trial plots. Relative to the standards set by Landon (1991), the percentage base saturation for soils of both Doliyo and Kumbursa trial fields were rated as high.

Eyasu (2017) also reported high percentage base saturation in the area with average values of 51% and 75% for intensive cereal systems and agroforestry systems respectively, and Dereje & Assefa (2015) characterized nitisols under annual crop production in Southwestern Highlands of Ethiopia as having high base saturation with average values of 44.7%.

7.1.4. Pre-treatment soil acidity

Soil pH is important agronomic parameter that affects nutrient availability to crops, lime requirement, and overall soil productivity. The mean pH value for the Doliyo wheat trial was 5.10(±0.005), indicating a highly acidic soil.

In corroboration with this finding, the result of the soil reaction test revealed that the reddish-brown soils of Walmara and Ejere Districts were characterized by strongly acidic pH with values ranging from 4.77 to 5.95 (Getachew, 2017). Eyasu (2017) also reported that the nitisols in the Southwestern Highlands of Ethiopia were highly acidic (5.29) for intensive cereal system to moderately acidic (6.12) for agroforestry systems.

According to Landon (1991), the optimum pH value for wheat production is 6 – 7, and Hagos & Hailemariam (2016) suggest that the optimum pH for cereal crop production is near 6.5. This implies that the soil pH of the trial site is below optimum range for wheat production and hence needs improvement. Amare *et al.* (2006) also recorded highly acidic soil pH in the Central Highlands of Ethiopia with values of as low as 4.1, and Woubshet *et al.* (2017) found that soils of Telecho Kebele in Walmara District were extremely acidic pH with average value of 3.8. Similarly, Getachew (2009) measured soil pH for the top 20 cm layer of soils in Walmara District, ranging from 4.30 to 5.12. The strongly acidic nature of the soil may be ascribed to both natural and anthropogenic factors. The natural factors constitute the acidic nature of the soil parent material coupled with high amount of rainfall, while continuous cultivation with little application of organic matter as well as frequent application of acidifying chemical fertilizers (mainly DAP and urea) are the main human induced factors.

The observed low pH at Doliyo experimental field of Walmara district suggests that availability of nutrients, such as phosphorus, to plants may be impaired due to fixation.

In strongly acidic soils, aluminum, hydrogen and manganese toxicities are expected, which also results in the deficiency of basic nutrients. For instance, Ca^{2+} uptake is inhibited at soil pH values of less than 5.5. At pH values lower than 5.5, only low amount of P can exist in available form due to reactions with Fe, Al and their hydrous oxides (Hagos & Hailemariam, 2016). As also reported by Getachew *et al.* (2014), soils with pH less than 5.5 are usually deficient in Ca^{2+}, Mg^{2+} and available P. This very low soil pH also results in reduced bacterial activity and consequent retardation of nitrification. So the observed low pH is likely to have reduced crop production. In order to raise the soil pH and overcome its negative effects on agricultural productivity, appropriate interventions, such as application of lime and compost are strongly recommended.

Unlike the case of Doliyo site trial field, soils of Kumbursa trial fields were slightly acidic/near neutral with the mean pH value of 6.89(±0.007). The soil pH at Kumbursa site was at the optimum level for both wheat and teff production. Similarly, Mesfin *et al.* (2012) reported soil pH values ranging between 7.07 and 7.32 in Bishoftu area.

Table 7.1. Pre-treatment physical and chemical soil properties

Sn	Soil texture (%)			BD (g/cm^3)	TN (%)	AP (ppm)	C:N	OC (%)	Exchangeable bases (meq/100g)				CEC (meq/100g)	PBS (%)	pH (H_2O)
	Sand	Silt	Clay						Ca^{2+}	Mg^{2+}	K^+	Na^+			
Dow1	16.3	23.9	59.8	1.31	0.134	12.20	10.67	1.43	12.96	2.36	0.29	0.15	31.96	49.31	5.09
Dow2	16.2	23.8	60.0	1.30	0.134	12.22	10.60	1.42	13.02	2.38	0.28	0.16	31.94	49.59	5.11
Dow3	16.2	23.7	60.1	1.29	0.133	12.21	10.83	1.44	13.00	2.37	0.28	0.17	31.98	49.47	5.10
Dow4	16.4	23.5	60.1	1.30	0.134	12.21	10.82	1.45	12.98	2.38	0.30	0.16	31.95	49.51	5.12
Dow5	16.4	23.6	60.0	1.31	0.133	12.21	10.83	1.44	12.97	2.37	0.29	0.17	31.97	49.42	5.10
Mean	**16.3**	**23.7**	**60.0**	**1.30**	**0.134**	**12.21**	**10.75**	**1.44**	**12.98**	**2.37**	**0.29**	**0.16**	**31.96**	**49.96**	**5.10**
S.E	**±0.045**	**±0.071**	**±0.055**	**±0.004**	**±0.001**	**±0.003**	**±0.048**	**±0.005**	**±0.011**	**±0.004**	**±0.004**	**±0.004**	**±0.007**	**±0.047**	**±0.005**
Kuw1	24.3	24.3	51.4	1.44	0.118	3.82	11.27	1.33	12.50	2.39	0.30	0.17	31.98	48.03	6.89
Kuw2	24.3	24.0	51.7	1.45	0.117	3.81	11.28	1.32	12.49	2.39	0.29	0.16	31.95	47.98	6.90
Kuw3	23.9	24.6	51.5	1.44	0.118	3.82	11.36	1.34	12.49	2.38	0.31	0.16	32.01	47.92	6.91
Kuw4	24.4	24.6	51.0	1.44	0.117	3.80	11.37	1.33	12.48	2.40	0.31	0.17	32.00	48.00	6.87
Kuw5	24.7	24.0	51.3	1.45	0.117	3.83	11.37	1.33	12.49	2.38	0.29	0.17	31.94	48.00	6.88
Mean	**24.3**	**24.3**	**51.4**	**1.44**	**0.117**	**3.82**	**11.37**	**1.33**	**12.49**	**2.39**	**0.30**	**0.17**	**32.00**	**47.99**	**6.89**
S.E	**±0.128**	**±0.134**	**±0.116**	**±0.002**	**±0.002**	**±0.005**	**±0.023**	**±0.003**	**±0.003**	**±0.004**	**±0.004**	**±0.003**	**±0.014**	**±0.018**	**±0.007**
Kut1	24.4	24.0	51.6	1.45	0.117	3.81	11.45	1.34	12.49	2.38	0.31	0.17	31.96	48.03	6.88
Kut2	23.8	24.7	51.5	1.45	0.118	3.83	11.19	1.32	12.50	2.39	0.30	0.17	32.00	48.00	6.90
Kut3	24.6	24.7	51.7	1.44	0.116	3.81	11.47	1.33	12.50	2.38	0.29	0.16	31.97	47.95	6.87
Kut4	24.0	24.3	51.7	1.44	0.117	3.82	11.20	1.31	12.48	2.39	0.30	0.17	32.01	47.92	6.91
Kut5	24.5	24.3	51.2	1.45	0.116	3.82	11.38	1.32	12.49	2.39	0.31	0.17	31.98	48.03	6.89
Mean	**24.3**	**24.4**	**51.3**	**1.45**	**0.117**	**3.82**	**11.28**	**1.32**	**12.49**	**2.39**	**0.30**	**0.17**	**31.98**	**47.99**	**6.89**
S.E	**±0.154**	**±0.134**	**±0.093**	**±0.002**	**±0.001**	**±0.004**	**±0.060**	**±0.005**	**±0.004**	**±0.002**	**±0.004**	**±0.002**	**±0.009**	**±0.022**	**±0.007**

Note: Sn (Sample number), Dow (Doliyo wheat trial plots), Kuw (Kumbursa wheat trial plots), Kut (Kumbursa teff trial plots), TN (Total nitrogen), AP (Available Phosphorus), C:N (Carbon to Nitrogen ratio), BD (Bulk Density), Ca^{2+} *(Exchangeable Calcium),* Mg^{2+} *(Exchangeable Magnesium),* K^+ *(Exchangeable Potassium),* Na^+ *(Exchangeable Sodium), CEC (Cation Exchangeable Capacity), BS (Base Saturation), pH (Soil pH)*

7.2. Post-treatment characterization of soil physical and chemical properties

7.2.1. Post-treatment soil bulk density

The result of post-treatment revealed that the average soil bulk density at the Doliyo site was significantly ($p < 0.05$) reduced from 1.30 g cm^{-3} for the pretreatment test and the control to 1.29 g cm^{-3} for the plots treated with only bioslurry, bioslurry + inorganic fertilizer, and bioslurry compost + inorganic fertilizer. A significant reduction ($p < 0.01$) in bulk density from the pre-treatment and the control to 1.28 g cm^{-3} was observed in the plots receiving only bioslurry compost (Table 7.2). Lower bulk densities in the cases of plots treated with bioslurry and bioslurry compost both individually as well as in combination with inorganic fertilizer indicates the contribution of organic fertilizers to enhancement of soil physical quality that will be reflected in improved soil structure, porosity and drainage capacity.

In the Kumbursa wheat plots, bulk density remained unchanged for plots treated with only bioslurry, bioslurry + inorganic fertilizer, and bioslurry compost + inorganic fertilizer (1.44g cm^{-3}), while a significant reduction ($P<0.05$) to 1.43 g cm^{-3} was recorded for plots that received bioslurry compost alone. An increase in bulk density from 1.44 g cm^{-3} to 1.45g cm^{-3} was observed for plots amended with inorganic fertilizer only, and for the control.

For the teff trial field of Kumbursa site, there was an increase in bulk density from 1.44g cm^{-3} to 1.45g cm^{-3} in the plots that received only inorganic fertilizer, whereas a decrease to 1.43g cm^{-3} was observed for plots amended with bioslurry compost. No significant change in bulk density was observed in the other treatments on either the wheat or teff plots at Kumbursa (Tables 7.2 & 7.3).

In line with the finding of this study, reduced application of organic fertilizer and frequent use of chemical fertilizer resulted in soil compaction and higher bulk density (Massah & Azadegan, 2016). As reported by Malik *et al.* (2014), soil bulk densities were reduced leading to improved structure in trial plots supplemented with organic manure compared to the control and plots treated with inorganic fertilizer alone. Soil bulk densities were also reduced after applying cattle manure in combination with inorganic NP fertilizer to potato fields in Masha District of Southwestern Ethiopian Highlands (Zewde *et al.*, 2018).

In the case of Kumbursa site, the effects of different fertilizer types on soil bulk density were found to be similar for the wheat and teff trial plots (Table 7.3). The bulk density of the nitisols at the Doliyo site was found to be more responsive to organic fertilizer applications than the vertisols of Kumbursa site. In order to achieve significant improvement in soil bulk density and hence improve soil qualities like aeration, drainage and tilth, organic fertilizers should be applied at higher rate for sufficiently long period of time.

7.2.2. Post-treatment total soil nitrogen, available phosphorus, organic carbon and carbon to nitrogen ratios

The total soil N in the Doliyo wheat plots remained unchanged (0.133%) for plots treated with inorganic fertilizer compared to the pre-treatment test and the control, while an increase to 0.135% was observed for plots amended with bioslurry and bioslurry + inorganic fertilizer, and a significant increase to 0.136% was seen in plots treated with bioslurry compost and bioslurry compost + inorganic fertilizer.

In the case of Kumbursa wheat plots, a significant increase in total soil N from 0.117% to 0.119% was observed for plots amended with bioslurry compost, while the change was not significant for the remaining treatments. In the teff plots, the change in total soil N was insignificant for all treatments.

In accordance with some treatments that received bioslurry and bioslurry compost individually and in integration with inorganic fertilizer in this study, total N increased as a result of applying organic fertilizer with or without inorganic fertilizer to potato fields (Aguilera *et al.*, 2012). Poultry manure application at the rate of 10 t ha^{-1} also significantly improved soil NO_3-N (Ogundijo *et al.*, 2014). The study conducted by Gumus & Seker (2017) also revealed that the soil TN content of degraded soil significantly improved as a result of applying spent mushroom compost. Higher soil total N was also observed in plots treated with compost compared to that of the control (Haute, 2014). As also reported by Ullah *et al.* (2008), soil total N increased due to application of mustard cakes and poultry manures. A trial experiment undertaken by Dejene *et al.* (2010) also revealed that combined application of inorganic and organic fertilizer to teff plots increased soil organic C and TN.

Significant improvement in soil TN was observed as a result of applying cow dung compared to the control as well as plots treated with sole inorganic fertilizer (Tanimu *et al.*, 2013).

The different fertilizer treatments tended to increase the stock of available soil P in all the three trial fields. However the observed increases were found to be significant only in the cases of plots amended with inorganic fertilizer ($p < 0.05$) and bioslurry compost with inorganic fertilizer ($p < 0.01$). For the Kumbursa wheat field, an increase in available soil P was only significant for the plots treated with bioslurry with inorganic fertilizer ($p < 0.05$) and bioslurry compost with inorganic fertilizer ($p < 0.01$). For the Kumbursa teff trial, it was only in the case of plots treated with bioslurry compost with inorganic fertilizer that an increase in available P was significant ($p < 0.05$). In agreement with this finding, the study conducted by Titilola (2006) revealed that plots treated with inorganic fertilizer at the rate of 400 kg ha^{-1} NPK 15-15-15 and inorganic + organic fertilizer at the rates of 200 kg ha^{-1} NPK 15-15-15 and 2.5 t ha^{-1} organic fertilizer to the Cassava field in Kenya resulted in an increase in available P by 8% and 9% respectively, while a reduction from 4.72 mg kg^{-1} to 3.37 mg kg^{-1} was seen in the case of unfertilized plots. The results from the trial experiments in the northwestern Highlands of Ethiopia also demonstrated that wheat and teff plots were characterized by improved available P after being amended with compost at the equivalent rate of recommended N and P as well as 50% of compost equivalence plus 50% N and P from inorganic fertilizer (Hagos & Abraha, 2016). A trial experiment undertaken by Dejene *et al* (2010) also revealed that combined application of inorganic and organic fertilizer to teff plots increased soil organic C and available P. Cow dung significantly improved available soil P compared to the control as well as plots treated with inorganic fertilizer alone (Tanimu *et al.*, 2013).

The highest available P content was recorded for the plots treated with chemical fertilizer at the rate of 96 kg ha^{-1} N and 69 kg ha^{-1} P, followed by plots treated with bioslurry compost + chemical fertilizers as well as bioslurry + chemical fertilizers, both at the rates of 96 kg ha^{-1} N and 69 kg ha^{-1} P. The post treatment available P measurement also exhibited that though the values were found slightly lower than that of the plots treated with chemical fertilizers and their combined applications with bioslurry compost and bioslurry, there was generally an improvement when compared to the baseline values of the pretreatment plots and the control.

In the wheat plots of the Doliyo site, there was no significant change in soil organic C increase for any of the treatments relative to that of the control and pretreatment test result (1.44%), except in the plots amended with bioslurry compost and bioslurry compost + inorganic fertilizer (Table 7.2). For the Kumbursa site, a significant change in organic C was only observed in the wheat plots treated with bioslurry compost and bioslurry compost + inorganic fertilizer (Table 7.2), and with bioslurry compost + inorganic fertilizer in the teff plots (Table 7.3).

Many other researchers have found similar responses in soil organic C to application of organic fertilizer, both alone and in combination with inorganic fertilizer. In agreement with findings of this study, soil organic C content was improved as a result of applying organic fertilizer with and without inorganic fertilizer (Aguilera *et al.*, 2012). Poultry manure application at the rate of 10 t ha^{-1} to maize fields significantly increased soil organic C, and the percentage increases over the control and plots treated with 120 kg NPK fertilizer respectively were 55.05 and 36.29 (Ogundijo *et al.*, 2014). As also reported by Gumus & Seker (2017), soil organic C increased with elevated rates of compost application. Increased soil organic C pool was observed for plots treated with compost (Haute, 2014). Application of mustard cakes and poultry manures increased soil organic C (Ullah *et al.*, 2008). An on-farm trial experiment on barely plots in Southwest Highlands of Ethiopia also revealed that soil organic C increased by 36% and 44.6% respectively due to application of 5 t ha^{-1} farmyard manure and vermicompost in combination with 75% recommended rates of inorganic N and P (Tamado & Mitiku, 2017). The stock of soil organic matter increased in the case of trial plots treated with the combination of compost and inorganic fertilizer compared to the plots that received sole inorganic fertilizer (Workneh, 2015). Addition of 7.5 t ha^{-1} organic fertilizer in combination with 75% of the recommended rate from inorganic N and P fertilizer to potato fields in Southwestern Highlands of Ethiopia significantly improved soil organic C stock when compared to the control (Zewde *et al.*, 2018). Application of spent mushroom compost significantly increased soil organic C (Gumus & Seker, 2017). Soil organic C significantly increased due to application of cattle manure (Dunjana, 2011). Addition of manure and compost alone as well as in combination with inorganic NP fertilizer to wheat and teff fields significantly improved soil organic C content (Getachew, *et al.*, 2014).

The application of 5 t ha^{-1}farmyard manure in combination with 75% recommended rates of inorganic N and P (17.25 kg ha^{-1} N and 34.5 kg ha^{-1} P_2O_5) was found to be superior and increased soil organic C content by 36% and 44.6%. Cow dung significantly improved soil organic carbon compared to the control as well as plots treated with sole inorganic fertilizer (Tanimu *et al.*, 2013).

Organic C contents of plots treated with sole bioslurry compost and sole bioslurry were higher than that of both the control and plots treated with chemical fertilizers only. The highest organic C content was observed in the trial plots treated with bioslurry compost followed by trial plots treated with bioslurry while the lowest organic C was recorded for the control and trial plots treated with inorganic fertilizer. Brar *et al.* (2015) observed that long term application of organic and inorganic fertilizers significantly increased the pool of soil organic C and improved different soil physical properties. The result of post treatment soil analysis undertaken by Mubo (2015) also demonstrated that plots treated with cow dung were characterized by significantly higher organic C content compared to the control and plots treated with sole application inorganic fertilizer.

The C: N ratio is an indicator of N turnover in soil and N availability to the plant and microorganisms. The C: N ratio for the Doliyo Site wheat trials were not significantly different in plots treated with inorganic fertilizer (10.83) or with bioslurry and inorganic fertilizer (10.82). However, significant C: N ratio decreases ($P < 0.05$) were observed for plots that received bioslurry, bioslurry compost and bioslurry compost + inorganic fertilizer. For the Kumbursa wheat trial field, changes in C: N ratios were insignificant in all plots, except those treated with bioslurry. In the case of the teff field, the change in C: N ratio was insignificant for all plots.

7.2.3. Post-treatment exchangeable bases, cation exchange capacity, percentage base saturation and soil reaction

For all the three trial fields, both Ca^{2+} and Mg^{2+} were significantly improved ($p < 0.05$) for the plots treated with bioslurry compost and bioslurry compost with inorganic fertilizer. For the Doliyo wheat field, the average K^{+} for the control and pre-treatment test was 0.297 meq per 100 g soil and the post treatment results revealed that there was improvement for all of the treatments which ranged from 0.298 meq per 100g soil for the plots amended with inorganic fertilizer to 0.311 meq per 100g soil in the case of the bioslurry compost with inorganic fertilizer treatments.

Similarly, Moyin-Jesu *et al* (2010) found that pig and poultry manures significantly increased the soil Ca^{2+} and Mg^{2+}content compared to that of the control.

As shown in Table 7.2, K^+ increased significantly compared to the control for plots amended with bioslurry, bioslurry compost and bioslurry compost combined with inorganic fertilizer. For the Kumbursa wheat field, a significant increase was observed for plots treated with bioslurry compost and bioslurry compost combined with inorganic fertilizer. For Kumbursa teff field, bioslurry, bioslurry compost, bioslurry with inorganic fertilizer and bioslurry compost with inorganic fertilizer treatments all resulted in a significant increase in soil K^+ (Table 7.3). Moyin-Jesu *et al* (2010) also observed that pig and poultry manures significantly improved soil K^+ as compared to that of the control, and cow dung significantly improved soil K^+ compared to the control and plots treated with only inorganic fertilizer Tanimu *et al.* (2013).

As shown in Tables 7.2 & 7.3, for all the three fields, there were no significant differences in the post-treatment soil Na^+ compared to both the control and the result of the pre-treatment average values.

In all of the three trial fields, the average CEC values were significantly ($p < 0.05$) higher than that of the control and pre-treatment values for the plots treated with bioslurry compost and bioslurry compost with inorganic fertilizer, while the differences were found to be insignificant for the remaining treatments (Tables 7.2 & 7.3). Sole application of both bioslurry compost and bioslurry as well as in combination with inorganic fertilizer led to significant increases ($P<0.05$) in CEC, and so can have more contributions to soil fertility amendment. This implies that application of organic fertilizer individually as well as in combination with inorganic fertilizer can contribute to more efficient nutrient availability to the crops. Basri *et al* (2013) also revealed that mixed use of inorganic and organic fertilizers in kenaf production resulted in increased soil CEC. Application of organic fertilizer to cassava, maize, melons and cowpeas increased soil CEC by 16% compared to that of the pre-treatment values (Titilola, 2006).

The percentage base saturation for the wheat plots at Doliyo increased from 47.92% for the control and plots treated with inorganic fertilizer to 48.02% in the case of plots amended with bioslurry compost, and this increase was found to be significantly different ($p < 0.05$).

For the Kumbursa wheat trial, an increase from pre-treatment values of 47.96% for the control to 48.03% after the trial was observed (Table 7.2), while an increase from 48.04% in the control plots to 48.12% for plots treated with bioslurry compost for Kumbursa Site teff trial field was observed (Table 4.3). The average percentage base saturations were significantly ($p < 0.05$) different from the control for plots amended with bioslurry compost and bioslurry compost + inorganic fertilizer for both wheat and teff fields.

7.2.4. Post-treatment soil acidity

The post-treatment soil pH measurement for all the three fields showed that only plots treated with bioslurry compost had a significantly higher pH compared to the control. There was a tendency for pH to fall in teff trial field of Kumbursa site while it remained unchanged for wheat fields of Doliyo and Kumbursa sites (Tables 7.2 & 7.3). Generally, it was observed that use of bioslurry compost increased soil pH compared to the use of inorganic NP fertilizers alone as well as compared to the control.

In corroboration with the result of this study, the soil pH was reduced by 0.3 to 0.7 units in plots treated with compost as compared with that of the control (Duong, 2013). Soil pH significantly increased as a result of compost application to maize plots (Haute, 2014). Soil pH significantly increased as a result of applying goat and poultry manure to coconut trees (Moyin-Jesu & Ogochukwu, 2014). Soil pH increased in plots treated with cattle manure in combination with NP inorganic fertilizer while it was reduced in the cases of plots treated with inorganic NP fertilizer alone (Zewde *et al.*, 2018). Sole application of organic fertilizer as well as application in combination with inorganic fertilizer significantly increased soil pH compared to the control plot and plots treated with sole inorganic fertilizer (Aguilera *et al.*, 2012). Application of poultry manure to maize field at the rate of 10 t ha^{-1} increased soil pH (Ogundijo *et al.*, 2014). An inorganic fertilizer application rate of 240 kg ha^{-1} N decreased the average values of soil pH compared to the control plot (Simansky *et al.*, 2017).

Table 7.2. Table 7.3. 1Average values of the post-treatment soil physical and chemical properties

Soil Parameters	On-farm wheat trials of Doliyo Site						On-farm wheat trials of Kumbursa Site					
	BS	BSC	IF	BS+IF	BSC+IF	Cntrl	BS	BSC	IF	BS+IF	BSC +IF	Cnrl
BD (gm/cm^3)	1.29*	1.28**	1.30	1.29*	1.29*	1.30	1.44	1.43*	1.45	1.44	1.44	1.45
TN (%)	0.135	0.136**	0.133	0.135	0.136*	0.133	0.118	0.119*	0.117	0.117	0.117	0.117
Av.P (ppm)	12.23	12.26	12.27*	12.26	12.28**	12.21	3.82	3.82	3.82	3.83*	3.85**	3.81
OC (%)	1.47	1.49*	1.45	1.46	1.48*	1.44	1.33	1.35*	1.32	1.33	1.34*	1.32
C:N	10.89*	10.95*	10.83	10.82	10.88*	10.83	11.28*	11.31	11.33	11.33	11.35	11.37
Ca^{2+} (meq/100g)	12.50	12.51*	12.49	12.50	12.52*	12.49	12.50	12.51*	12.48	12.49	12.50*	12.49
Mg^{2+}(meq/100g)	2.38	2.39*	2.37	2.38	2.39*	2.37	2.38	2.38	2.38	2.39*	2.39*	2.38
K$^+$ (meq/100g)	0.308*	0.311*	0.298	0.306	0.307*	0.297	0.312*	0.318*	0.303	0.306	0.314*	0.305
Na$^+$ (meq/100g)	0.167	0.168	0.162	0.164	0.166	0.162	0.168	0.168	0.166	0.168	0.170	0.163
CEC (meq/100g)	32.01*	32.03**	25.49	32.00	32.01*	31.97	32.01*	32.03**	32.00	32.00	32.01*	31.98
BS (%)	47.99	48.02*	47.92	47.98	47.98	47.92	48.01	48.03*	47.97	48.00	48.02*	47.96
pH	5.12	5.13*	5.11	5.12	5.12	5.11	6.90	6.91*	6.87	6.90	6.90	6.88

Note: TN (Total nitrogen), Av.P (Available Phosphorus), C:N (Carbon to Nitrogen ratio), BD (Bulk Density), Ca^{2+} *(Exchangeable Calcium), Mg*$^{2+}$ *(Exchangeable Magnesium), K*$^+$ *(Exchangeable Potassium), Na*$^+$ *(Exchangeable Sodium), CEC (Cation Exchangeable Capacity), BS (Base Saturation), pH (Soil pH), BS (Bioslurry), BSC (Bioslurry Compost), IF (Inorganic Fertilizer), Cntrl (Control)*

*Average values followed by * and ** are significantly different at P<0.05 and P<0.01 respectively*

Table 7.3. Average values of the post-treatment soil physical and chemical properties

Soil Parameters	On-farm teff trials of Kumbursa Site					
	BS	BSC	IF	BS+IF	BSC+IF	Control
BD (gm/cm^3)	1.44	1.43*	1.45	1.44	1.44	1.44
TN (%)	0.118	0.118	0.117	0.117	0.117	0.117
AP (ppm)	3.82	3.83	3.82	3.82	3.84*	3.81
OC (%)	1.33	1.33	1.32	1.33	1.34*	1.32
C:N	11.29*	11.28*	11.35	11.34	11.35	11.37
Ca^{2+} (meq/100g)	12.51	12.53*	12.50	12.51	12.52*	12.50
Mg^{2+} (meq/100g)	2.39	2.40*	2.39	2.39	2.40*	2.39
K^+ (meq/100g)	0.321*	0.324*	0.310	0.324*	0.326*	0.313
Na^+ (meq/100g)	0.168	0.170	0.168	0.168	0.170	0.170
CEC(meq/100g)	32.02	32.03*	32.01	32.02	32.03*	32.02
BS (%)	48.08	48.12*	47.99	48.06	48.09*	48.04
PH	7.00	7.02*	6.99	7.00	7.01	6.99

*Note: TN (Total nitrogen), Av.P (Available Phosphorus), C:N (Carbon to Nitrogen ratio), BD (Bulk Density), Ca^{2+} (Exchangeable Calcium), Mg^{2+} (Exchangeable Magnesium), K^+ (Exchangeable Potassium), Na^+ (Exchangeable Sodium), CEC (Cation Exchangeable Capacity), BS (Base Saturation), pH (Soil pH), BS (Bioslurry), BSC (Bioslurry Compost), IF (Inorganic Fertilizer), Cntrl (Control); average values followed by * and ** are significantly different at $P<0.05$ and $P<0.01$ respectively*

7.3. Effects of different types and rates of fertilizer on soil nitrogen and phosphorus balances

As shown in figures 7.1, 7.2 and 7.3, increasing the application rates of NP from the five fertilizer types resulted in corresponding increasing uptake for all of the three trial fields. Nitrogen balances were found to be negative for the plots treated with 32 kg ha^{-1} N and 23 kg ha^{-1} P, and with 64 kg N ha^{-1} and 46 kg P ha^{-1} , while positive balances were observed for P for all fertilizer types and rates of the three trial fields. For the Doliyo wheat field, N balances were found to be positive for application of N at the rate of 96 kg ha^{-1} except in the case of plots amended with bioslurry compost combined with inorganic fertilizer for which the balance was -2 kg ha^{-1}.

As also demonstrated in figures 7.1, 7.2 and 7.3, higher N mining and more negative N balances were observed in plots treated with 50% of the recommended rates of N (32 kg ha^{-1}) compared to plots treated with 100% of the recommended rates (64 kg ha^{-1}).

For the Doliyo wheat field, the N balance ranged from -41.2 kg ha^{-1} for plots amended with 50% of the recommended rate from inorganic N and plots treated with bioslurry compost combined with inorganic fertilizer to -32.1kg ha^{-1} for half of the recommended rate of inorganic fertilizer only (Figure 7.1).

The N balances for 100% of the recommended rate of N (64 kg ha^{-1}) varied from -17 kg N ha^{-1} for bioslurry combined with inorganic fertilizer to -10.6 kg N ha^{-1} for bioslurry compost with inorganic fertilizer (Figure 7.1). For the Kumbursa wheat field, for 50% of the recommended N rate, the N balance lay between -35.3kg ha^{-1} for bioslurry compost combined with inorganic fertilizer plots and -24.8 kg ha^{-1} for sole application of inorganic fertilizer. The average balances for 100% of the recommended rate varied from -9.2kg ha^{-1} for treatment with bioslurry compost combined with inorganic fertilizer to -2.1kg ha^{-1} for sole bioslurry compost. In the case of the Kumbursa teff field, the N balances for 50% of the recommended rate varied from -39.3kg ha^{-1} for bioslurry compost combined with inorganic fertilizer to -25.9kg ha^{-1} for sole bioslurry; the average N balances for 100% of the recommended rate were within the range of -33.2kg ha^{-1} for bioslurry compost in combination with inorganic fertilizer to -8.3kg $ha^{-1}$for bioslurry alone. Therefore, the N balances were found to be more negative for 50% of the recommended rates than 100% of the recommended rates in all of the treatments. From the N balances of the different rates and types of fertilizer, it can be learned that an increased rate of N fertilizer application leads to improvement of soil N balance while also resulting in higher uptake by the crops and yielding better crop productivity.

For the soil P balances, positive values were observed for all of the fertilizer types and rates with increasing soil P stock with corresponding increase of P application rate. The P balances ranged from 2.7 kg ha^{-1} for the plots amended with 50% of the recommended rate (23kg P ha^{-1}) from bioslurry compost combined with inorganic fertilizer to 48.8 kg ha^{-1} for the plots treated with 150% of the recommended rate (69 kg ha^{-1}) from bioslurry alone. It was observed that despite the increased stock of soil P, there existed a deficiency in available P, and this is likely to be due to P fixation. The soils of all the three trial fields were characterized by the predominance of clay particles which probably resulted in P fixation and consequent deficiency of this nutrient in available form to the crops.

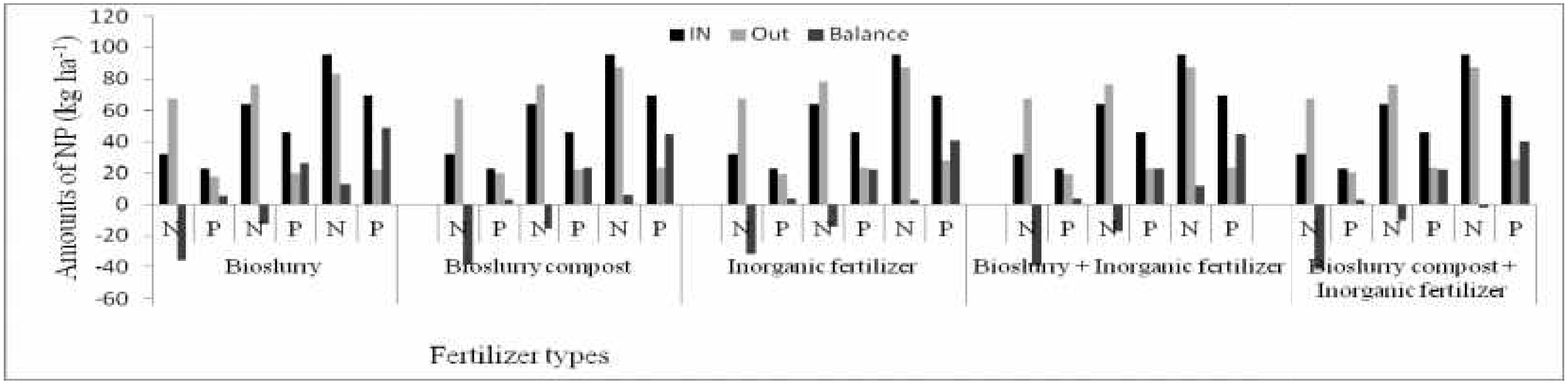

Figure 7.1. Nitrogen and phosphorus balances for plots treated with 50%, 100% & 150% of the recommended NP rates respectively as applied from the different fertilizer types for Doliyo Site wheat field.

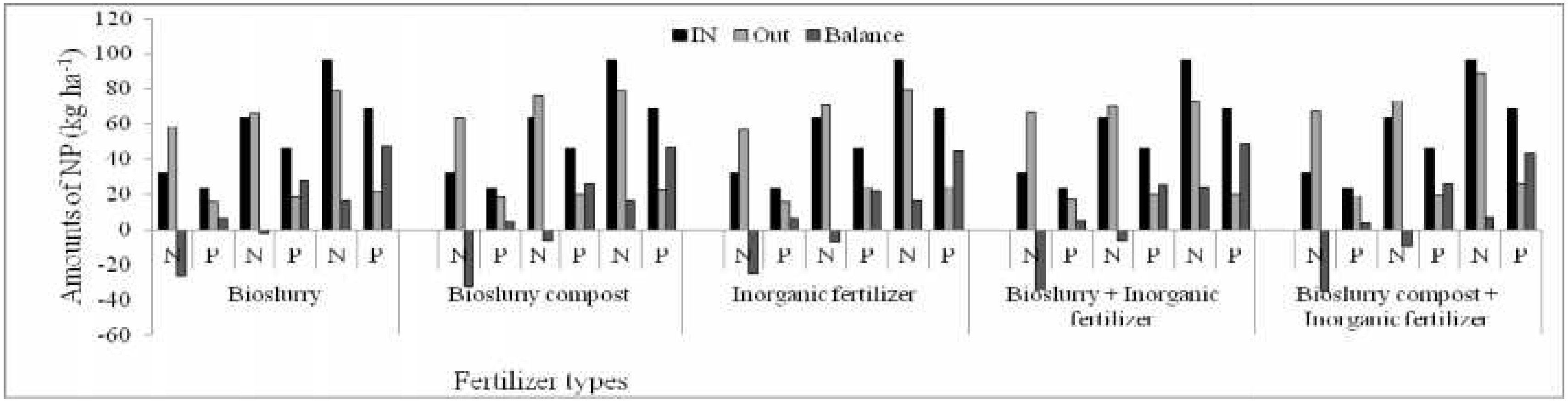

Figure 7.2. Nitrogen and phosphorus balances for plots treated with 50%, 100% & 150% of the recommended NP rates respectively as applied from the different types for Kumbursa Site wheat field

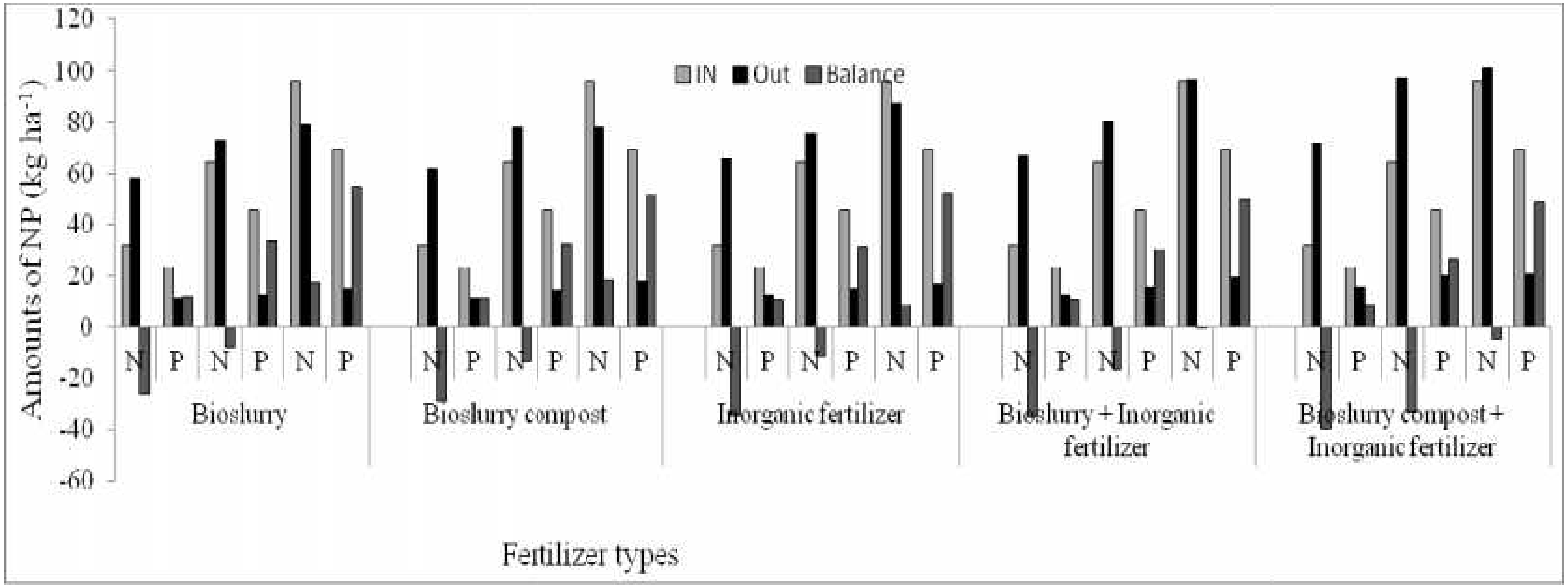

Figure 7.3. Nitrogen and phosphorus balances for plots treated with 50%, 100% & 150% of the recommended NP rates respectively as applied from the different types for Kumbursa Site teff fields.

Chapter 8

Comparative evaluation of the agronomic responses, nutrient use efficiencies and apparent nutrient recoveries of wheat and teff under individual and combined applications of organic and inorganic fertilizers

This unit is devoted to presentation of the results and discussion of the agronomic responses for the different rates and types of fertilizer applied to wheat and teff. The study is aimed at determining appropriate rates of organic (bioslurry and bioslurry compost) and inorganic (DAP and Urea) fertilizers individually as well as in combination for optimum wheat and teff production. This study also tries to compare and contrast the agronomic responses, nutrient use efficiencies and apparent nutrient recoveries of wheat and teff under application of different fertilizer types.

8.1. Total above ground biomass

Regardless of the type of fertilizer applied, total above ground biomass for both wheat and teff trials increased with increasing N and P rates (Figures 8.1 (a), (b) & (c)). However, variations were observed in response to rates among the trial plots treated with the different fertilizer types. For both wheat and teff trials, the highest average values at any given rate of N and P were achieved in plots treated with bioslurry compost + inorganic fertilizer, while the lowest (but significantly higher than that of the control plots) were obtained from plots treated with bioslurry alone (Figures 8.1 (a), (b) & (c)).

For the Doliyo wheat trial, the highest total above ground biomass (12459 (±81) kg ha^{-1}) was obtained from plots that received 150% of the recommended rate (96 kg N and 69 kg P) ha^{-1}, from combined bioslurry compost and inorganic fertilizer, while the lowest (i.e. 5350 (±28) kg ha^{-1}) was recorded for the control (Figure 8.1 (a)).

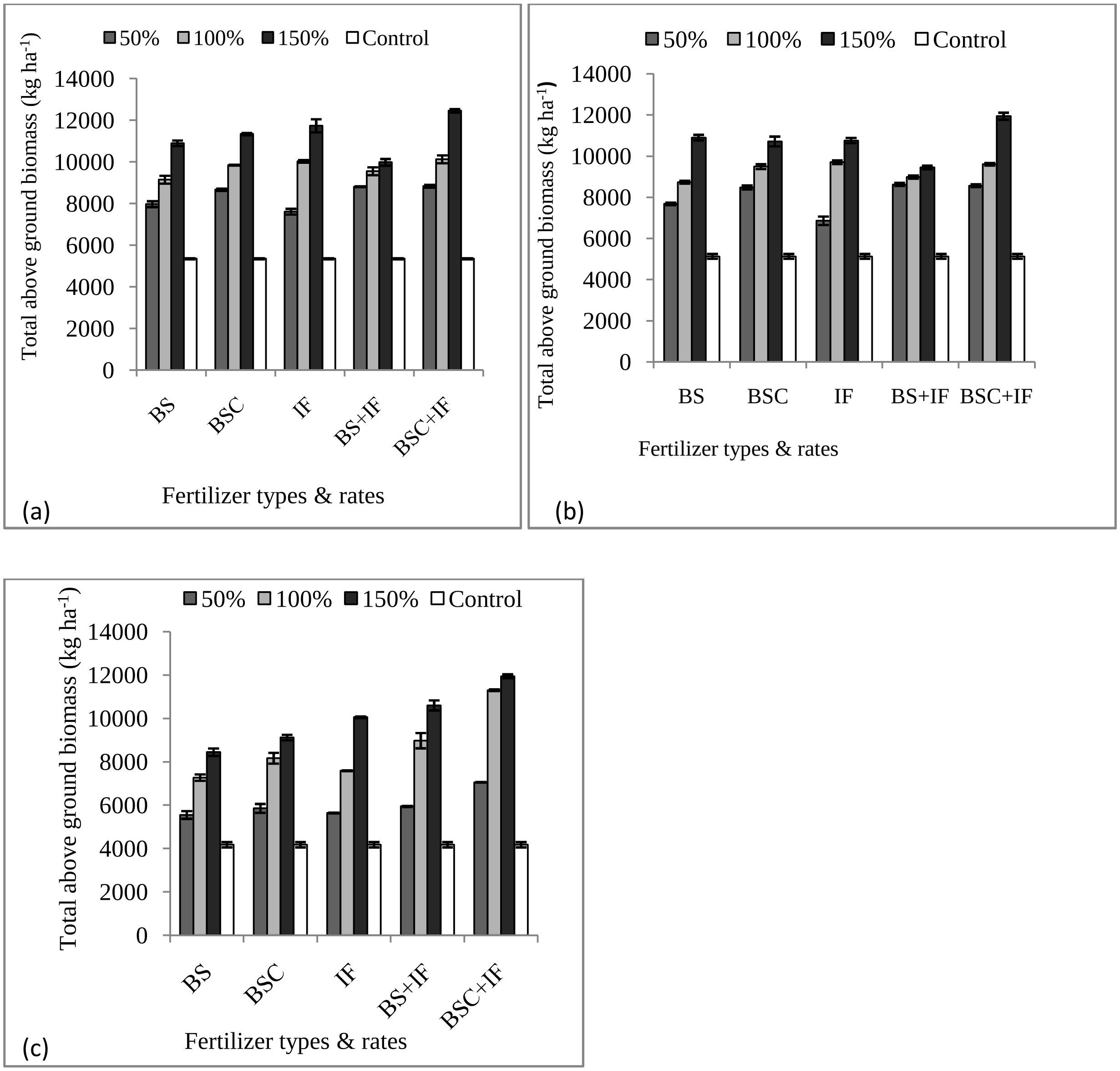

Figure 8.1. Average total above ground biomass of wheat at Doliyo (a), wheat at Kumbursa (b) & teff at Kumbursa (c) trial plots for varying rates of nitrogen and phosphorus applied from different types of fertilizer in the 2014 and 2015 cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = Combination of bioslurry and inorganic fertilizer; BSC+IF = Combination of bioslurry compost and inorganic fertilizer

Similarly, the average total above ground biomass for the wheat trials in Kumbursa also increased with increasing application of N and P (Figure 8.1 (b)).

For a given rate of N and P, the highest average total above ground biomass (11941 (±171) kg ha^{-1}) was again obtained from plots treated with 150% of the recommended rate from bioslurry compost combined with inorganic fertilizer, and 150% inorganic fertilizer while the lowest average value (5131 ±117 kg ha^{-1}) was harvested from the control. The next lowest (6860 (±204) kg ha^{-1}) was obtained from plots treated with 50% of the blanket recommendation rate (32 kg N and 23 kg P) ha^{-1} from inorganic fertilizer alone.

The teff trials also showed an increase in total above ground biomass with increased rates of N and P application for all the five treatments (Figure 8.1 (c)). Again, at any given rate of N and P application, the highest average total above ground biomass (11946 (±87) kg ha^{-1}) was obtained from trial plots treated with 150% of the recommended rate of N and P in a combined application of bioslurry compost and inorganic fertilizer, while the lowest but still by far higher than that of the control (5552 (±178) kg ha^{-1}), was obtained from the trial plots treated with bioslurry alone at the rate of half the recommendation rate (32kg N & 23kg P) ha^{-1}.

The strong response in total above ground biomass to increased application of N and P implied that both 50% of the recommended rate (32 kg N and 23 kg P) ha^{-1} and 100% of the recommended rate (64 kg N and 46 kg P) ha^{-1} were too low to achieve the highest yield; raising the rates to 150% of the recommended rate (96 kg N and 69 kg P) ha^{-1} showed increased yields for all the five different fertilizer types. In corroboration with this finding, biomass yield of wheat in increased from 10492 kg ha^{-1} for the plots treated with 23 kg ha^{-1} to 11364 kg ha^{-1} for the plots receiving 69 kg ha^{-1} (Woyema *et al.*, 2012). Increased teff biomass yields in response to increased application of slow release urea were reported by Okubay *et al.* (2014). Linear increase in all agronomic parameters with increased rates of N & P applications were observed in the Central Highlands of Ethiopia (Birhan, *et al.*, 2017). A trial experiment conducted on food barely (Hordeum Vulgare L.) on nitosols at Hulla District , Southern Ethiopia revealed that the total above ground biomass increased, and with 1263 kg ha^{-1} in response to applying 200 kg ha^{-1} NPSB blended fertilizer; an increase by 22.4% over the recommended rate and 70.4% over the control (Melkamu et al., 2019).

8.2. Grain yield

The response in grain yield was similar to the total above ground biomass; average wheat and teff grain yields increased with increasing rates of N and P application for all of the five fertilizer treatments (Figure 8.2 (a), (b) & (c)). For the Doliyo wheat trial, the highest average wheat grain yield (5130 (±38) kg ha^{-1}) was recorded for plots treated with 150% of the recommended rate as bioslurry compost + inorganic fertilizer, while the lowest (1769 (±54) kg ha^{-1}) was harvested from control plots (Figure 8.2 (a)).

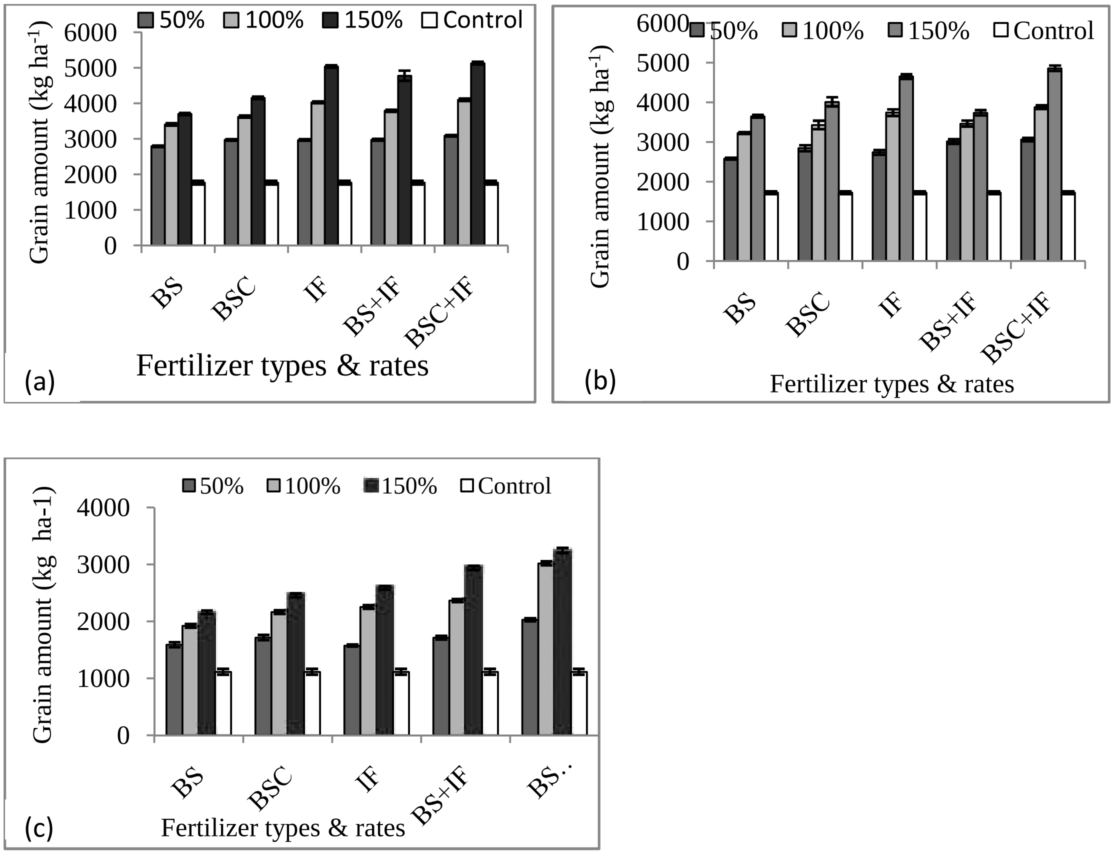

Figure 8.2. Average grain yield amounts of Doliyo wheat (a), Kumbursa wheat (b) and Kumbursa teff (c) trial plots for varying rates of nitrogen & phosphorus applied from different types of fertilizer during 2014 & 2015 main cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = combination of bioslurry and inorganic fertilizer; BSC+IF = combination of bioslurry compost and inorganic fertilizer

As shown in Figure 8.2 (b), in the Kumbursa wheat trial, the highest grain yield (4858 (±69) kg ha^{-1}) was also obtained from plots that received the highest rates of N and P from bioslurry compost with inorganic fertilizer, while the lowest (1724 (±34) kg ha^{-1}) was harvested from control plots.

The general trend of higher grain yield in response to higher N and P applications was also observed on teff trials, with the highest value (3242 (±45) kg ha^{-1}) for plots treated with 150% of the recommended rate of bioslurry compost and inorganic fertilizer, while the lowest (1113 (±51) kg ha^{-1}) was obtained from the control plots (Figure 8.2 (c)).

The total above ground biomass and grain yield responses were different for the different fertilizer types. The lowest average total above ground biomass (9243 kg ha^{-1}) was observed in the case of plots treated with bioslurry alone, while the highest average value (10477 kg ha^{-1}) was obtained from plots treated bioslurry compost and inorganic fertilizer; but the variations among the different fertilizer types ($P<0.097$) were insignificant (Table 8.1).

As shown in Table 8.1, though the variations among the five treatments were observed to be insignificant the average total above ground biomass ranged from 9105 kg ha^{-1} (the lowest) for the plots amended with bioslurry alone to 10037 kg ha^{-1} (the highest) for the plots treated with bioslurry compost combined with inorganic fertilizer. Unlike the responses for wheat trials of both the Doliyo and Kumbursa Sites, the total above ground biomass for teff trials of Kumbursa site varied significantly ($P<0.000$) among the five fertilizer types with the average values ranging from 7090 kg ha^{-1} for plots treated with sole bioslurry to 10102 kg ha^{-1} for the plots that received bioslurry compost in combination with inorganic fertilizer.

Similarly to total above ground biomass, bioslurry alone resulted in the lowest average grain yields while the highest values were obtained from those plots treated with bioslurry compost combined with inorganic fertilizer for both the wheat and teff trials (Table 8.1). The average grain yields for the Doliyo wheat field ranged from 3299 kg ha^{-1} to 4106 kg ha^{-1} while that of Kumbursa wheat trial plots varied from 3150 kg ha^{-1} to 3933 kg ha^{-1}; these variations for both trial fields were significant ($P<0.01$). For the teff, the highest and the lowest average grain yields respectively were 2761 kg ha^{-1} and 1889 kg ha^{-1} and the variations were significant ($P<0.000$).

Table 8.1. Summary of the analysis of variations in total above ground biomass and grain yields among the plots treated with different fertilizer types

Field Site and crop type	Agronomic parameter (kg ha^{-1})	Fertilizer type					P value
		BS	BSC	IF	BS+IF	BSC+IF	
Doliyo wheat field	Total above ground biomass	9342	9953	9795	9450	10477	0.097
	Grain yield	3299	3582	4010	3715	4106	0.004*
Kumbursa wheat field	Total above ground biomass	9105	9561	9109	9019	10037	0.100
	Grain yield	3150	3429	3708	3403	3933	0.003*
Kumbursa teff field	Total above ground biomass	7090	7714	7764	8507	10102	0.000**
	Grain yield	1889	2109	2138	2338	2761	0.000**

*Note: BS (Bioslurry), BSC (Bioslurry Compost), IF (Inorganic Fertilizer), * (variations are significant at $P<0.01$); ** (variations are significant at $P<0.001$)*

Higher N & P rates from all of the five fertilizer types resulted in corresponding higher wheat and teff grain yields. Boldea *et al.* (2015) also observed that maize yields increased linearly with increasing applications of nitrogen fertilizer. The result from maize trials experiment conducted by Workneh (2015) also showed that yields from plots treated with compost and inorganic fertilizer resulted in higher grain yields, increasing by 78% and 26% compared to that of the control and plots treated with inorganic fertilizer alone respectively. Whereas the result of this study suggested that the recommended rate of N and P fertilizer application is below optimum level for both wheat and teff. Abay *et al.* (2011) recommended lower rate of application (30 kg ha^{-1} and 20 kg ha^{-1} P) for optimum production of teff in Hossana and Areka respectively. This demonstrates that fertilizer application rates should be locally tailored for the different localities instead of just relying on one blanket recommendation for the whole of Ethiopia. Other examples where combined use of organic and inorganic fertilizer has been shown to improve crop yield are given by Mitiku *et al*. (2014) for barley in Southwestern Ethiopia.

Similar to the finding of this study, a trial experiment conducted on wheat in Ude kebele revealed that grain yield increased from 3341 kg ha^{-1} to 3996 kg ha^{-1} due to corresponding increase in nitrogen application rate from 23 kg ha^{-1} to 69 kg ha^{-1}. Application of 175-150-125 (NPK) resulted in increase of wheat yield by 51.8% over the control (Malghani *et al.*, 2010).

A study conducted on maize in Pakistan also revealed general increase in grain yield with increasing NP application; but further increase beyond the optimal level resulted in yield decline. In the Central Highlands of Ethiopia (Arsi Districts), results from trial experiment demonstrated that wheat grain yields increased by 83, 156, 233 and 288% over the control on vertisols while increases by 45, 62, 98 and 150% were observed on the nitosols as a resut of applying 20.5, 41, 82 and 164 kg N ha^{-1} respectively (Birhan *et al.*, 2017). Wheat yield increased from 1498 kg ha^{-1} for the control to 4219, 4781 and 5012 kg ha^{-1} as a result of applying 120, 240, and 360 kg N ha^{-1} respectively. Application of 200 kg ha^{-1} in Central Ethiopian Highlands resulted in wheat grain yield of 4900 kg ha^{-1}; an increase over the recommended rate and the control respectively by 22.4% and 70.4%.

8.3. Use efficiencies and apparent recoveries of nitrogen and phosphorus in wheat and teff

For all the five fertilizer types, a general trend of decreasing nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) with increased N and P application rates was observed (Figures 8.3 (a), (b) & (c)). The highest average values of NUE were recorded for the plots treated with 50% of the blanket recommendation rate (32 kg ha^{-1} N & 23 kg ha^{-1} P), while the lowest values were obtained from the plots receiving 150% of the recommended rate (96 kg ha^{-1} N & 69 kg ha^{-1} P).

8.3.1. Doliyo wheat trials

The NUE varied from 19.1(±0.4) kg wheat grain per kg N, obtained from plots treated with 150% of the recommended rate of N and P as bioslurry alone, to 36.7(±1.2) kg grain per kg N from the plots treated with 50% of the recommended rate as combined bioslurry compost and inorganic fertilizer (Figure 8.3 (a)).

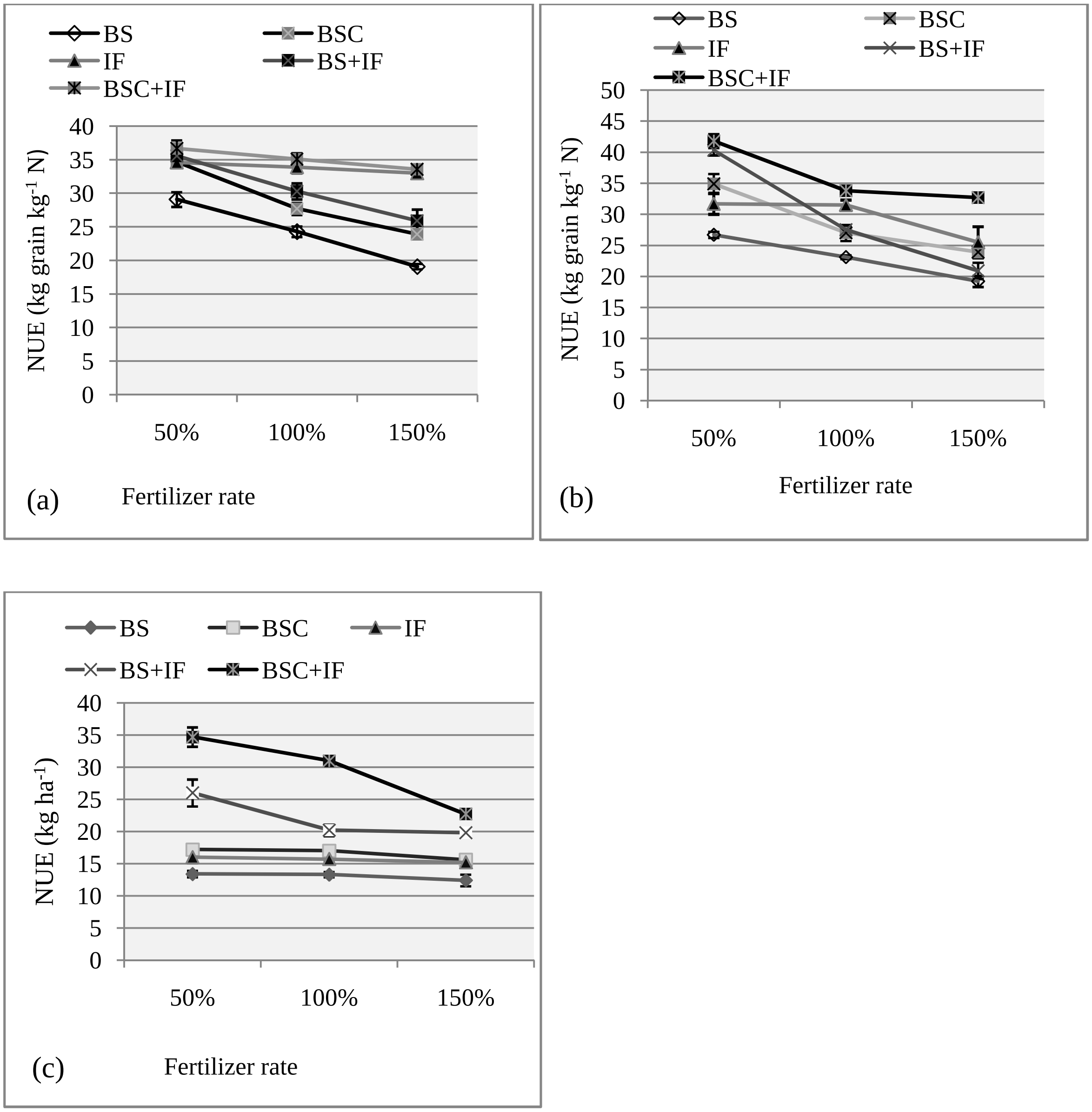

Figure 8.3. Average nitrogen use efficiencies as applied from different fertilizer types at varying rates for wheat at Doliyo site (a), wheat at Kumbursa site (b) & teff at Kumbursa site (c) On-farm trials for 2014 & 2015 main cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = combination of bioslurry and inorganic fertilizer; BSC+IF = combination of bioslurry compost and inorganic fertilizer

Similarly, the lowest PUE (26.7(±1.3) kg grain per kg P) was obtained in plots treated with 150% of the recommended rate as bioslurry alone, while the highest PUE (53.7 (±1.3) kg grain per kg P) was obtained from plots that received 50% of the recommended rate as combined bioslurry compost and inorganic fertilizer (Figures 8.4 (a), (b) & (c).

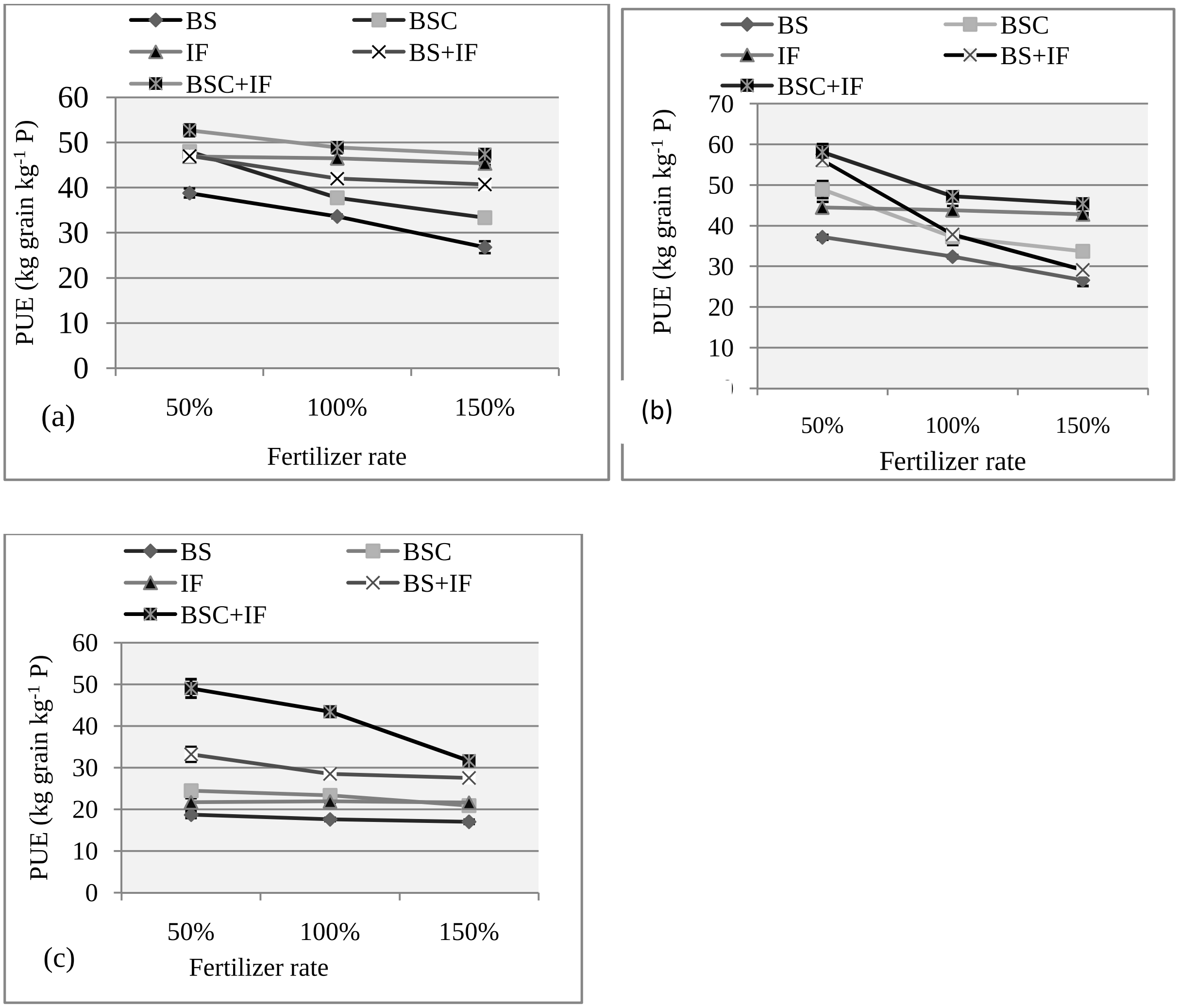

Figure 8.4. Average phosphorus use efficiencies as applied from different fertilizer types at varying rates for wheat at Doliyo Site (a), wheat at Kumbursa site (b) & teff at Kumbursa Site (c) On-farm trials for 2014 & 2015 main cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = combination of bioslurry and inorganic fertilizer; BSC+IF = combination of bioslurry compost and inorganic fertilizer

8.3.2. Kumbursa wheat trials

Again, the average NUE and PUE decreased with increasing rates of N and P application for all five types of fertilizer (Figures 8.3 (b) & 8.4 (b)). Both NUE and PUE increased in the order of plots treated with bioslurry, bioslurry compost, inorganic fertilizer, combined bioslurry and inorganic fertilizer, and combined bioslurry compost and inorganic fertilizer (Figures 8.3 & 8.4).

8.3.3. Kumbursa teff trials

As shown in Figures (8.3 (c) & 8.4 (c)), both NUE and PUE were inversely related with N and P application rates for all fertilizer types. The average NUE varied from 11.8 (±0.9) kg grain per kg N to 34.7 (±1.5) kg grain per kg N (Figure 8.3 (c), while PUE ranged from 17.0 (±0.5) kg grain per kg P to 49.0 (±2.2) kg grain per kg P (Figure 8.4 (c); with the highest and the lowest average values respectively obtained from plots treated with 50% of the recommended rate of combined bioslurry compost and inorganic fertilizer and bioslurry alone at the rate of 150% of the recommended rate.

8.4. A linear regression model to determine the effect of fertilizer type on total above ground biomass and nutrient use efficiencies

As shown in Table 8.2, the highest total above ground biomass responses to added nutrients in wheat for both the Doliyo and Kumbursa sites was obtained from plots treated with only inorganic fertilizer, while the lowest was in the combined bioslurry and inorganic fertilizer plots. The response in total above ground biomass to N ranged from 18 kg kg^{-1} N at Doliyo and 12.5 kg kg^{-1} N at Kumbursa for plots treated with combined bioslurry and inorganic fertilizer to 64.4 kg kg^{-1} N at Doliyo and 59.3 kg kg^{-1} N at Kumbursa for plots only treated with inorganic fertilizer. Similarly, the response in total above ground biomass to P ranged from 25.5 kg kg^{-1} P at Doliyo and 17.9 kg kg^{-1} P at Kumbursa for plots treated with bioslurry and inorganic fertilizer to 89.6 kg kg^{-1} P at Doliyo and 84.8 kg kg^{-1} P at Kumbursa for plots only treated with inorganic fertilizer. This indicates that more benefit is seen in crop growth by increasing the rate of inorganic fertilizer application compared to the other treatments.

It also reflects the higher above ground biomass (and yields) achieved with low applications of bioslurry or bioslurry compost combined with inorganic fertilizer than with inorganic fertilizer alone; this implies that better choice of fertilizers for resource poor farmers is a combined application of organic and inorganic fertilizer.

Similarly, the highest response in grain yield was observed for the inorganic fertilizer application, while the lowest response was to the application of bioslurry alone (Table 8.2). The response in grain yield to N ranged from 14.2 kg kg^{-1} N at Doliyo and 10.4 kg kg^{-1} N at Kumbursa for plots treated with bioslurry to 32.4 kg kg^{-1} N at Doliyo and 29.7 kg kg^{-1} N at Kumbursa for plots treated with inorganic fertilizer. The response to P ranged from 19.7 kg kg^{-1} N for the Doliyo plot treated with bioslurry and 15.7 kg kg^{-1} N for the Kumbursa plots treated with bioslurry and inorganic fertilizer to 45.0 kg kg^{-1} N at Doliyo and 41.6 kg kg^{-1} N at Kumbursa for plots only treated with inorganic fertilizer. This reflects the higher availability of nutrients in the inorganic fertilizer than in the organic fertilizers.

By contrast, for the teff trial at Kumbursa, the highest (76.4 kg kg^{-1} N and 106.3 kg kg^{-1} P) was observed in the combined bioslurry compost and inorganic fertilizer amendment, with the lowest total above ground biomass response to nutrients (45.2 kg kg^{-1} N and 62.9 kg kg^{-1} P) being obtained in the plot amended with bioslurry alone (Table 8.3). This reflects the lower yields observed in the teff bioslurry only plots, indicating the need for additional plant-available nutrients and again suggesting the need for a combined application of organic and inorganic fertilizer.

Table 8.2. Linear regression model equations and correlation coefficients indicating the effects of N & P on the total above ground biomass of wheat for Doliyo and Kumbursa Site On-farm trials

Nutrient & its source	Doliyo site wheat trial field		Kumbursa site trial field	
	Agronomic parameter & model equation	R^2	Agronomic parameter & model equation	R^2
N (BS)	$Y_{TAGBM} = 6417+45.7x_N$	0.906	$Y_{TAGBM} = 7483+26.8x_N$	0.262
P (BS)	$Y_{TAGBM} = 6417+63.6x_P$	0.906	$Y_{TAGBM} = 5885.7+70.0x_P$	0.944
N (BSC)	$Y_{TAGBM} = 7285+41.7x_N$	0.986	$Y_{TAGBM} = 7277+34.7x_N$	0.760
P (BSC)	$Y_{TAGBM} = 7285+58.0x_P$	0.986	$Y_{TAGBM} = 7322+46.7x_P$	0.853
N (IF)	$Y_{TAGBM} = 5671+64.4x_N$	0.920	$Y_{TAGBM} = 5211+59.3x_N$	0.759
P (IF)	$Y_{TAGBM} = 5671+89.6x_P$	0.920	$Y_{TAGBM} = 5206+84.8x_P$	0.891
N (BS + IF)	$Y_{TAGBM} = 8277+18.0x_N$	0.660	$Y_{TAGBM} = 8200+12.5x_N$	0.648
P (BS +IF)	$Y_{TAGBM} = 8277+25.5x_P$	0.660	$Y_{TAGBM} = 8198+17.9x_P$	0.765
N (BSC +IF)	$Y_{TAGBM} = 6858+56.5x_N$	0.940	$Y_{TAGBM} = 6537+53.2x_N$	0.847
P (BSC +IF)	$Y_{TAGBM} = 7290+67.1x_P$	0.885	$Y_{TAGBM} = 6657+73.5x_P$	0.920

Note: N (nitrogen), BS (bioslurry), BSC (bioslurry compost), IF (inorganic fertilizer, Y_{TAGBM} (total above ground biomass– kg ha^{-1}), X_N (unit increase in the amount of nitrogen– kg ha^{-1}), X_P (unit increase in the amount of phosphorus – kg ha^{-1})

Table 8.3. Linear regression model equations and correlation coefficients indicating the effects of N & P on the grain yields of wheat for Doliyo and Kumbursa Site On-farm trials

Nutrient & its source	Doliyo site wheat trial field		Kumbursa site trial field	
	Agronomic parameter & model equation	R^2	Agronomic parameter & model equation	R^2
N (BS)	$Y_{NUE}= 2392 + 14.2x_N$	0.927	$Y_{NUE} = 2519 +10.4x_N$	0.392
P (BS)	$Y_{PUE}= 2392 +19.7x_N$	0.927	$Y_{PUE}= 2078 + 23.3x_P$	0.966
N (BSC)	$Y_{NUE} = 2401+ 18.4x_N$	0.977	$Y_{NUE}=2262 +17.7x_N$	0.685
P (BSC)	$Y_{PUE} = 2401 + 25.1x_P$	0.977	$Y_{PUE} = 2260+ 25.4x_P$	0.807
N (IF)	$Y_{NUE} = 1939+ 32.4x_N$	0.994	$Y_{NUE} = 1756 +29.7x_N$	0.859
P (INFR)	$Y_{PUE} = 1939+ 45x_P$	0.994	$Y_{PUE} = 1797 + 41.6x_P$	0.961
N (BS + IF)	$Y_{NUE}= 2314 + 22.0x_N$	0.885	$Y_{NUE}= 2700 +10.7x_N$	0.619
P (BS +IF)	$Y_{PUE} = 2314 + 30.4x_P$	0.885	$Y_{PUE}= 2682+ 15.7x_P$	0.769
N (BSC +IF)	$Y_{NUE}= 2063 + 32.0x_N$	0.992	$Y_{NUE} = 2102 +27.8x_N$	0.863
P (BSC +IF)	$Y_{PUE} = 2320 + 37.6x_P$	0.923	$Y_{PUE}= 2136+ 39.1x_P$	0.970

Note: N (nitrogen), BS (bioslurry), BSC (bioslurry compost), IF (inorganic fertilizer, Y_{GRAIN} (grain yield amount – kg ha^{-1}), X_N (unit increase in the amount of nitrogen – kg ha^{-1}), X_P (unit increase in the amount of phosphorus – kg ha^{-1})

Table 8.4. Linear regression equations and correlation coefficients indicating the effects of N & P on the total above ground biomass and nutrient use efficiencies of teff for Kumbursa Site

Nutrient & its source	Doliyo Site wheat trial field		Kumbursa Site wheat trial field	
	Agronomic parameter & model equation	R^2	Agronomic parameter & model equation	R^2
N (BS)	$Y_{TAGBM} = 4196+45.2x_N$	0.893	$Y_{NUE}= 1317 +8.9x_N$	0.876
P (BS)	$Y_{TAGBM} = 4196+62.9x_P$	0.893	$Y_{PUE}= 1317 + 12.4x_P$	0.876
N (BSC)	$Y_{TAGBM} = 4444+51.1x_N$	0.846	$Y_{NUE}=1366 +11.6x_N$	0.905
P (BSC)	$Y_{TAGBM} = 4444+71.1x_P$	0.846	$Y_{PUE} = 1366+ 16.2x_P$	0.905
N (IF)	$Y_{TAGBM} = 3354+68.9x_N$	0.994	$Y_{NUE}= 1127 +15.8x_N$	0.939
P (INFR)	$Y_{TAGBM} = 3354+95.9x_P$	0.994	$Y_{PUE}= 1127 + 22.0x_P$	0.939
N (BS + IF)	$Y_{TAGBM} = 3851+72.8x_N$	0.893	$Y_{NUE}= 1115 +19.0x_N$	0.976
P (BS +IF)	$Y_{TAGBM} = 4432+85.8x_P$	0.833	$Y_{PUE}= 1295+ 22.0x_P$	0.862
N (BSC +IF)	$Y_{TAGBM} = 5212+76.4x_N$	0.834	$Y_{NUE}= 1546 +19.1x_N$	0.854
P (BSC +IF)	$Y_{TAGBM} = 5212+106.3x_P$	0.834	$Y_{PUE}= 1546+ 106.3x_P$	0.854

Note: N (nitrogen), BS (bioslurry), BSC (bioslurry compost), IF (inorganic fertilizer, Y_{TAGBM} (total above ground biomass – kg ha^{-1}), Y_{GRAIN} (grain yield amount – kg ha^{-1}), X_N (unit increase in the amount of nitrogen – kg ha^{-1}), X_P (unit increase in the amount of phosphorus – kg ha^{-1})

8.5. Apparent nitrogen and phosphorus recovery of wheat & teff

As shown in Figures 8.5 (a), (b), & (c), for both wheat and teff inverse relationships were observed between the amount of N and P applied, and the apparent recovery of N and P. The highest recovery efficiencies for both N and P were obtained from the trial plots treated with 50% of the recommended rate (the lowest rate) of N and P for all fertilizer types, while the lowest values were recorded for plots treated with 150% of the recommended rates (the highest rates). For all of the wheat and teff trials, the highest percentage of apparent N and P recovery was obtained from plots treated with bioslurry compost and inorganic fertilizer while the lowest values were observed in the case of plots that received only bioslurry (Figures 8.6 (a), (b) & (c).

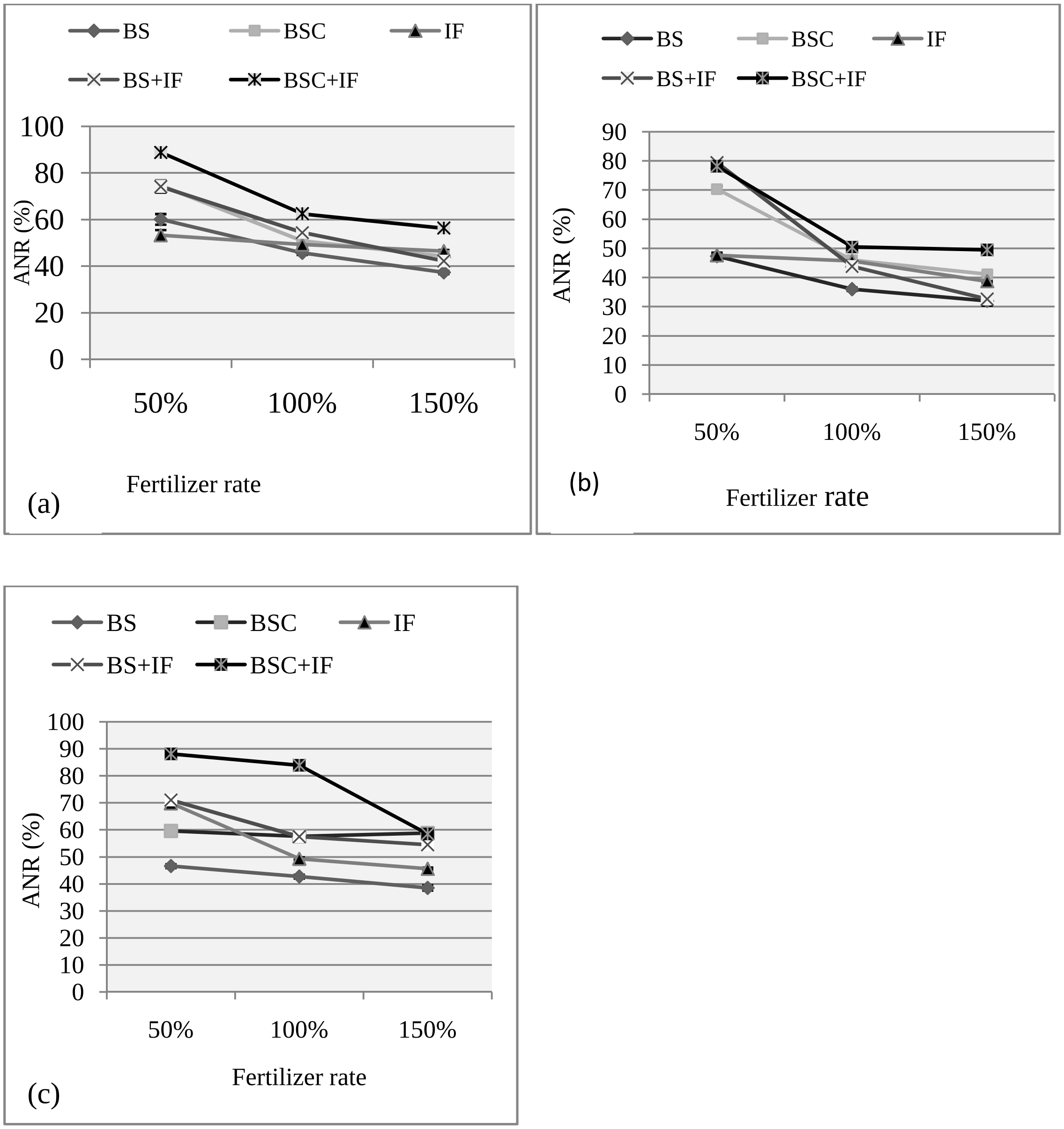

Figure 8.5. Average nitrogen recovery (ANR) of wheat as a result of applying varying rates of N & P from the different fertilizer types for Doliyo trials in 2014 and 2015 cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = combination of bioslurry and inorganic fertilizer; BSC+IF = combination of bioslurry compost and inorganic fertilizer

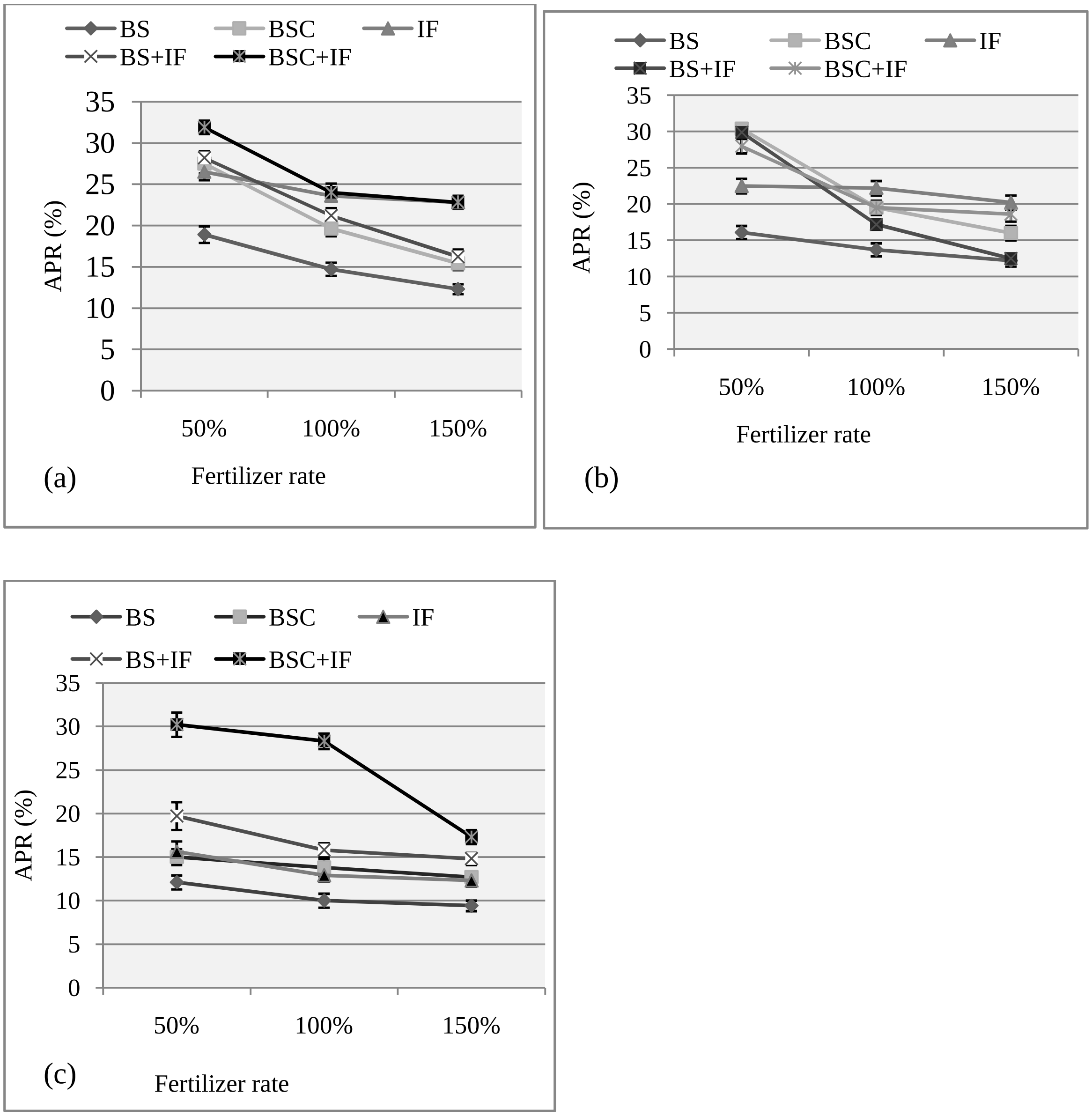

Figure 8.6. Average apparent phosphorus recoveries (APR) of wheat as a result of applying varying rates of N & P from the different fertilizer types for Doliyo trials in 2014 and 2015 cropping seasons

Where: BS = Bioslurry; BSC = Bioslurry compost; IF = Inorganic fertilizer; BS+IF = combination of bioslurry and inorganic fertilizer; BSC+IF = combination of bioslurry compost and inorganic fertilizer

Chapter 9

Household Energy-Soil Nutrients Recycling-Crop Production Nexus in the Central Highlands of Ethiopia: a synthesis

The findings of the study imply that household energy is strongly intertwined with soil fertility amendment, GHGs emissions and household finances in Kumbursa Village, Central Highlands of Ethiopia. This study revealed that large scale shift to agricultural wastes for fuel has greatly reduced the recycling of nutrients to the soil and hence seriously threatened sustainability of crop production. As a result, the agricultural sector, which has a large potential role in economic growth, food security and poverty alleviation, has remained stagnant due to inherent low soil fertility and low level of soil amendment. The soaring price of inorganic fertilizers, which is increasing beyond the purchasing power of the poor smallholder farmer, has been frequently mentioned as a factor prohibiting application of adequate amounts of inorganic fertilizer. In such a situation of low access to inorganic fertilizers, the poor smallholder farmers of the Ethiopian Highlands should at least partly use the organic resources at their disposal to increase soil fertility and improve crop production. However, due to acute firewood shortage, there has been an immense shift to farm generated resources such as crop residues, animal wastes and farmyard manure, for fuel instead of recycling them to the soil.

The use of inefficient traditional open fires for cooking by the majority of farm households (90%) has further exacerbated the problem of agricultural waste removal from the faming system for fuel.

9.1. Loss of carbon and nutrients through burning organic wastes

The results from the survey of household energy use under the business-as-usual scenario revealed that all farm households in Kumbursa village were almost entirely dependent on biomass fuel with a dramatic shift towards using agricultural wastes as fuels (mainly dung cakes and crop residues); indicating households are moving down the energy ladder. In Kumbursa village, crop residues and dung cakes accounted for 80(±3) % by energy content and 85(±4) % by dry mass weight of total biomass fuel consumption.

Such large scale reliance on agricultural wastes for fuel in Kumbursa Village has virtually removed the longstanding tradition of utilizing these organic resources to increase soil fertility. The mean nutrient losses were 109(±8) kg yr^{-1}per household for nitrogen(N) (59(±2) kg $ha^{-1}yr^{-1}$); 26(±2) kg yr^{-1} per household for phosphorus (P) (13.9(±0.3) kg $ha^{-1}yr^{-1}$); 150(±11) kg yr^{-1}per household for potassium (79(±2) kg $ha^{-1}yr^{-1}$); and 3000(±300) kg yr^{-1} per household for organic carbon (C) (2100(±40) kg $ha^{-1}yr^{-1}$).

Due to lack of communal lands for biomass fuel collection, farm households in Kumbursa were almost totally dependent on their own land holdings for fuel, with production and consumption rates directly related to their resource endowment. So rich farmers lost significantly more carbon and nutrients in fuel than farmers in other wealth groups. However, these losses were spread over a larger area, so losses per land area were significantly higher for medium and poor than for rich farmers. This means that the land of poorer farmers is likely to become degraded more rapidly due to fuel limitations than that of rich farmers, so increasing the poverty gap. The estimated financial loss per household due to not using dung and crop residues as organic fertilizer was 162(±8) US$ yr^{-1}. However, this is less than their value as fuels, which was 490(±20) US$ yr^{-1}. Therefore, farmers will only be persuaded to use these valuable assets as soil improvers if an alternative, cheaper fuel source can be found.

9.2. Land use and Land cover change as underlying indicator of the shift from firewood to agricultural wastes for fuel in the Central Highlands of Ethiopia

Land use and land cover change is a good indicator of the trends in biomass fuel supply. As shown in Figures 9.1- 9.6 and Tables 9.1- 9.4, the area of land under forest or plantation in Nano Genete, the kebele where the Doliyo study site is located, has reduced by 20% since 1986. This is linked to the lack of conversion in the area to superior energy sources, such as electricity and biogas for cooking, while population pressure is increasing the demand for biomass fuel. As a result farm households in the Central Highlands of Ethiopia including the study Kebeles (Nano Genete and Ude) have been forced to switch to inferior and less efficient agricultural wastes (cattle dung and crop residues) to meet their energy demands. As shown in this study, dung cakes and crop residues accounted for about 85% of the total energy demand in Kumbursa Village (one of the three villages in Ude kebele).

The proportion of the Ethiopian population relying on biomass fuels (wood, charcoal, crop residues and dung) for household energy provision has remained almost constant for the last 30 years, accounting for 93% in 1982 (FAO, 1986) and still over 90% in 2015 (Getamesay *et al*, 2015). However, the forest coverage, which was about 7% in 1982 (FAO, 1986), has now been reduced to less than 3%, representing a loss of around 32.5 million m^3 firewood (Fekadu, 2015). The decline in fuel wood consumption has been compensated for by an increase in use as fuels of sawdust and dung, which increased by 473% and 832% respectively (Gaia, 2012). Due to the dwindling stock of woody biomass in Kumbursa, we observed a wide scale switch to crop and livestock residues, diverting these organic wastes from their traditional use as soil fertilizers. A study conducted by Abebe *et al.* (2015) also revealed that deforestation near Ude Kebele has reduced fuel wood to the level of insufficiency and this in turn has led to a conversion to agricultural wastes for fuel.

An increase in the price of biomass fuels also implies an increased fuel supply shortage. In 1986, the average price of dried dung cakes and firewood at the nearby Bishoftu market was 0.20 ETB kg^{-1} and 0.25 ETB kg^{-1} respectively (Senait, 1986). The survey conducted in Bishoftu market in 2015 revealed that the average price of dung cakes was 2.00 ETB kg^{-1} (an increase by a factor of 10 compared to 1986) while the price of firewood was ETB 1.80 kg^{-1} (an increase by a factor of 7 compared to 1986).

As shown in Table 9.1, the proportion of land under forest or plantation in Nano Genete in 1986 was 34.2% (3248.6 ha) which was reduced to 32.9% (3097.1 ha) in 2000 and further reduced to 27. 5% (2595.9) in 2016. This means forest land and plantation were reduced by 4.7% between 1986 and 2000, 16.2% for the years 2000 to 2016 and 20.1% for the period from 1986 to 2016 (Table 9.2). This suggests an increasing decline in firewood supply and a consequent increase in the shift to inferior biomass fuel sources. As also shown in Table 9.1, the land under grassland decreased from 3744.7 ha (39.8%) in 1986 to 2776.6 (29.5%) in 2000 and continued to further reduce to 1351.7 ha (14.3%) in 2016, suggesting reducing opportunities to collect dung from the common grazing land, and increased reliance on own holdings for fuel. As shown in Table 9.2, the land covered by grassland was reduced by 968.1 ha (25.9%) from 1986 to 2000, 1424.9 ha (51.3%) from 2000 to 2016, and 2393 (63.9%) from 1986 to 2016.

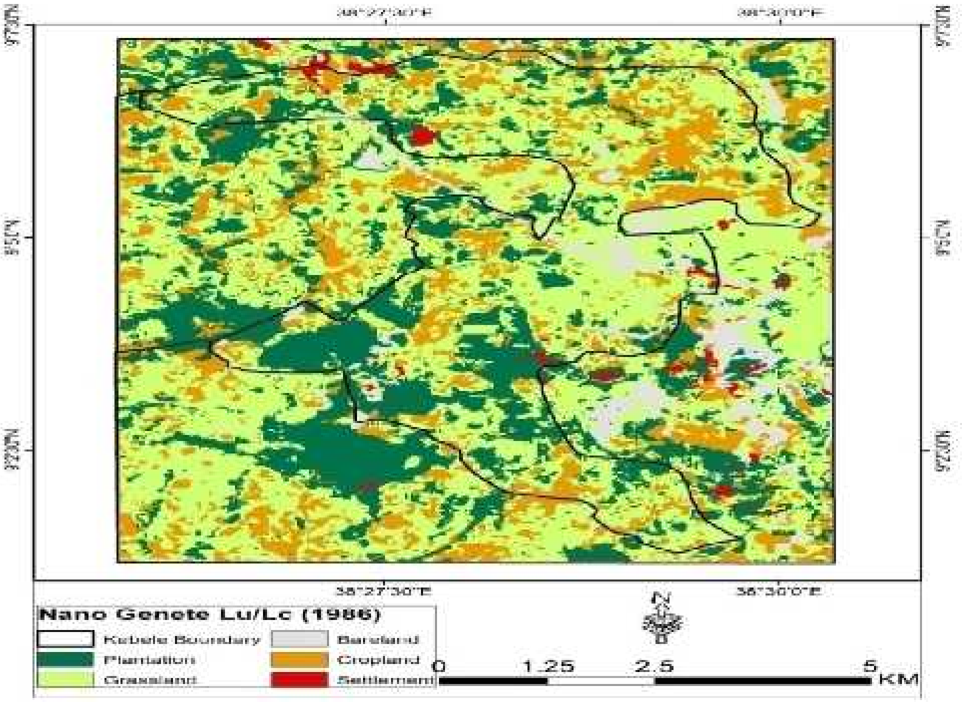

Figure 9.1. Land use/Land cover map of Nano Genete in 1986 (Source: Erdas Imagine and Arc GIS 10)

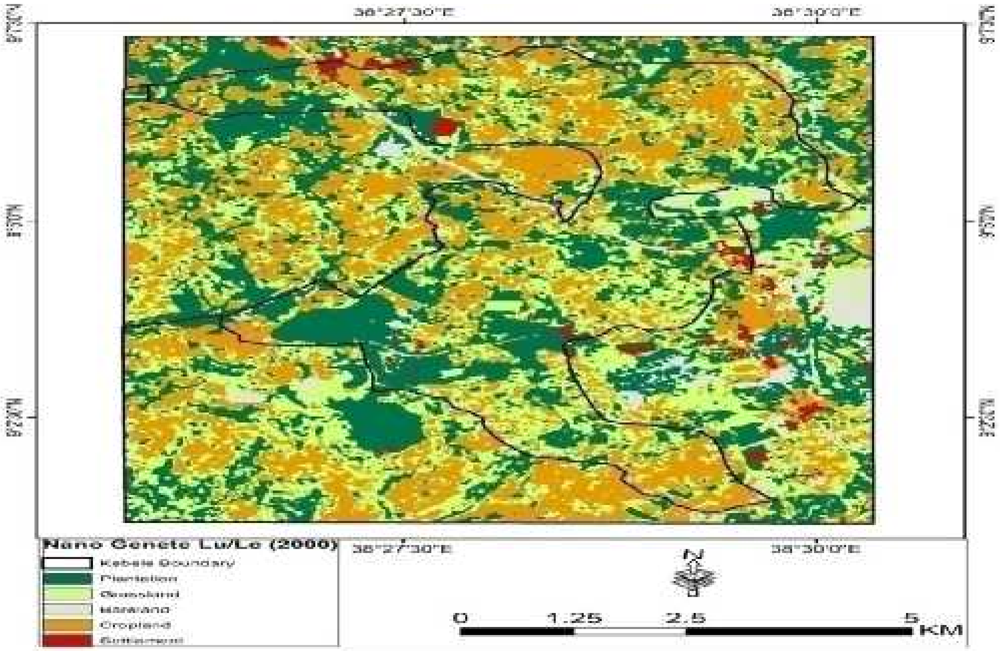

Figure 9.2. Land use/Land cover map of Nano Genete in 2000 (Source: Erdas Imagine and Arc GIS 10)

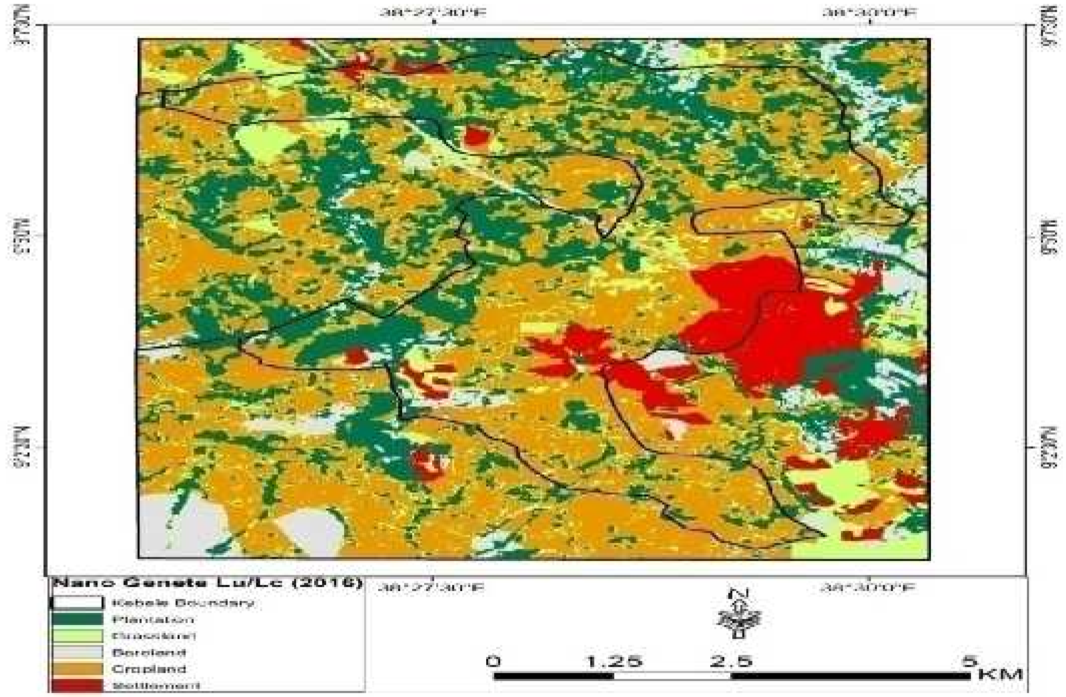

Figure 9.3. Land use/Land cover map of Nano Genete in 2016 (Source: Erdas Imagine and Arc GIS 10)

Table 9.1. Land use/Land cover types in Nano Genete kebele during 1986-2016

Land use / Land cover type	1986		2000		2016	
	Ha	%	Ha	%	Ha	%
Forest/plantation	3248.6	34.5	3097.1	32.9	2595.9	27.5
Grassland	3744.7	39.8	2776.6	29.5	1351.7	14.3
Bareland	434.3	4.6	304.9	3.2	654.1	6.9
Cropland	1890.9	20.1	3120.4	33.1	4146.5	44.0
Built-up area	94.9	1.0	114.4	1.2	678.6	7.2
Total	9413.4	100.0	9413.4	100.0	9426.9	100.0

Table 9.2. Land use/Land cover changes in Nano Genete kebele during 1986-2016

Land use / Land covertype	1986-2000		2000-2016		1986-2016	
	Ha	%	Ha	%	Ha	%
Forest/plantation	-151.5	-4.7	-501.2	-16.2	-652.7	-20.1
Grassland	-968.1	-25.9	-1424.9	-51.3	-2393.0	-63.9
Bareland	-129.4	-29.8	349.2	114.5	219.8	50.6
Cropland	1229.5	65.0	1026.2	32.9	2255.6	119.3
Built-up area	19.5	20.6	564.2	493.2	583.7	615.4
Total	0.0	0.0	13.5	0.1	13.5	0.1

In Ude kebele, land under forest or plantation also underwent dramatic reduction during the years 1986 to 2016 (reduced from 2093.3 ha (34.1%) in 1986 to only 292.7 ha (4.8%) in 2016 (Table 9.3). As shown in Table 9.4, forest and plantation land was reduced by 1060.5 ha (50.7%), 740 ha (71.7%) and 1800.6 ha (86%) for the years from 1986 to 2000, 2000 to 2016 and 1986 to 2016 respectively. This explains the reason why firewood in Kumbursa village is so scarce, forcing almost all the households in the village to switch to dung cakes and crop residues for fuel.

Grassland also decreased from 1793.8 ha (29.2%) in 1986 to 1287.7 ha (19.7%) in 2016 respectively (Table 9.3); and this was a reduction by 585.1 ha (32.6%) in 2016 compared to its size in 1986 (Table 9.4). So similarly to Nano Genete, grassland decreased with time, implying little chance of collecting dung for fuel from common grazing lands.

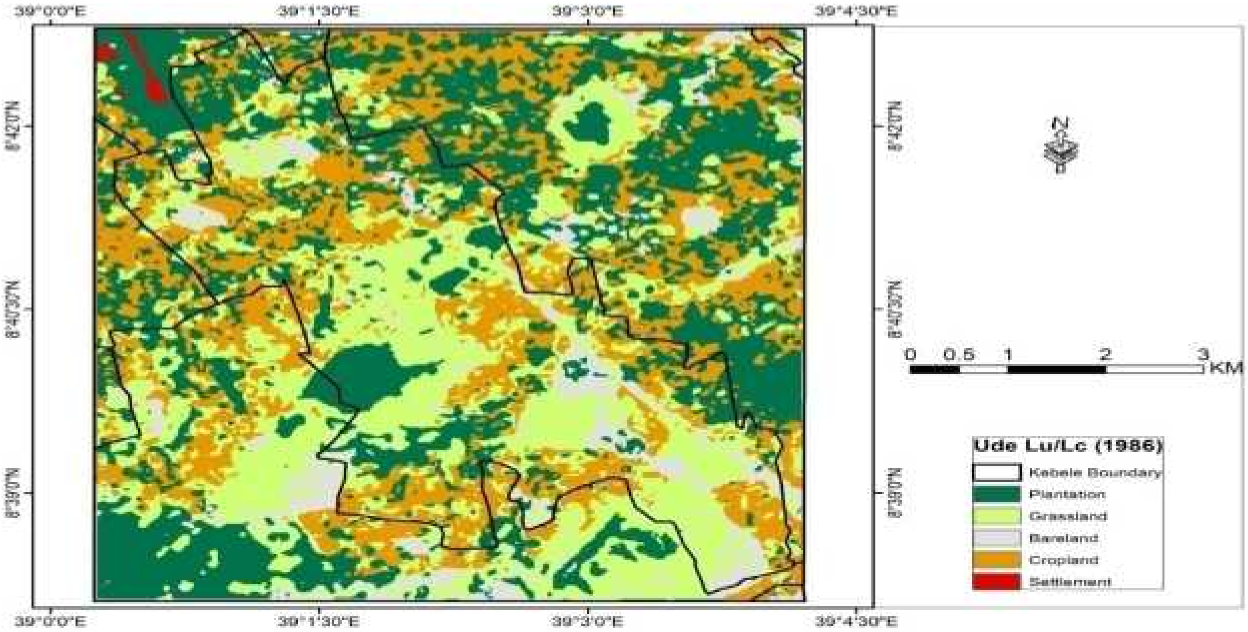

Figure 9.4. Land use/Land cover map of Ude kebele in 1986 (Source: Erdas Imagine and Arc GIS 10)

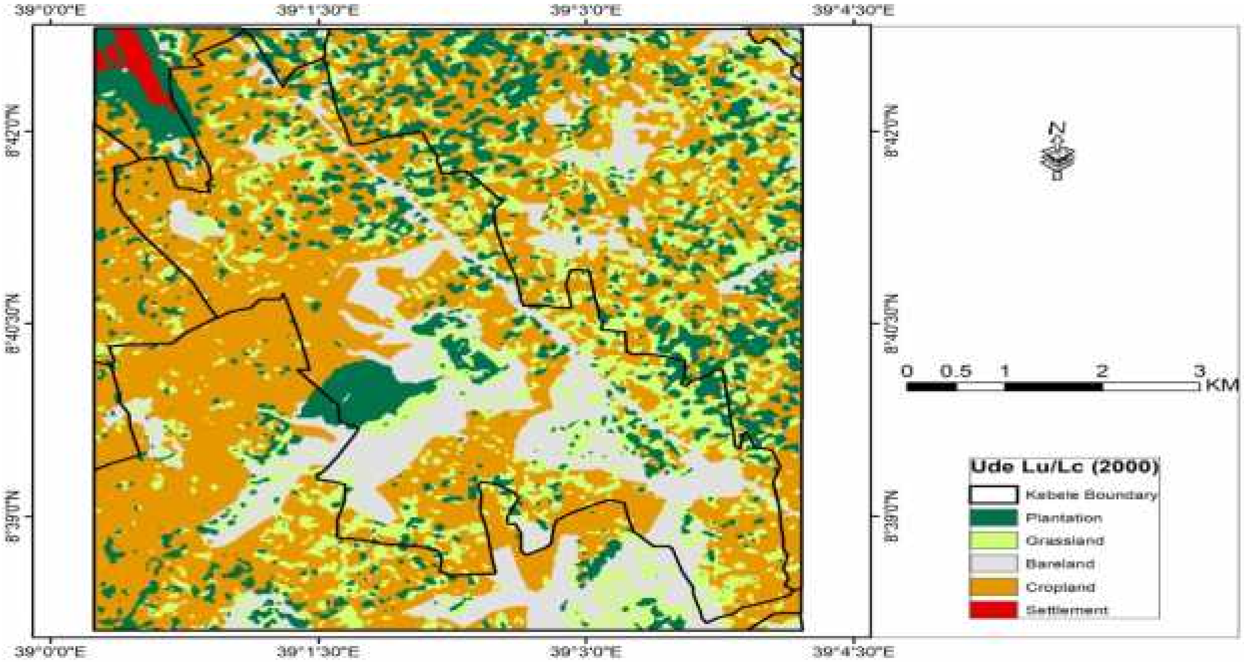

Figure 9.5. Land use/Land cover map of Ude kebele in 2000 (Source: Erdas Imagine and Arc GIS 10)

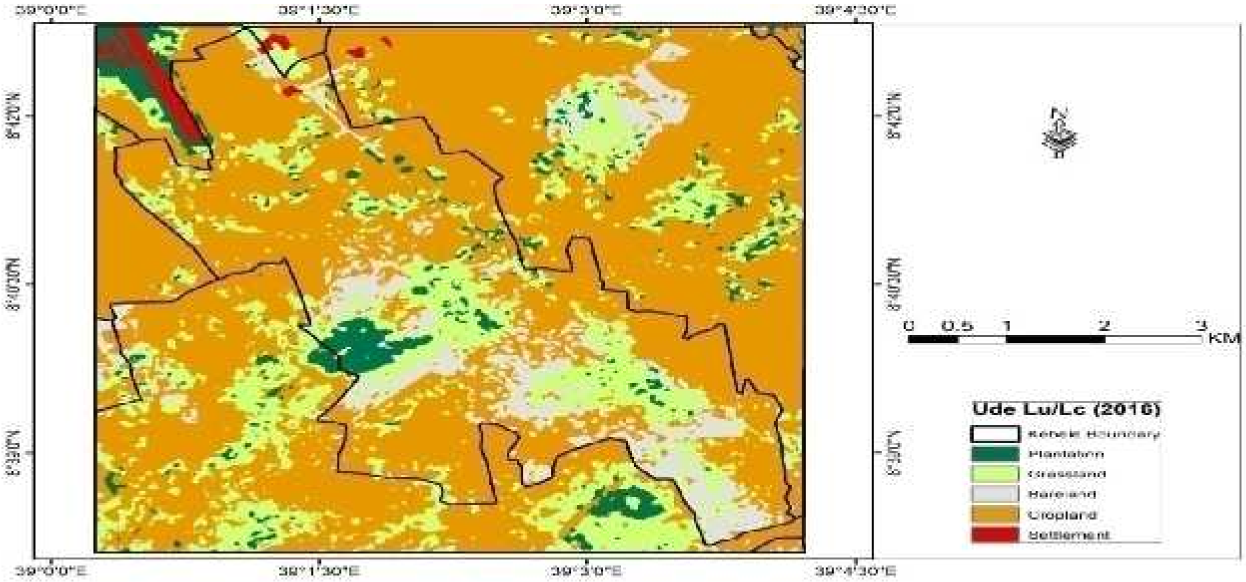

Figure 9.6. Land use/Land cover map of Ude kebele in 2016(Source: Erdas Imagine and Arc GIS 10)

Table 9.3. Land use/Land cover types in Ude kebele during 1986-2016

Land use / Land covertype	1986		2000		2016	
	Ha	%	Ha	%	Ha	%
Forest/plantation	2093.3	34.1	1032.8	16.8	292.7	4.8
Grassland	1793.8	29.2	1174.3	19.1	1208.7	19.7
Bareland	449.2	7.3	934.2	15.2	452.9	7.4
Cropland	1793.3	29.2	2971.5	48.4	4134.4	67.3
Built-up area	15.5	0.3	32.5	0.5	52.1	0.8
Total	6145.2	100.0	6145.2	100.0	6140.9	100.0

Table 9.4. Land use/Land cover changes in Ude kebele during 1986-2016

Land use / Land covertype	1986-2000		2000-2016		1986-2016	
	Ha	%	Ha	%	Ha	%
Forest/plantation	-1060.5	-50.7	-740.0	-71.7	-1800.6	-86.0
Grassland	-619.5	-34.5	34.4	2.9	-585.1	-32.6
Bareland	485.0	108.0	-481.3	-51.5	3.7	0.8
Cropland	1178.2	65.7	1162.9	39.1	2341.1	130.5
Built-up area	16.9	108.8	19.6	60.3	36.5	234.7
Total	0.0	0.0	-4.4	-0.1	-4.4	-0.1

9.3. Potential of improved cookstoves and biogas digesters to reduce organic wastes burnt as fuels

Having realized the acute scarcity of firewood and consequent widespread shift of farm households to agricultural wastes (dung and crop residues) for fuel, the potential contribution of improved cookstoves and small scale biogas digesters in reducing biomass fuel use and in increasing the availability of cattle dung and crop residues for recycling to farmland was investigated. Therefore, *mirt* and mud-stoves, with and without parallel use of biogas, were assessed in terms of their potential contribution to increase the availability of crop residues and cattle dung for application to fields, improve household finances and reduce greenhouse gases emissions.

As observed in the field based kitchen performance test, controlled cooking test and end-users satisfaction surveys, substitution of a three-stone open fire with a *mirt* or mud-stove both with and without biogas resulted in significant improvement of fuel use efficiency ($p<0.01$) with the highest saving in fuel achieved by the *mirt* stove together with biogas (53.6%) and lowest by the mud-stove without biogas (32.1%).

The potential per household savings in biomass fuel were 2842 kg yr^{-1} for the mud-stove, 4061 kg yr^{-1} for the *mirt* stove, 4511 kg yr^{-1} for the mud-stove with biogas, and 5028 kg yr^{-1} for the *mirt* stove with biogas.

This resulted in reductions in greenhouse gas emissions of 4532 (±32) CO$_2$e yr^{-1} for the mud stove, 6371(±42) kg CO$_2$e yr^{-1}for the *mirt* stove, 6954(±51) kg CO$_2$e yr^{-1}for the mud-stove with biogas and 7667(±43) kg CO$_2$e yr^{-1}for the *mirt* stove with biogas. The financial gains per household from the sale of biomass fuels saved by replacement of the three-stone open fire were 6145 (±95) ETB yr^{-1}(279.3 (±4.3) US$ yr^{-1}) for the mud-stove, 8630 (±115) ETB yr^{-1}(392.3(±5.2) US$ yr^{-1}) for the *mirt* stove, 9406 (±139) ETB yr^{-1} (427.5(±6.3) US$ yr^{-1}) for the mud-stove with biogas, and 10354 (±57) ETB yr^{-1} (470.6(±2.6) US$ yr^{-1}) for the *mirt* stove with biogas. Potential financial gains per household from substitution of commercial fertilizer and gains from carbon trading respectively were 1488 (±12) ETB yr^{-1} (67.6 (±0.55) US$ yr^{-1}) +1634 (±24) ETB yr^{-1}(74.3(±1.1) US$ yr^{-1}) = 3122(±36) ETB yr^{-1}(142(±1.65) US$ yr^{-1}) for the mud-stove; 2761 (±15) ETB yr^{-1}(125.5(±0.7) US$ yr^{-1}) +2298 (±30) ETB yr^{-1}(104.5(±1.4) US$ yr^{-1}) = 5059(±45) ETB yr^{-1}(230(±2.1) US$ yr^{-1}) for the *mirt* stove, 3308 (±19) ETB yr^{-1}(150.4(±0.9) US$ yr^{-1}) +2508 (±35) ETB yr^{-1}(114(±1.6) US$ yr^{-1}) = 5816(±54)ETB yr^{-1}(264(±2.5) US$ yr^{-1}) for the mud-stove with biogas, and 3450 (±7) ETB yr^{-1}(156.8(±0.3) US$ yr^{-1}) +2764 (±168) ETB yr^{-1}(125.6(±7.6) US$ yr^{-1}) = 6214(±175) ETB yr^{-1}(282.5(±7.9) US$ yr^{-1}) for *mirt* stove with biogas. So, even if carbon trading is included, the short-term financial benefit of selling saved biomass fuel is greater than the benefits of using it as a soil improver. The outcome from the cookstove performance evaluation confirmed that wide scale dissemination of improved cookstoves combined with biogas technology has great potential to enhance the availability of cattle dung and crop residues for field application, but households are still unlikely to do this while there is greater financial gain from selling biomass fuels.

9.4. Impacts of incorporating extra organic wastes on soils

Following on from the findings on the potential contribution of improved cookstoves and small scale biogas digesters to enhance agricultural waste availability for application to farmlands, on-farm trials were established to determine the impacts of incorporating the extra organic fertilizer on the physical and chemical properties of the soil and the agronomic responses to these applications of wheat and teff. Pre-treatment and post test soil characterization were undertaken; the pretreatment assessment evaluated the status of the soil compared to standard values from literature for crop production, while the post treatment assessment investigated the impacts of the different treatments on the soil properties.

The soil texture of the three trials were clay to clay loam, which is suitable for cereal crop production while the bulk densities (1.30 g cm^{-3} to 1.45 g cm^{-3}) were high to very high, suggesting that soil compaction was a problem. The soil total N (0.117% to 0.134%) was very low, available P (12.21ppm for Doliyo and 3.82 mg kg^{-1} for Kumbursa) was rated as medium and low, respectively, and organic C (1.32 to 1.44%) was very low. The C: N ratios (10.75 to 11.37) were within the optimum ranges for crop production. The soil cation exchange capacity (ranging from 31.98 meq per 100g to 37.97 meq per 100g), and base saturation (47.99% to 49.96%) were rated as high. The soil pH at Doliyo was strongly acidic (5.10) while that of Kumbursa was neutral (6.89). The observed suboptimal levels of total N, available P and organic C as well as the very high bulk densities imply the need for application of organic fertilizers for improving these soil parameters.

The post treatment soil test results revealed that application of bioslurry and bioslurry compost individually as well as in combination with inorganic fertilizer tended to decrease soil bulk density, while the likely increases of total N, available P, organic C, C: N ratios, exchangeable bases, cation exchange capacity, and percentage base saturation and pH were observed. For plots treated only with bioslurry compost, soil bulk densities were significantly reduced ($p < 0.01$), while total N and organic C significantly increased ($p < 0.01$) for Doliyo, and ($p < 0.05$) for Kumbursa. A significant increase ($p < 0.05$) in soil total N, available P and organic C were also observed for plots amended with bioslurry compost and inorganic fertilizer at the Doliyo site.

There was significantly higher ($p < 0.01$) soil available P for plots receiving bioslurry compost and inorganic fertilizer in all of the three trials. Plots only amended with inorganic fertilizer were also characterized by significantly higher available P ($p < 0.05$) in the Doliyo wheat field. In all treatments of the Doliyo wheat field, C: N ratios significantly decreased ($p < 0.05$) while they remained unchanged for the plots treated only with inorganic fertilizer at Kumbursa. Exchangeable bases (Ca^{2+}, Mg^{2+} and K^{+}), cation exchange capacity and percentage base saturation were also improved as a result of applying bioslurry and bioslurry compost individually as well as combined with inorganic fertilizer while no improvement was observed for plots treated only with inorganic fertilizer. Significant increase ($p < 0.05$) in soil pH was observed in the case of plots amended only with bioslurry compost for Doliyo wheat field.

The study also revealed that the uptake of nutrients and soil nutrient stocks were increased with increased rates of fertilizer application for all of the treatments with relatively better performance for the plots treated with combined bioslurry and inorganic fertilizer. Therefore, application of organic fertilizer in combination with inorganic fertilizer was found to be a better option than the application of inorganic or organic fertilizer alone, providing higher crop yield while also maintaining soil fertility; therefore, this practice should be encouraged. However, there might be a need to increased input of organic fertilizer to sustain the soil fertility.

9.5. Impacts of incorporating extra organic wastes on crop production

The impacts were also evaluated on the different agronomic parameters of wheat and teff of bioslurry and bioslurry compost individually, as well as in combination with inorganic fertilizer, as compared to inorganic fertilizer alone. The results from the on-farm trials revealed that both total above ground biomass and grain yields linearly increased with increased application rates of N and P for all of the treatments. The highest agronomic responses were obtained from plots treated with bioslurry compost combined with inorganic fertilizer and the lowest from plots treated with bioslurry alone. The highest average values of total above ground biomass for Doliyo wheat, Kumbursa wheat and Kumbursa teff trials respectively were (12459 (±81) kg ha^{-1}, (11941±171 kg ha^{-1}) and (11946 kg ha^{-1}) while the corresponding average grain yields were 5130 kg ha^{-1}, 4858 kg ha^{-1} and 3273 kg ha^{-1}.

The comparisons of the effects of the different fertilizer types when the three different rates were aggregated showed that the variations in total above ground biomass for wheat trials of both Doliyo and Kumbursa were insignificant while that of the Kumbursa teff trial were significant ($p < 0.000$). However, the variations in grain yields for wheat trial of both Doliyo and Kumbursa were significant ($p < 0.01$) while that of the teff trial of Kumbursa were significant ($p < 0.000$). For all fertilizer types and trial fields, nitrogen and phosphorus use efficiencies decreased with increased N and P application rates. The increase in grain yield varied from 14.2 to 32.4 kg kg^{-1} N, and from 23.3 to 41.6 kg kg^{-1} P for the Doliyo wheat field; from 10.4 to 29.7 kg kg^{-1} N and 19.7 to 45 kg kg^{-1} P for the Kumbursa wheat field; and from 11.8 to 34.7 kg kg^{-1} N and 16.6 to 48.0 kg kg^{-1} P for the Kumbursa teff field. For all of the treatments and the trial, agronomic response to N and P were inversely related to application rates.

9.6. Recommendations

Under the business as-usual-scenario, the interaction between household energy and soil nutrients recycling in the Central Highlands of Ethiopia was proved to be negative and hence unsustainable. Both KPT and CCT stove performance evaluations have shown that replacing the widely used traditional three-stone open fire with improved cookstoves and biogas digesters can have substantial potential to contribute to increased availability of cattle dung and crop residues for soil fertility improvement, mitigation of GHG emissions and improvement of household finances. Thus, wide scale substitution of open fire stoves with improved cookstoves can significantly contribute to the reversal of the prevailing food insecurity problem and energy crisis while also playing a decisive role in abating GHGs emissions and improving household finances in Central Highlands of Ethiopia in general and Kumbursa Village in particular.

Both governmental and non-governmental organizations should therefore work towards wide scale dissemination of fuel efficient cookstoves, small scale biogas technology and other modern energy options side-by-side with tree plantations on degraded lands and expansion of agroforestry for enhancing fuel wood availability.

Application of bioslurry and bioslurry compost should also be encouraged because of the added benefits of supplying a range of macro and micro plant nutrients that are not found in NP fertilizers. The combined organic and mineral fertilizer input enhances crop production through alleviation of multiple nutrient limitations and may improve the nutrient use efficiencies and apparent nutrient recoveries.

The agronomic responses of wheat and teff to the different fertilizer types suggested that combined application of organic and inorganic fertilizers should be encouraged to improve agronomic performance as well as soil properties.

Moreover, the blanket recommendations used in Ethiopia was found to be below the optimum level for both of the study sites; therefore, site specific recommendations for fertilizer applications is highly recommended.

Integrated application of organic and inorganic fertilizers should be encouraged, not only for better agronomic performance and intensification of the crop production systems, but also for improving soil physical and chemical properties. Farmers should be encouraged to use compost from available organic resources to complement the inorganic fertilizers recommended for crop production. Integrated use of chemical and organic fertilizers should be scaled up and widely adopted not only to narrow the prevailing gap between the potential and actual crop productivity, but also because of its eco-friendliness and easily adaptable nature to the varying biophysical and socioeconomic conditions.

There might be a need to increase the level of organic fertilizer applied to sustain the soil fertility. Addition of compost and bioslurry as well as in combination with inorganic fertilizer improves soil nutrient status and it can serve as a complement to inorganic fertilizer. It has also beneficial effect in that application of organic fertilizer can reduce the dependence on mineral fertilizer in low input crop production systems of the Central Ethiopian Highlands.

Integrated utilization of organic and inorganic fertilizer should be promoted for attaining higher crop yield and sustainable soil use. In order to raise the soil pH and overcome its negative effects on agricultural productivity, appropriate interventions such as application of lime, is strongly recommended. Increased utilization of organic resources in crop production is vital for reducing soil bulk densities while also improving soil organic C, total soil N and available P.

Finally, further experimentation is required on application rates of different fertilizer types on different soil types found in different agroecologies.

References

Abay, A., Kelsa, K., Tesfaye, D. (2011) *Application of NP fertilizers for better production of tef (Eragrostis tef (Zucc.) Trotter) on different types of soils in Southern Ethiopia.* Journal of Natural Sciences Research, 1/1 (6-16).

Abd El-Mohsen, A. A., Mahmoud, G.O. (2013) *Modeling the influence of nitrogen rate and plant density on seed yield, yield components and seed quality of safflower.* Amer. J. Exper. Agri. 3/2 (336 - 360).

Abebayehu, A., Eyasu, E. (2011) *Soil nutrient stock evaluation under different land use types in the smallholder farming systems of Jimma Zone, Ethiopia.* International Journals of Agricultural Research, 6/9 (707-713).

Abebe, B., Bluffstone, R., Zenebe, G., Martinsson, P., Alemu, M., Vieider, F. (2015) *Do improved biomass cookstoves reduce fuel consumptions and carbon emissions? Evidence from rural Ethiopia using a randomized treatment trial with electronic monitoring.* Policy Research Working Paper 7324.

Abebe, D., Koch, F. S., Alemu, M. (2011) *Coping with Fuel Wood Scarcity: Household Responses in Rural Ethiopia. Department of Economics Working Paper Series, University of Pretoria, Pretoria.*

Abebe, D., Koch, S. F. (2011) *Covariates of fuel saving technologies in urban Ethiopia.* World Renewable Energy Congress, Linköping, Sweden, 8-13 May 2011.

Abebe, N., Kuyper, T. W., de Neergaard, A. (2015) *Agricultural waste utilization strategies and demand for urban waste compost: Evidence from smallholder farmers in Ethiopia*. Waste Management, 4 (82-93).

Abebe, Z., Deressa, H. (2017) *The effect of organic and inorganic fertilizers on the yield of two contrasting soybean varieties and residual nutrient effects on the subsequent finger millet crop.* Agronomy, 7/42 (1-15).

Abera, A. B. (2016) *The implication of wood-burning stove efficiency for environment, health and* CO_2 *emissions in the Jogo Gudedo Watershed, Ethiopia.* Academic Research Journal of Agricultural Science and Research, 4/4 (154-163).

Accenture (2015) *Enhancing market for delivery of improved cookstove development and promotion support in Ethiopia: Market analysis, recommendations and program plan final.* Accenture Development Partnerships, UK.

Ada'a Liben woreda Office of agriculture (2005). *Annual report of the woreda*

Adkins, E., Tyler, E., Wang, J., Siriri, D., Modi, V. (2010) *Field testing and survey evaluation of household biomass cookstoves in rural Sub-Saharan Africa.* Energy for Sustainable Development 14(172-185).

Adugnaw, B. (2014) *Environmental degradation and management in Ethiopian highlands: Review of lessons learned, Debre Tabor University, Department of Geography and Environmental Studies, Debre Tabor, Ethiopia.* Available online at http://www.sciencepublishinggroup.com/j/ijepp(accessed 08/07/15).

African Development Bank Group (2010) *Smallholder agriculture in East Africa; Trends, Constraints and Opportunities.* Working Paper Series, No 105

Aguilera, J., Motavalli, P. P., Gonzales, M. A., Valdivia, C. (2012) *Initial and residual effects of organic and inorganic amendments on soil properties in potato-based cropping system in the Bolivian Andean Highlands.* American Journal of Experimental Agriculture; 2/4 (641-666).

Ahmed, M., Tebarek, L. (2016) *The energy-gender nexus: a case study among urban and peri-urban female headed households in Arba Minch Town, Southern Ethiopia.* EJOSSAH Vol. XII, No.1.

Aklilu, A. (2006) *Caring for the Land: Best Practices in Soil and Water Conservation in Beressa Watershed, Highlands of Ethiopia.* PHD Dissertation, Wageningen University,Wageningen

Alemayehu, M. (2006) *Country pasture/forage profiles: Ethiopia*. Rome: Food and Agriculture Organizations of the United Nations.

Alemtsehay, T. (2012) *Improving crop production by field management strategies using crop water productivity modeling : case study of tef (Eragrostis tef (zucc.) Trotter) production in Tigray, Ethiopia.* PHD thesis, Katholieke Universiteit Leuven, Belgium.

Alemu, A., Tamado, T., Jamal, A. (2016) *Effects of compost and inorganic NP rates on growth, yield and yield components of teff (eragrostis tef (zucc.) trotter) in Girar Jarso District, Central Highlands of Ethiopia.* Jz Fertil Pestic, 7/2.

Alemu, M., Zenebe, G., Menale, K., Kölin, G. (2009) *Income alone doesn't determine adoption and choice of fuel types: Evidence from Tigrai and major cities in Ethiopia.* Environment for Development, Policy Brief.

Alemu, M, Kohlin, G. (2008) *Biomass consumption and dung as manure: evidence from rural households in the Amhara region of Ethiopia.* Environment for Development Discussion Paper Series,EfD DP 08-17, Gothenburg, Sweden. Available online at http://www.rff.org/files/sharepoint/WorkImages/Download/EfD-DP-08-17.pdf (accessed 14/07/16).

Amanullah and Almas, L. (2009) *Partial factor productivity, agronomic efficiency, and economic analysis of maize in wheat-maize cropping system in Pakistan.* Selected paper prepared for presentation at the Southern Agricultural Economics Association Annual Meetings, Atlanta, Georgia, January 31-February 3, 2009.

Amare H., J. A. Priess, E. Veldkamp, Lesschen, J. P. (2006) *Smallholders' soil fertility management in the Central Highlands of Ethiopia: implications for nutrient stocks balances and sustainability of agroecosystem.* Nutrient Cycling in Agroecosystems 75 (135–146).

Amare H., Priess J., Veldkamp E., Demil T. and Lesschen J. P. (2005) *Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances.* Agri. Ecosystems and Environment 108:1-16.

Amare, H., Priess, A. J., Veldkamp, E., Lesschen, J. P. (2006) *Smallholders' soil fertility management in the Central Highlands of Ethiopia: Implications for nutrient stocks, balances and sustainability of agroecosystems.* Nutr Cycl Agroecosyst: DOI 10.1007/s10705-006-9017-y.

Amogne, A. (2014) *Factors affecting the adoption of fuel efficient stoves among rural households in Borena woreda: North central Ethiopia.* International Journal of Energy Science (IJES), 4/5 (141-154).

Amujoyegde, B. J., Opabode, J. T., Olayinka, A. (2007) *Effect of organic and inorganic fertilizer on yield and chlorophyll content of maize (Zea mays) and Sorghum Sorghum bicolour (L.) Moench.* African Journal of Biotechnology, 6/16 (1869-1873).

Anderson, M. J., Ingram, J. S. (1993) *Tropical biology and fertility:* A handbook of methods. 2nd edn. CAB International: Willingford, UK

approaches (3rd ed.). California: SAGE.

Arif, M. (2011) *Effect of different rates of nitrogen and phosphorus fertilizers on growth and yield of maize.* J. Agric.Res. 49/3 (333 - 340).

Arthurson, V. (2009) *Closing the global energy and nutrient cycles through application of biogas residue to agricultural land* – potential benefits and drawbacks, energies, 2 (226 – 242).

Asres, T., S. (2012) *The current status of traditional biomass energy utilization and its alternative renewable energy technology in Amhara Region of Ethiopia.* MSc. Thesis, KTH, School of Industrial Engineering and Management, Stockholm, Sweden. Available online at http://www.divaportal.org/smash/get/diva2:577167/FULLTEXT01.pdf (accessed 14/07/16).

Assefa, A. (2005) *Farm Management in Mixed Crop-livestock Systems in the Northern Highlands of Ethiopia. PHD.* Dissertation, Wageningen University and Research Center, the Netherlands

Assefa, A. (2008) *Indigenous soil nutrient supply and effects of fertilizer application on yield, N, P and K uptake, recovery and use efficiency of barely in three soils of Teghane, the Northern Highlands of Ethiopia.* African Journal of Agricultural Research, 3/10 (688-699).

Assefa, A., van Keulen H, Mitiku H, Oosting S. J. (2007) *Nutrient dynamics on smallholder farms in Teghane, Northern Highlands of Ethiopia.* In: *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities* (edsBationo A, Waswa B, Kihara J, KimetuJ) pp. (365-378) Springer, Wageningen, The Netherlands.

Assefa, A., **V**an Keulen, H. (2009) *Modelling soil nutrient dynamics under alternative farm management practices in the Northern Highlands of Ethiopia*. Soil Tillage Res. 103 (203-215)

ATA [Agricultural Transformation Agency] (2013a) *Results of 2012 New Teff Technology Demonstration Trials.*

ATA [Agricultural Transformation Agency] (2013b) *Status of soil resources in Ethiopia and priorities for sustainable management.* GSP for Eastern and Southern Africa, March 25 – 27, 2013, Nairobi, Kenya.

Avery, L. M, Yongabi, K, Tumwesige V, Strachan, N, Goude P. J. (2014) *Potential for pathogen reduction in anaerobic digestion and biogas generation in Sub-Saharan Africa.* Biomass and Bioenergy, 70, 112 -124.

Badege, B. (2001) *Deforestation and Land Degradation in the Ethiopian Highlands: A Strategy for PHysical Recovery.* Paper presented at International Conference on Contemporary Development Issues 16 – 18 August, 2001, Michigan, Kalamazoo, U.S.A.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, B. et al. (2007) Performance *testing for monitoring improved biomass stove interventions: Experiences of the household energy and health project.* Energy for Sustainable Development, Vol. XI, No 2.

Bailis, R., Drigo, A., Ghilardi, O., Masera, O. R. (2015) *The carbon footprint of traditional woodfuels.* Nature Climate Change; 5, 266-272.

Bailis, R., Smith, K. R., Edwards, R. (2004) *The kitchen performance test, version 1.5, household Energy and health programme.* Shell Foundation.

Balesh, T. (2005) *Integrated Plant Nutrient Management in Crop Production in the Central Ethiopian highlands.* Department of International Environment and Development Studies, Noragric, Norwagian University of Life Sciences, Norway.

Baliyan, S.P., Madhava Raos, K.S. (2012) *Response of different combinations of manure and fertilizers to the yield of rape crop.* Int.J. Agril. Res. Innov. & Tech. 2/2 (44-47).

Basri Akbar, M., H., Abdu, A., Jusop, s., Ahmed, O. H., Abdul-Hamid, H., *et al.* (2013) *Effects of mixed organic and inorganic fertilizers application on soil properties and growth of kenaf (Hibiscus Cannabinus L.) cultivated on Bris soils.* AJAS, 10/12 (1586 – 1597).

Batey, T. (2009) *Soil compaction and soil management -a review.* Soil Use and Management. 25(4): 335-345.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smalling, E., Thiombiano, L. (2006) *African soils: Their profitability and productivity of fertilizer use.* Background paper prepared for fertilizer Summit, Nigeria, Abuja.

Bayeh, B. (2010) *Assessment of bread wheat production, marketing and selection of N-efficient bread wheat (Tritium aestivum L.) varieties for higher grain yield and quality in North Western Ethiopia.*PHD thesis, Bahir Dar University, Bahir Dar, Ethiopia. Available online athttps://cgspace.cgiar.org/handle/10568/3614 (accessed 14/07/16).

Behailu, K. (2015) *Soil fertility mapping and fertilizer blending.* ATA, November 17, 2015.

Bekalu, A., Tenaw, W. (2015) *Effect of method of sowing and time of Di-Ammonium PHosphate (DAP) fertilizer application on yield and yield components of teff ((Eragrostis tef (Totter) at Shebedino, Southern Ethiopia.* Adv Crop Sci Tech, 3/2.

Bereket, H., Dawit, H., Mehretab, H., Gebremedhin, G. (2014) *Effects of mineral nitrogen and phosphorus fertilizers on yield and nutrient utilization of bread wheat (Tritcum aestivum) on the sandy soils of Hawzen District, Northern Ethiopia.* Agriculture, Forestry and Fisheries, 3/3 (189-198).

Betelhem, M.N., Wondwossen, B., E. (2016) *Renewable energy for climate change mitigation: An overview of biogas energy in East Africa.* Proceedings of the Final Conference on the Energy-Agro-Food Nexus in East Africa; pp 15-28.

Birhan, A., Sofiya, K., Temesgen, D., Kassu, T. *et al* .(2017) *Crop response to fertilizer application in Ethiopia: a review.* Ethio. J. Natur.Res. 16(21 - 48).

Bodruzzaman, M. Meisner, C.A., Sadat, M. A., Hossain, M. I. (2010) *Long term effects of applied organic manures and inorganic fertilizers on yield and soil fertility in wheat-rice cropping pattern.* 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August, 2010, Brisbane Australia, Published on DVD.

Bogale, G. (2014) *Resources and nutrients flows in smallholders' farming systems of Kumbursa Village, Ada'a District, Central Ethiopia.* Master thesis submitted to the College of Social Sciences, Addis Ababa University in partial fulfillment of the requirements for the Degree of Master of Arts in Geography and Environmental Studies Specialization: Land Resources Management.

Boldean, M., Sala, F., Rawashdeh, H., Luchian, D. (2015) *Evaluation of agricultural yield in relation to the doses of mineral fertilizers.* Journal of Central European Agriculture, 16/2 (149 - 162).

Bonten, L.T.C., Zwart, K.B., Rietra, R.P.J.J., Postma, R., Haas de M.J.G. (2014) *Bio-slurry as fertilizer; Is bio-slurry from household digesters a better fertilizer than manure?* A literature review. Wageningen, Alterra Wageningen UR (University & Research Centre), Alterra report 2519.

Brar, A.S., Singh, J., Singh, G., Kaur, G. (2015) *Effects of long term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize-wheat rotation.* Agronomy 5 (220-238).

Bruulsema, T.W., Fixen, P.E., Synder, C.S. (2004) *Fertilizer nutrient recovery in sustainable farming systems.* Better Crops, 88/4.

BSP (2007) *Review of Literature on Effects of Slurry Use on Crop production.* Final Report, Freelance Consultant, Post Box #2314, Kathmandu, Nepal.

Campbell, I. (2005) *Environmental assessment and screening report on the project: Improving productivity and market success (IPMS) of Ethiopian farmers; pilot learning woreda*: Ada'a, IPMS Environmental Screening Report.

Carter, M. R., & Gregorich, E. G. (Eds.). (2008) *Soil sampling and methods of analysis*, 2nd edition. Boca Raton: Taylor and Francis Group, LLC.

Chinthapalli, B., Dagne, T. D., Vijaya Chitra, D.S., Melaku, B. L. (2015) *A comparative study on the effects of organic and inorganic fertilizers on agronomic performance of Faba Bean (Vicia Faba L.) and Pea (Pisum Sativum L.).* Agriculture, Forestry and Fisheries, 4/6(263-268).

Cohen, L., Manion, L., & Morrison, K. (2007) *Research methods in education (6th Edition).* London: Routledge.

Creswell, John W. (2009) *Research design: qualitative, quantitative, and mixed methods*

CSA [Central Statistical Agency] (2011) *Welfare Monitoring Survey: Basic population characteristics, Education, Health, Child care and Breast feeding*. Addis Ababa, Ethiopia.

Dagninet A., Endeblhatu, A., Awole M. (2015) *Enhancing biomass energy efficiency in rural households of Ethiopia.* Journal of Energy and Natural Resources, 4 (27-33).

DARC *[DebreZeit Agricultural Research Center] (2015) DebreZeit, Ethiopia. unpublished.*

Dawit, G. D. (2012) *Assessment of biomass fuel resource potential and utilization in Ethiopia: sourcing strategies for renewable energies.* International journal of renewable energy research 2 (1) 131 – 139. Available online at http:// cleancookingstoves.org/resources files/assessment-biomass-fuel-resource.pdf (accessed 14/07/16).

Dawit, M., Elizabeth, B., Tekie, A., Ringler, C. (2015) *Food versus Fuel: Examining tradeoffs in the allocation of biomass energy sources to domestic production uses in Ethiopia.* Paper presented at Agricultural and Applied Economics Association and Western AgriculturalEconomics Association Annual Meeting, Sanfrancisco, CA, July 26-28.

Debela, H. (2007) *Human influence and threat to biodiversity and sustainable living.* EthiopianJournalof Educational Science, 3(86-95).

Dejene, K., Dereje, A., Daniel, G. (2010) *Synergistic effects of combined application organic and inorganic fertilizers on yield and yield components of teff (Eragrostis Tef (Zucc.) Trotter) under terminal drought at Adiha, Northern Ethiopia.* Journal of the Drylands, 3/1 (158-164).

Demeke, M., D. Marcantonio F. (2013) *Analysis of incentives and disincentives for teff in Ethiopia.* Technical notes series, MAFAP, FAO, Rome.

Demiss, M., Tekalign, M., Sokolowski, E., Nachmansohn, J. (2017) *Potash fertilization of teff and wheat in the Highlands of Ethiopia.* Int Potash inst, efc No. 48, March 2017.

Dereje, G., Assefa, A. (2015) *Determinants of integrated soil fertility management adoption under annual cropping system in Arsamma Watershed, Southwestern Ethiopian Highlands.* African Geographical Review, DOI: 10.1080/19376812.2015.1088390.

Diressie, H. (2011) *Crop residue management and farm productivity in smallholder crop livestock system of dry land North Wollo, Ethiopia.* MSc Thesis Plant Production Systems, Wageningen University.

Diriba, S. G, Nigussie, D. R., Kebede, W., Getachew, T., Sharma, J. J. (2015) *Effect of Nitrogen, PHosphorus and Sulphur fertilizers on growth, yield and economic returns of garlic (Allium Sativum L.).* Sci., Technol. and Arts Res. J., 4/2 (10-22).

Doberman, A. R. (2005) *Nitrogen use efficiency-State of art*. Agronomy and horticulture – Faculty publications, paper 316. http://digitalcommons.unl.edu/agronomyfacpub.

Dong, W., Zhang, X., Wang, H., Dai, X., Sun, X., Qiu, W., Yang, F. (2012) *Effect of Different Fertilizer Application on the Soil Fertility of Paddy Soils in Red Soil Region of Southern China.* PLoS ONE 7(9): e44504. doi:10.1371/journal.pone.0044504.

Dou, F., Soriano, J., Tabien, R. E., Chen, K. (2016) *Soil texture and cultivar effects on rice (Oryza Sativa L.) grain yield, yield components and water productivity in three water regimes.* PLOS ONE 11 (3).

Drechsel, P. and Gyiele, L. A. (1999) *The economic assessment of soil nutrient depletion, Analytical issues for framework development.* International Board for Soil Research.

Drechsel, P., Gyiele, L., Kunze, D., Cofie, O. (2001) *Population density, soil nutrient depletion, and economic growth in Sub-Saharan Africa.* Ecological Economics, 38(251-258).

Drost, A., E. (2011) *Validity and reliability in social science research, Educational research and perspectives.* Vol.38, No 1, California State University, Los Angeles.

Dubey, V., Patel, A. K., Shukla, A., Shukla, S., Singh, S. (2012) *Impact of continuous use of chemical fertilizer.* IJERD, 3/11(13-16).

Dunjana, N. (2011) *Effects of soil fertility management practices on selected soil physical properties, water use efficiency and crop productivity in Murewa small farming area.* MPHil, Department of Soil Science and Agricultural Engineering, University of Zimbabwe.

Duong, T.T. (2013) *Compost effects on soil properties and plant growth.* Doctoral Thesis, the University of Adelaide, Australia.

EARO [Ethiopian Agricultural Research Organization] (2001) *Narrowing the Rift: Teff Research and Development.* Proceedings of the “International workshop on Teff Genetics and Improvement”, 16 – 19 October, 2000,Debrezeit,Ethiopia.

EAS [Ethiopian Academy of Sciences] (2017) *The demographic dividend: Imperative for Ethiopia's transformation*; Policymaker's booklet.

Edwards, S. Fentaw, E, and Hailu, A. (2010) *Bioslurry as an organic input for Improved agricultural production.* Addis Ababa, Ethiopia.

Ehui, S. K. and Spencer, D.S.C. (1993) *Measuring the sustainability and economic viability of tropical farming systems: a model from sub-Saharan Africa.* Agricultural Economics 9: 279-296.

Elisabeth, D., DeVries, B., Herold, M, Verchot, L., Müller, R. (2014) *Fuelwood Savings and carbon emission reductions by the use of improved cooking stoves in an Afromontane Forest, Ethiopia.* Land, 3, 1137-1157.

Energy for Sustainable Development (2017) *Mirte, Ethiopia*. Available online at: http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm.

Energypedia (2017) *List of Stoves in Ethiopia.* Available online at: https://energypedia.info/wiki/List_of_Stoves_in_Ethiopia.

Environment Protection Authority (2011) *GEF portfolio identification document*. Addis Ababa: Environmental Protection Authority of Ethiopia.

EPA [Environment Protection Authority] (2011) *GEF portfolio identification document*. Addis Ababa: Environmental Protection Authority of Ethiopia.

EUEI [European Union Energy Initiative] (2013) *Biomass energy strategy Ethiopia; Energy for development.* Policy Paper, Eschborn, Germany.

Eyasu, E. (2002) *Farmers perceptions of change and management of soil fertility.* SOS Sahel-Sahel and Institute of Development studies. Addis Ababa Ethiopia.

Eyasu, E. (2009) *Approaches for Integrated Soil Fertility Management in Ethiopia:* A review, Addis Ababa, Ethiopia

Eyasu, E. (2017) *Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian Highlands.* Environmental Systems Research (2017) 6:20.

Eyasu, E., Morse, S. Belshaw, S.G.R. (1998) *Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia.* Agriculture, Ecosystems & Environment. 71 (1-3): 93-113

Eyasu, E., Scoones I. (1999) Perspectives on soil fertility change: A case study from southern Ethiopia. *Land Degradation and Development* 10 (3): 195–206.

Fairhurst, T. (2012) *Africa soil health consortium: handbook for integrated soil fertility management*. Nairobi: CAB International.

FAO [Food and Agriculture Organization] (1986) *Ethiopian Highlands Reclamation Study.* Report prepared for the government of Ethiopia.

FAO [Food and Agriculture Organization] (2011) *Ethiopia country programming framework.* Office of the FAO representative in Ethiopia to AU and ECA-Addis Ababa 2011.

Fayera, A., Adugna, D., Muktar, M. (2014) *Evaluation of tef [Eragrostis tef (Zuccgani) Trotter] responses to different rates of NPK along with Z and B in Didessa District, Southwestern Ethiopia.* World Applied Sciences Journal, 32/11 (2245-2249).

FDRE [Federal Democratic Republic of Ethiopia] (2011) *Ethiopia's Climate Resilient Green Economy (CRGE*), Addis Ababa, Ethiopia.

FDRE [Federal Democratic Republic of Ethiopia] (2016) *Growth and Transformation Plan II (GTP II)* . (2015/16 - 2019/20), Volume I: Main Text.

Fekadu, G. (2015) Forest loss and climate change in Ethiopia. *Research Journal of Agriculture and Environmental Management,*4**(**216-224).

Fekede, T. (2010) *Review article on the basis of distiniction between quantitative and qualitative research in social science: Reflection on ontological, epistemological and methodological perspectives.* Ethiop. J. Educ. & Sci.; 6/1 (97 - 108).

Fissehaye, M., Mitiku, H., Fassil, K. Alemteshay, T., Charles, Y. (2009) *Response of teff (eragrostis (tef) trotter) to phosphorus and nitrogen on vertisol at North Ethiopia.* Journal of the Drylands, 2/1 (8-14).

Fresew, B., Nigussie, D., Adamu, M., Tamado, T. (2018) *Effect of nitrogen uptake and use efficiency of bread wheat (Triticum aestivum L.) varities on vertisols of Central Highlands of Ethiopia.* Agric. & Food Secur.

Funsho, F. E., Oluwafemi, A. B., Joseph, A. (2015) *Comparative evaluation of organic and inorganic manure on sweet pepper performance in two ecological zones of Nigeria.* Amer. J. Exper. Agri., 6/5 (306 - 309).

Getachew, A. (2009) *Ameliorating effects of organic and inorganic fertilizers on crop productivity and soil properties on reddish-brown soils.* The 10th review workshop of the Ethiopian society of soil. Ethiopian Institute of Agricultural Research;

Getachew, A., VanBeek, C., Bird, M. I. (2014) *Influence of integrated soil fertility management in wheat and teff producivity and soil chemical properties in the highland tropical environment.* Journal of Soil Science and Plant Nutrition; 14 (532-545).

Getachew, B., Hailu, T., Anteneh, G., Kebebew, A., Gizaw, M. (2008) *Highly client-oriented breeding with farmer participation in Ethiopian cereal Teff [Eragrostis tef (Zucc.)Trotter]*. AJAR, 3/1 (022-028).

Getachew, B., Hailu, T., Anteneh, G., Kebebew, A., Gizaw, M. (2008) *Highly client-oriented breeding with farmer participation in Ethiopian cereal Teff [Eragrostis tef (Zucc.)Trotter]*. AJAR, 3/1 (022-028).

Getachew, E., Sonder, K. and Heegde, F. (2006) *Report on the feasibility study of a national programme for domestic biogas in Ethiopia.* For SNV – Ethiopia

Getachew, S., Aune, J. B. (2014) *Maize response to fertilizer dosing at three sites in the Central Rift Valley of Ethiopia.* Agronomy, 4 (436-451).

Getamesay, B., Workneh, N. Getachew, E. (2015) *Energy poverty in Addis Ababa city.* Ethiopian JournalEconomics and Sustainable Development; 6(26-34).

GIZ (2014) *Energizing development (EnDev) Ethiopia: Improved cookstoves (ICS).* Bonn and Escoborn. Available at: http://endev.info/ethiopia.

Granderson, J., Sandhu, S. J., Vasquez, D., Ramirez, E., Smith, K. R. (2008) *Fuel use and design analysis of improved woodburning stoves in the Guatemalan Highlands.* Biomass Bioenergy, 33 (306-315).

Gryseels, G. (1988) *Role of livestock on mixed smallholder farms in the Ethiopian highlands. A case study from the Baso and WorenaWereda near DebreBerhan.* PH.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Gudina ,T., Nonhebel, S. (2015) *Bio-wastes as an alternative household cooking energy source in Ethiopia.* Energies, 8(1965-1983).

Gumus, I., Seker, C. (2017) *Effects of spent mushroom compost application on the physicochemical properties of degraded soil.* Solid Earth, 8 (1153-1160).

Gwavuya, S. G., Abele, S. Barfuss, I., Zeller, M., Muller, J. (2012) *Household energy economics in rural Ethiopia: A cost-benefit analysis of biogas energy.* Renewable Energy, 48(202-209).

Habte, J., Likyelesh, G. (2013) *Variations in major traits of Gynogenically derived Teff [Eragrostis tef (Zucc.)Trotter] lines evaluated in Central Highlands of Ethiopia.* Ethio.J. Appl. Sci. Technol. 4(50-64)

Haftamu, G., Mitiku, H., Yomoah, C. F. (2009) *Tillage frequency, soil compaction and N-fertilizer rate effects on yield of teff (Eragrostis Tef (Zucc) Trotter) in Central Zone of Tigray, Northern Ethiopia.* MEJS, 1/1 (82-94).

Hagos, B. G., Abraha, A. D. (2016) *A review: on effect of phosphorus fertilizer on crop production in Ethiopia.* Journal of Biology, Agriculture and Healthcare; 3/6 (117-120).

Hailemariam, T. (2011) *The impact of shadow price and farmers' impatience on the allocation of a multipurpose resource in Ethiopia.* The 13th Annual BIOECON Conference "Resource Economics, Biodiversity Conservation and Development", September 2011.

Hailu, A. (2010) *The effect of compost on soil fertility enhancement and yield increment under smallholder farming – A case of Tahtai Mai Maichew District –Tigray Region, Ethiopia.* Dissertation submitted in the fulfillment of the requirements for Doctor of PHilosophy in Agricultural Sciences.

Hanna, R., Oliva, P. (2013) *Moving up the energy ladder: the effect of an increase in economic well-being on the fuel consumption choices of the poor in India.*Unpublished.

Hartemink, A. E. (2006) *Assessing soil fertility decline in the tropics using soil chemical data.* Advances in Agronomy, Vol 89, DOI: 10.1016/S0665-2113(05)89004-2.

Haute, J.V. (2014) *Evaluation of the effects of compost on soil properties, performance and yield of maize and beans in Kenya.*

Hazelton, P., Murphy, B. (2007) *Interpreting soil test results. What do all the numbers mean?* Melbourne: CSRO Publishing.

Hedon (2017) *Lakech stove.* Available online at: http://support.hedon.info/View+Stove&itemId=11487.

Henao, J., Baanante, C. (2006) *Agricultural Production and Soil Nutrient Mining in Africa.Implications for Resource Conservation and Policy Development*. International Fertilizer Development Center: Muscle Shoals AL.

Hilawe, L., Getenet, T., Asrat, Y. (2011) *Low carbon Africa: Leap-frogging to a green future.* Ethio-Resource Group and Christian Aid Ethiopia. Available at christianaid.org.uk/low-carbon-africa.

Husan, M. R., Islam, M. R., Faried, K., Mian, M. H. (2014) *Nitrogen use efficiency and rice yields as influenced by the application prilled urea and urea super granule with or without organic manure.* J. Bangladesh Agri. Univ. 12/1 (37-43).

Hussey, J., Hussey, R. (1997) *Business Research.* Palgrave: Basingstoke.

Idiata, D. J., Ebiogbe, M., Oriakhi, H., Iyalekhue, H. (2013) *Woodfuel usage and the challenges on the environment.* International Journals of Engineering Sciences, 2(110-114).

IEA [International Energy Agency] (2011) *World Energy Outlook 2011.* Energy for all, Financing Access for the poor. OECD/IEA.

IEA [International Energy Agency] (2014) *Africa energy outlook: afocus on energy prospects in SSA, World Energy Outlook Special Report.* Available online at www.iea.org(accessed 17/02/13).

IEW [International Energy Workshop] (2013) https://youtu.be/27OTQg5k6-s *Household energy transition in developing countries:* Two alternative frameworks for analysis, International Energy Agency (IEA), Paris.

IFDC [International Fertilizer Development Center] (2012) *Ethiopian Fertilizer Assessment.* In Support of the African Fertilizer and Agribusiness Partinership.

IFPRI [International Food Policy Research Institute] (2010) *Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system.*

IFPRI [International Food Policy Research Institute] (2012) *Seed, fertilizer and agricultural extension in Ethiopia: Sustainable solutions for ending hunger and poverty.*

IFPRI [International Food Policy Research Institute] (2013) *Fertilizer in Ethiopia: An assessment of policies, value chain and profitability.* IFPRI Discussion Paper 01304.

INFORSE [*International network for sustainable energy, manual on sustainable energy solutions for poverty reduction in South Asia*] (2006) Available online at http://www.inforse.org/asia/(accessed 12/04/15).

IOB (2013) *Renewable Energy; Access and Impact: A systematic literature review of the impact on livelihoods of interventions providing access to renewable energy in developing countries;* Ministry of Foreign Affairs, The Netherlands.

IPCC [Intergovernmental Panel on Climate Change] (2007) *Climate change:* the physical science basis, in: Contribution of Working Group I to the FourthAssessment Report of the Intergovernmental Panel on Climate Change,Cambridge University Press, Cambridge and New York.

IRENA [International Renewable Energy Agency] (2018) *Sustainable Rural Bioenergy Solutions in Sub-Saharan Africa: A Collection of Good Practices*, International Renewable Energy Agency, Abu Dhabi.

Isabel, B., Gwavuya, S., Abele, S., Muller, J. (2011) *Improving household energy systems in rural Ethiopia: A comparative study of traditional energy sources and biogas.* Conference on international research on food security, natural resource management and rural development, October 5-7, 2011.

Jan I, Khan, H. Hayat, S. (2012) *Determinants of rural household energy choices: an example from Pakistan. Policy journalof environmental Studies,* 21(635 – 641).

Kassahun, B., Hager, H. Mekonnen, K. (2013) *Woody and non-woody biomass utilization for fuel and implications on plant nutrients availability in Mukehantuta Watershed in Ethiopia*. African Crop Science Journal, 21(625-636).

Kebebew, A., Solomon, C., Zerihun, T. (2013) *Achievements and prospects of teff improvement;* Proceedings of the Second International Workshop, November 7 – 9, Debre Zeit, Ethiopia.

Kefyalew, E. (2011) *Fertilizer consumption and agricultural productivity in Ethiopia.* EDRI working paper 03, Addis Ababa, Ethiopia.

Ketema, S. (1997) *Teff (Eragrostisteff (Zucc.)) trotter: Promoting the conservation and use of underutilized and neglected crops,* International Plant Genetics Resources Institute, Rome, Italy, Available online athttp://www.bioversityinternational.org/uploads/tx_news/Teff_Eragrostis_teff__Zucc.__Trotter_279.pdf (accessed 14/07/16).

Killham, K. (2010) *Integrated soil management: moving towards globally sustainable agriculture:* foresight project on global food and farming futures. *Journal of Agricultural Science, 149*, 29-36.

Kindu, T. (2017) *Mirt stove distribution project.* Available online at: https://kindutrust.org/projects/mirt-stove-distribution-project/.

Kooser, S. H. (2014) *Clean cooking: The value of clean cookstoves in Ethiopia.* Journal of Environment and Resource Economics at Colby, Vol 01, Iss. 01, Article 03. Available at http: // digitalcommons.colby.edu/jerec/vol01/iss10/3.

Lambe, F, Jarisoo, M., Wanjiru, H., Senyagwa, J. (2015) *Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action.* Prepared by Sewidish Environment Institute, Stockholm and Nairobi, for the New Climate Economy/Working paper: Available at http:// new climate economy.report/misc/Working-Papers.

Landon, J. R. (1991) *Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and sub-tropics*. New York: Longman Scientific and Technical, and John Willey and Sons, Inc.

Lemlem, T. (2016) *Biogas technology adoption in rural Ethiopia: Its effect on the crisis of deforestation.* Journal of Energy Technologies and Policy, 6/1.

Li, D., Luo, P., Han, X., Yang, J. (2018) *Influence of long-term fertilization on soil physicochemical properties on a brown soil.* IOP Conf. Ser. Earth Environ. Sci. 108 042027.

Lulseged, T.; Tilahun, A.; Kihara J; Degefie, T.; Schulz S. (eds.) (2017) A review of soil fertility management and crop response to fertilizer application in Ethiopia: towards development of site- and context-specific fertilizer recommendation. CIAT Publication No. 443. International Center for Tropical Agriculture (CIAT), Addis Ababa, Ethiopia. 86 p. Available at:http://hdl.handle.net/10568/82996

Malghani, A. L., Malik, A. U., Sattar, A. *et al.*(2010) Response of growth and yield of wheat to NPK fertilizer. Sci.Int. (Lahore) 24/2(185-189).

Malik, S. S., Chauhan, R. C., Laura, J. S. Kapoor, T., Abhilashi, R. Sharma, N. (2014) *Influence of organic and synthetic fertilizers on soil physical properties*. Int.J.Curr.Microbiol.App.Sci 3/8 (802-810).

Maltas, A., Charles, R., Jeangros, B., Sinaj, S. (2012) *Effect of organic fertilizers and reduced tillage on soil properties, crop nitrogen response and crop yield: Results of a twelve years experiment in Changins, Switzerland.* Soil & Tillage Research, 126 (11-18).

Mariana ,C. R. (2008) *Quantifying the contribution of crop-livestock integration to African farming*. PHD Thesis, Wageningen University, The Netherlands.

Masera, O. R., Saatkamp, B.D., Kammen, D. M. (2000) *From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model.* World Development, 28(2083-2103).

Massah, J., Azadegan, B. (2016) *Effect of chemical fertilizers on soil compaction and soil degradation. Agricultural Mechanization in Asia, Africa and Latin America,* 47/1 (44-50).

Mathew, O. O., Sola, A. F., Oladiran, B. H., Amos, A. A. (2013) *Efficiency of Neyman allocation procedure over other allocation procedures in stratified random sampling.* AmJ. Theo Appl Stat, 2(122-127). Available online at http://article.sciencepublishinggroup.com/pdf/10.11648.j.ajtas.20130205.12.pdf (accessed 14/07/16).

Mehedi, T. A., Siddique, M. A., Shahid, S. B. (2012) *Effects of Urea and cow dung on growth and yield of carrot.* J. Bangladesh Agri. Univ., 10/1 (9-13).

Melkamu, H., Gashaw, M., Wassie, H. (2019) *Effect of different blended fertilizer on yield and yield components of food barely (Hordeum Vulgare L.) on nitosols at Hulla District, Southern Ethiopia.* J. Agric. Sci. & Resear.; 7/1(49 - 56).

Mercy Corps (2010) *Basic guide to fuel efficient stoves and emission testing.* Portland OR 97204, USA; Edinburgh, EH9 1NJ, UK.

Mesfin, K., Sheleme, B., Yifru, A. (2012) *Modelling the Influence of Floriculture Effluent on Soil Quality and Dry Matter Yield of Wheat on Vertisols at Debre Zeit, Ethiopia.* Journal of Environment and Earth Science, 2/2 (40-50).

Mesfin, K., Tekalegn, T. (2011) *Indexing soil P to recommend for Durum Wheat in East Shewa, Oromia Region.* Ethiopian Institute of Agricultural Research (EIAR), Report and Opinion, 2011; 3(1).

Mesfin, K., Zemach, S. (2015) *Effects of nitrogen and phosphorus fertilizer rates on yield and yield components of Barely (Hordeum Vulgarae L.) varieties at Damot Gale District, Wolaita Zone, Ethiopia.* American Journal of Agriculture and Forestry, 3/6 (271-275). http://www.sciencepublishinggroup.com/j/ajaf.

Minase, N.A., Masafu M. M., Geda, A.E., Wolde, A. T. (2015) *Smallholders managed manure nutrient losses and their implications on environment.* Environment and Ecology Research, 3(4) 82-88.

Mitiku, W., Tamado, T., Singh, T.N., Teferi, M. (2014) *Effects of integrated nutrient management on yield and yield components of food barely (Hordeum Vulgare L.) in Kaffa Zone, Southwestern Ethiopia.* Sci. Technol. Arts Res.J. 3/2 (34 – 42).

Morteza, A., S. (2013) *Study on replacement probability of composted organic manure with chemical fertilizer in safflower (Carthamus tinctorius L) organic farming.* Int. J. Agr. and Cr. sc., IJACS/2013/6-19/1304-1311.

Moyin-Jesu, E. I., Adekayode, F. O. (2010) *Comparative evaluation of different organic fertilizers on soil fertility improvement, leaf mineral composition and growth performance of African Cherry Nut (Chrysophyllum Albidium L) seedlings.* J.Amer.Sci., 6/8 (217-223).

Moyin-Jesu, E. I., Ogochukwu, A. I. (2014) *Comparative evaluation of different organic fertilizers on soil fertility improvement, leaf mineral composition and growth performance of coconut (Cocos Nucifera L.) seedlings.* International Journal of Plant & Soil Sciences; 3/6 (737-750).

Mubo, O., A. (2015) *Efficacy of NPK and cow dung combinations on performance of chilli pepper (Capiscum annuum L) and their influence on soil properties.* IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS), 8/7 (31-35).

Mulu, M. G. (2016) *Biogas technology adoption and its contribution to rural livelihood and environment in Northern Ethiopia, the case of Ofla and Mecha Woredas.* Addis Ababa University, Addis Ababa, Ethiopia.

Mulu, M. G., Belay, S., Getachew, E., Tilahun, W. S. (2016) *The environmental benefits of domestic biogas technology in rural Ethiopia.* Biomass Bioenerg; 90(131-138).

Mulugeta, D., Mamo, T., Sokolowski, E., Nachmansohm, J. (2017) *Potash fertilization of teff and wheat in the Highlands of Ethiopia.* International Potash Institute, e.ifc No. 48, March 2017.

Murphy, B.W. (2014) *Soil organic matter and soil function - Review of the literature and underlying data.* Department of the Environment, Canberra, Australia.

MWIE [Ministry of Water Irrigation and Energy] (2014) *Bio-fuel development experience of Ethiopia.*

Nafiu, A. K., Abiodum, M. O., Okpara, I. M., Chude, V. O. (2012) *Soil fertility evaluation: a potential tool for predicting for fertilizer requirements in Nigeria.* African Journal of Agricultural research, 7/47 (6204-6214).

NBPE [National Biogas Program Ethiopia] (2008) *Program Implementation Document.* Addis Ababa, Ethiopia

Ndwiga, T., Kei, R.M., Jepngetich, H., Korrir, K. (2014) *Assessment of health effects related to the use of biomass fuel and indoor air pollution in Kapkokwon sub-location, Bomet county, Kenya.* Open Journal of Air Pollution; 3(61-69).

NMSA [National Meteorological Services Agency] (2005) *Assessment of drought in Ethiopia.* NMSA, Addis Ababa, Ethiopia.

NMSA [National Meteorological Services Agency] (2009) *Assessment of drought in Ethiopia.* NMSA, Addis Ababa, Ethiopia.

NRCCA (2016) *Soil fertility management:* Study Guide.

Ogundijo, D. S., Adetunji, M.T., Azeez, J. O., Arowolo, T. A. (2014) *Effect of organic and inorganic fertilizers on soil organic carbon, PH, ammonium-nitrogen, nitrate-nitrogen and some exchangeable cations.* International Journal of Environmental Sciences; 3/4 (243-249).

Ogwumike, O. F., Ozughalu, M. U. Abiona, A. G. (2014) Household *Energy Use and Determinants: Evidence from Nigeria.* International Journal of Energy Economics and Policy, 4(248-262). www.econjournals.com.

OIDA [Oromia Irrigation Development Authority] (2000) *Keteba-Gembi Small Scale Irrigation;* Project final design draft, Adama.

OIDA [Oromia Irrigation Development Authority] (2002) *Ful-Tino Small Scale Irrigation* Project final design draft, Adama.

Okubay, G., Heluf, G., Tareke, B. (2014) *Response of Teff (Eragrostis tef) to different rates of slow release and conventional urea fertilizers in vertisols of southern Tigray, Ethiopia.* Adv plants Agric Res, 1/5.

Olsen S.R., Cole C.V., Watanabe F.S. and Dean L. A. (1954) *Estimation of available phosphorus in soils by extraction with sodium bicarbonate.* USDA circular No. 939, USDA, Washington DC

Omojolaibi, A. J. (2015) *Reducing Energy Poverty in Africa: Barriers and the Way Forward.* International Association for Energy Economics, *Unpublished.*

Omotayo, O. E., Chukwuka, K. S. (2009) *Soil fertility restoration techniques in Sub-Saharan Africa using organic resources.* Afri. J. Agric. Resear., 4/3 (144-150).

Onoja, O., Anthony, I. O. (2012) *Econometric Analysis of Factors Influencing Fuel Wood Demand in Rural and Peri-Urban Farm Households of Kogi State*. J. Sust. Dev. Pol.;

Pathank, H., Jain, N., Bhatia, A., Mohanty, S., Gupta, N. (2009) *Global warming mitigation potential of biogas plants in India.* Environmental Monitoring and Assessment, 157/ 1-4(407-418).

Qiu, S. L., Wang, L. M., Huang, D. F., Lin, X. J. (2014) *Effects of fertilizer regimes on tea yields, soil fertility and soil microbial diversity.* Chilean J. of Agric. Resear., 74/3 (333-339).

Rai, N., Ashiya, P., Rathore, D.S. (2014) *Comparative study of the effect of chemical fertilizers and organic fertilizers on Eisenia foetida.* IJIRSET; 3(12991-12998).

Raj, A., Jhariya, M.K., Toppo, P (2014) *Cow dung for ecofriendly and sustainable productive farming.* Environmental Science, 3/10(201-202).

Rao, T.N. (2007) *Improving nutrient use efficiency: The role of beneficial management practices.* Better Crops, India.

Remigios, V., M. (2014) *The Significance of Culture as a Household Energy Determinant: The Case of Chiwundura Communal Area, Zimbabwe.* Fort Hare Institute of Social and Economic Research, University of Fort Hare.

Risseeuw, N. (2012) *Household Energy in Mozambique: A study on the socioeconomic and cultural determinants of stove and fuel transitions.* Faculteit der AardLevenswetenschappen, VrijeUniversiteit

Roberts, T. L. (2008) *Improving nutrient use efficiency.* Turk. J. Agric. For., 32(177-182).

Rufino, M. C. (2008) *Quantifying the contribution crop-livestock integration to African farming.* PHD Thesis, Wageningen University, The Netherlands.

Sahlemedhin, S., Taye, B. (2000) *Procedures for soil and plant analysis*: Technical Paper No. 74. National Soil Research Center and Ethiopian Agricultural Research Organization, Addis Ababa.

Samuel, F. G. (2002) *Household's Consumption Pattern and Demand for Energy in Urban Ethiopia*. University of Alberta, Canada.

Sanginga, N. (2012) *Closing the yield gap through integrated soil fertility management. Paper presented at the scramble for natural resources: more food, less land?"* Conference conducted by the Crawford Fund for International Agricultural Research, 9-10 October, 2012, Canberra, Australia.

Sanginga, Woomer, P.I. (2009) *Integrated soil fertility management in Africa: Priciples, practices and development process.* Tropical Soil Biology and Fertility Institute of the International Center for Tropical Agriculture. Nairobi.263 PP.

SEI [Stockholm Environment Institute] (2008) *Market Barriers to Clean Cooking Fuels in Sub-Saharan Africa: A Review of Literature.* An SEI Working paper, Stockholm, Sweden. Web: www.sei.se

SEI [Stockholm Environment Institute] (2013) *Assessing the climate impacts of cookstove projects: Issues in Emissions Accounting.* SEI Working Paper Series No. 201301, Sweden, Stockholm.

Seid, Y., Bezabih, Y., Sahu, O. (2014) *Biogas production using geomembrane plastic digesters as alternative rural energy source and soil fertility management, sustainable energy* 2(1) (12-19).

Semple, S., Apsley A, Wushishu A, Smith, J. U. (2014) *Commentary: Switching to biogas -what effect could it have on indoor air quality and human health? Biomass and Bioenergy*,70(125-129).

Senait, S. (1986) *The economics of a biogas digester*. Livestocks Economics Division, Addis Ababa, Ethiopia; Unpublished.

Shane, A., Gheewala, H.S., Kasali, G. (2015) *Potential, barriers and prospects of biogas production in Zambia.* Journal of sustainable energy and environment, 6(21 – 27).

Shehu, H. E., Ezikiel, C.S., Kwari, J. D., Sandabe, M. K. (2008) *Agronomic efficiency of N, P and K fertilization sesame (Sesamum indicum) in Mubi Region, Adamawa State, Nigeria.* Nature and Science, 8/8.

Simansky, V., Kovacik, P., Jonkzak, J. (2017) *The effect of different doses of N fertilization on the parameters of soil organic matter and soil sorption complex.* Journal of Ecological Engineering; 8/3 (104-111).

Singh, V., Pant, A.K., Bahtnagar, A., Bhatt, M. (2017) *Evaluation of nutrient expert based fertilizer recommendation for growth, yield and nutrient uptake of maize hybrids and soil properties in maize-wheat cropping system in mollisols.* Int.J.curri. Microbiol.App.Sci., 6/10 (3539 - 3550).

Smith, J. U., Abegaz A, Matthews, R., *et al.* (2014) *What is the potential for biogas digesters to improve soil fertility and crop production in Sub-SaharanAfrica*? *Biomass and Bioenergy*, 70(58-72).

Smith, J. U., Assefa, A., Robin, M., Madhu, S., Bob, O., Vianney, T., Pete, S. (2013b) *What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa?* (Submitted to Journal of Biomass & Bioenergy).

Smith, J. U., Assefa, A.,, Robin, M., Madhu, S., Bob, O., Vianney, T., Pete, S. (2013a) *What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa?* (Submitted to Journal of Biomass & Bioenergy).

SNV [Netherlands Development Organization] (2011) *Brief report 2010 and plan 2011 of the Working Group on Domestic Biogas under the Energy for All Partnership.* Retrieved on October 26, 2011, from http://www.snvworld.org/en/Pages/Publications-item.aspx?publication=596.

Spielman, D., Dawit, K., Dawit, A. (2011) *Seed, fertilizer, and agricultural extension in Ethiopia* . (Ethiopia Strategy Support Program, ESSP II Working Paper 020). Addis Ababa: International Food Research Policy Institute. Retrieved from http://www.ifri.org/sites/default/files/publications/esspwp20.pdf

Subedi, M., Matthews, R., Pogson, M., *et al.* (2014) *Can biogas digesters help to reduce deforestation in Africa?* Biomass and Bioenergy, 70(87-98).

Suge, J. K., Omunyin, M. E., Omami, E. N. (2011) *Effects of organic and inorganic sources of fertilizer on growth, yield and crop quality of eggplant (Solanum Melongena L).* Arch. Appl. Sci. Res. 3/6 (470-479).

Tadesse, D. (2017) Nutrient management practices for sustainable maize production in Ethiopia: A review. Sky J. Agri. Resear. 6/2 (028-040).

Tamado, T., Mitiku, W. (2017) *Effect of combined application of organic and mineral nitrogen and phosphorus fertilizer on soil physico-chemical properties and grain yield of food barely (Hordeum Vulgare L.) in Kaffa Zone, Southwestern Ethiopia.* MEJS, 9/2 (242-261).

Tanimu, J., Uyovbisere, E.O., Lyocks, S.W.J., Tanimu, Y. (2013) *Effects of cow dung on the growth and development of maize crop.* Greener J. Agri. Sci. 3/5 (371-383).

Tegbaru, B. (2016) The role of DSM in transforming agriculture: The case of Ethiopian Soil System (EthioSIS). 7th Global DSM Workshop 2016, 27 June - 1 July, 2016, Aarhus, Denmark; ATA.

Teklu, E., Hailemariam, T. (2009) *Agronomic and economic efficiency of manure and urea fertilizers use on vertisols in Ethiopian Highlands.* Agricultural Sciences in China, 8/3 (352-360).

Temesgen, K. (2001) *Effect of sowing date and nitrogen fertilization on yield related traits of teff (eragrostis tef) on vertisols of Kobo area, North Wollo.* M.Sc. Thesis presented to Alemaya University. 67p.

Thomas, F. (2015) *Sustainable Land Management in Kilimanjaro Region opportunity for up scaling success and learning from experience: Performance of efficient fuel saving stoves and potential for livelihood improvement.* Journal of Environment and Earth Science, 5/7(19-23).

Tilahun G, Mekibeb, F., Asnake, F., Million, E. (2015) *Genotype x environment interaction and stability analysis for yield and yield related traits of Kabuli-type chickpea (cicer arietinum L. in Ethiopia.* African Journal of Biotechnology, 14(1564-1575).

Titilola, A. O. (2006) *Effects of fertilizer treatments on soil chemical properties and crop yields in cassava –based cropping system.* J. Appl. Sci. Res. 2/12 (1112 – 1116).

Treiber, U. M. (2012) *Fuel and stove diversification in the light of energy transition and technology adoption theory.* Noragric Department of International Environment and Development Studies, Norway.http://www.umb.no/noragric.

TSBF [Tropical Soil Biology and Fertility Institute] (2009) *Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Processes.* Sanginga N. and Woomer P.L. (eds.). Nairobi, Kenya.

Tumwesige, V. (2011) *Small-Scale Biogas digester for Sustainable Energy production in Sub-Saharan Africa.* First World Sustainability Forum Centre for Research in Energy and Energy Conservation, Makerere University, Kampala, Uganda.

Tumwesige, V., Fulford, D., Davidson, G. C. (2014) *Biogas appliances in Sub-Sahara Africa.* Biomass and Bioenergy, 70(40-50).

Ullah, M. S., Islam, M. S., Islam, M. A., Haque, T. (2008) *Effects of organic manures and chemical fertilizers on the yield of brinjal and soil properties.* **J.** Bangladesh Agril. Univ. 6/2 (271–276).

UNDP [United Nations Development Program] (2012) *Integrating Energy Access and employment creation to accelerate progress.*

Van der Kroon , B., Bouwer, R., Beukering, P.J. H. (2013) *The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis*. Renewable Energy and Sustainable Energy Reviews, 20 (504 - 513).

Vanlauwe, B., Chianu, J., Giller, K., Mokwunye, U., Pypers, P., … Sanginga, N. (2010) *Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. 19th World Congress of Soil of Science: Soil Solutions for a changing world, Brisbane, Australia.* Retrieved from http://www.iuss.org/19th WCSS/Symposium /pdf/0944.pdf

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S. (2015) *Integrated soil fertility management in Sub-Saharan Africa.* Soil; 1(491-508). www.soil-journal.net/1/491/2015/doi:10.5194/soil-1-491-2015

Vanlauwe, B., Ramisch, J. J., Sanginga, N. (2009) *Integrated soil fertility management in Africa: From knowledge to implementation.* Tropical Soil Biology and Fertility Institute (TSBF), International Center for Tropical Agriculture (CIAT), Nairobi, Kenya; (257-270).

Vanlauwe, B., Wendt, J., Giller, K. E., Corbeels, M., Gerard, B., Nolte, C. (2014) *A fourth principle is required to define conservation agriculture in Sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity.* Field Crops Research, 155(10-13).

Van-Reeuwijk, L. P. (1993) *Procedures for soil analysis, 4th Ed.* The Netherlands: International Soil Reference and Information Center.

Wachera, R.W. (2014) *Assessing the challenges of adopting biogas technology in energy provision among dairy farmers in Nyeri County, Kenya.* MSC Thesis, School of Environmental Studies of Kenyatta University.

Wakena, T. (2006) *Operational Analysis of the Cascaded Wadecha-Belbela Reservoir System.* (Ada'a Liben Woreda Oromia Region), Arba Minch University.

Walmara Agriculltural Office (2014) *Annual report.* Unbplished material.

Winrock International (2007) *Biogas for Better Life: An African Initiative, A Cost Benefit Analysis of National and Regional Integrated Biogas and Sanitation Programs in Sub-Saharan Africa,* Draft Final Report

Woldeamlak, B. (2003) *Towards integrated watershed management in Highland Ethiopia: the Chemoga Watershed case study.* PHD thesis, Wageningen University, Wageningen.

Wolde-Giorgis ,W. (2002) *Renewable energy for rural development in Ethiopia: the case for new energy policies and institutional reform.* Energy Policy, 30(1095-1105).

Workneh, B. (2015) *Compost and fertilizer-Alternatives or complementary? Management feasibility and long-term effects on soil fertility in an Ethiopian Village.* Doctoral Thesis, Uppsala, Swedish University of Agricultural Sciences.

World Bank (2010) *Mainstreaming Adaptation to Climate Change in Agriculture and Natural Resources Management Projects.* Washington: World Bank.

Woubshet, D., Selamyihun, K., Tolera, A., Raghavaiah, C.V. (2017) *Effects of lime, blended fertilizer (NPSB) and compost on yield and yield attributes of barely (Hordium Vulgare L.) on acid soils of Wlamara District, West Showa, Ethiopia.* Ethiop.J. App.Sci.Technol.; 8/2 (84-100).

Woyema, A., Bultosa, G., Taa, A. (2012) *Effect of different nitrogen fertilizer rates on yield and yield related traits for seven durum wheat (Triticum turigidum L. var Durum) Cultivars grown at Sinana, Southeastern Ethiopia.* Afr. J. F. Agr. Nutr. and Dev. 12/3(6079 - 6094).

WWAO [Walmara Woreda Agricultural Office] (2010). Quarter Report 2010. Unpuplished

Yiheyis, A.Y. (2015) *Tourism resources in Ethiopia: Huge possession versus under utilization.* The International Journal of Humanities and Social Sciences; 3/9 (306-311).

Yimenu, F., Chemeda, D. (2010) *Climate resources analysis for use of planning in crop production and rainfall water management in the Central Highlands of Ethiopia, the case of Bishoftu District, Oromia Region.* Hydrol.Earrth Syst. Sci. Discuss. 7(3733-3763).

Yonas, M., Raghavaiah, C.V., Habtamu, A. (2016) *Production potential of tef (Eragrostis tef (Zucc.) Trotter) genotypes in relation to integrated nutrient management on vertisols of Mid Hilands of Oromia Region of Ethiopia, East Africa.* Adv Crop Sci Tech, 4/6, DOI: 10.4172/2329-8863.1000249.

Yongabi, K., Avery, M. L., Pertiwiningrum, A. (2014) *A commentary on occupational infectious diseases due to agricultural practices in Sub-Saharan Africa.* Biomass and Bioenergy,70(99-111).

Yosef, A. B. (2007) *Assessing environmental benefits of mirt stove with particular reference to indoor air pollution (carbon monoxide and suspended particulate matter) and energy conservation.* Thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements of Master of Science in Environmental Science, Addis Ababa, Ethiopia.

Zenebe , G., Van Kooten, G. C., Van Sost, D. P. (2006) *Land degradation in Ethiopia: What do stoves have to do with it?* Contributed paper for presentation at the international association of Agricultural Economists Conference, Wageningen University, The Netherlands, Wageningen.

Zenebe, G., Abebe, D., Alemu, M., Toman, M. et al. (2014) Can improved biomass cookstoves contribute to REDD+ contracts in low income countries? Initial results from a randomized trial in Ethiopia. Environmental Economics Policy Forum for Ethiopia/Ethiopian; Development Research Institute, Ethiopia.

Zenebe, G., Alemu, M., Adane, T., Assefa, S. (2012) *Carbon markets and mitigation strategies for Africa/Ethiopia: Literature review and the way forward.* EDRI report 14. Addis Ababa: Ethiopian Development Research Institute.

Zerihun, Y. A. (2015) *The benefits of the use of biogas energy in rural areas in Ethiopia: A case study from Amhara National Regional State, Fogera District.* African Journal of Environmental Science and Technology, 9/4(332-345).

Zewde, I., Tamado, T. Lemma, W., Ali, M. (2018) *Effect of combined application of cattle manure, mineral nitrogen phosphorus fertilizer on soil physico-chemical characteristics and tuber yield of potato (Solanum Tubersome L.) in Masha District, Southwestern Ethiopia.* J. Environ. Sci. Nat. Res.; 14/5 (001-017).

Zhong, H., Wang, Q., Zhao, X. *et al.* (2014) *Effects of different nitrogen applications on soil physical, chemical properties and yield in maize (zea mays, L.).* Agricultural Sciences, 5(1440-1447).

Appendices

Appendix A: Structured survey questionnaire

Addis Ababa University, College of Social Sciences

Department of Geography and Environmental studies

A Questionnaire to be completed by Farmers of Kumbursa Village, Ada'a District

Dear Farmers,

These questionnaires are meant to gather information for a study on small holder's farming system of Ada'a District to quantify resource and nutrient follow and carbon. I hope that the research outcomes contribute to the improvement of soil fertility and land management practices.
Note: i) The response you give will not have any negative impact on you.
ii) Please feel free and respond what you think is correct.

Thank you in advance of your cooperation!

Yours faithfully,

Dugassa Negash

Part I: Questionnaire for Farmers to quantify resource and nutrient flows

1. Enumerator: --------------------------------
2. Date of interview: ----------------------
3. Site ---------------------
4. PA's ------------------------- 5. Village/ Got ---------------------

6. GPS coordinates at / near the farm of respondent

a. Latitude: ---------------- b. Longitude: ------------------- c. Altitude ----------------

a. General information

7. Name of respondent:-----------
8. Gender: 1) Male 2 Female ------------------
9. Age of the respondent

1) 19-29 years, 2) 30-40 years, 3) 41-51 years, 4) Above 51 years

10. Is the respondent head of the HH? [Y/N] ------- 0= No 1= Yes

11. Family size

1) Small (up to 4) 2) Medium (5-8) 3) Large (>8)

b. Overall land holding and land use characteristics

12. What is the total size of land you own in ha? 1) <1 , 2) 1-2, 3) 2-4, 4) >4
13. Do you have serious problem of land shortage? problem? 1) Yes, 2) No
14. If your answer to Q13 is yes, how do you solve the problem?
    1) Rented, 2) Crop Shared, 3) Gift, 4) None/others, specify_______________
15. From the total land you own in ha, how much was allocated last year for?
    1) Crop production ------------
    2) Grazing land for livestock ------------
    3) Homestead ---------------- What?
    4) Woodlot
16. From total land you own how much was allocated last year for:

    1. wheat--------------

    2. Barley-----------------
    3. Teff--------------------
    4. Faba bean----------------
    5. Potato-------------------
    6. Chickpea
    7. others, specify
17. Distance of your each plot from the household

Crop/plot	<0.5 km	0.5-1km	1-1.5 km	1.5-2km
Wheat				
Barley				
Teff				
Faba bean				
Potato				

c. Sources and utilization of fertilizers

18. Do you use fertilizer to your farmland? 1) Yes, 2) No

19. If the answer to Q18 is yes, what types of fertilizer do you use?
    1) Chemical fertilizers
    2) Manure
    3) Compost
    4) Others
20. Where/ How do you get these fertilizers?
    1) Buying
    2) Producing in the house
    3) Both
    4) Others
21. Do you face any problem to obtain fertilizers?
    1) Yes
    2) No
22. If the answer is yes, what is the problem?
    1) Expensive to buy
    2) Transportation
    3) Both problems
    4) others, specify
23. What type of fertilizer and amount you use

Crop grown	Area allocated in ha	Fertilizer used	
		Type of fertilizer	Amount Used kg/ha
1. Barely			
2 .Wheat			
3.Teff			
4.Faba bean			
5.potato			
6.Chickpea			

Code of fertilizer type
1) Urea 2) DAP 3) Manure 4) Compost

24. Do you think that the amount of fertilizer that you apply to your cropland is adequate?
A) Yes B) No

d. Crop and residue production

25. How much grain and residue you produced in Qt last season

Crop grown	Area allocated in ha	Yield (Qt/ha)	Residue (Qt/ha)
1. Barely			
2 .Wheat			
3.Teff			
4.Faba bean			
5.potato			
Chickpea			

e. Crop and residue utilization

26. How do you cover your household expenditure such as education fee, clothing, land tax and food seasoning items?

A) Selling crops and crop residues
B) Selling animal products and live animals
C) Income from off-farm activities
D) Trading, E) Others, specify.

27. In which season of the year do you face serious financial problem?
A) winter
B) summer
C) autumn
D) spring
E) constant throughout the year
28. In which season of the year do you sell most of your crops?
A) Immediately after harvest
B) During summer when crop price is more expensive
C) Whenever I face financial problem

29. For what purpose do you use the crop produced?

Crop		Utilization of crop product in Qt.		
	household food	Sale	Both & household food	Other uses
1.Wheat				
2.Barley				
3.Teff				
4.Faba bean				
5.Potato				

30. What do you do with the crop residue?

Crop	**Utilization of crop residues in kg**			
	Leave on land for soil fertility improvement	Feed for livestock	Sale	Fuel for cooking
1.Wheat				
2.Barley				
3.Teff				
4.Faba bean				
5.Potato				
6. Chikpea				

f. Households' animal production

31. What type and amount of animals do you own?

Animal type	Number of animals	Average weight	TLU
1.cow/ cattle			
2.sheep			
3.goat			
4.horse			
5.mule			
6.donkey			
7.Ox			
8.hen			
9. other			

g. Animal manure production and utilization

32. How much animal manure was produced in Kg last year? -----------------------

33. For what purpose do you use the animals waste (dung)?
1) As fuel 2) As Manure for farmland, 3) For market, 4) For home building

Part II Questionnaire for socio-economic base line study small holders' Farming system to establish pilot biogas digester.

1. Interviewee data:
1.1 Name of the respondent: ____
1.2 Contact: ____
1.3 Date of assessment: ____
1.4 GPS data:___________________________
1.6 How many people, including you, live in your house? ____☐__________

How many children are there under the age of 5 years? ☐
How many children of school age (5-16 years)?
How many children are in boarding schools? ☐
How many adults? ☐

1.7. Have you been involved in community training?

a) Yes b) No

If yes; can you please provide details and the nature of the training?

____

____

2. Energy demand assessment:

2.1 How many meals do prepare per day (incl. Breakfast, lunch and dinner)? ___________________

2.2 How many minutes or hours do you spend cooking per meal? a) Breakfast____ b) Lunch ____ c) Dinner ____ d) Lunch and Dinner ____

2.3 Do you boil drinking water? Yes/No

2.4 How much water does your household boil in a week?
a)5L/ ____ b) 10L____ c) 20L____

2.5 How big are your cooking pots?
a) Between 1L and 2L/ _______ b) Between 3L and 5L_______ / Over 5L/ _______

2.6 How many rooms do you light during the night?

2.7 ____

2.8 How many hours do you light these rooms?___________________________________

2.9 Do you currently use a solar lamp? Yes/No

2.10 Energy usage and cost

2.11

Energy source	Usage (units / time)	Unit Cost (Birr / unit)	Cost each transport (Birr)	Purpose e.g. cooking, lighting, boiling, e.t.c
Kerosene				
Candles				
Charcoal				
Firewood				
Cow dung				
Alternative energy source (specify)				

2.12. Household fuel supply

Fuel source	Where does your household get fuel?	What is the distance of the fuel source from your household?	What difficulties do you face to get this fuel?	How does your household store the fuel?
Kerosene				
Candles				
Charcoal				
Firewood				
Cow dung				
Alternative energy source (specify)				

2.12 What is the type (species) of firewood collected from the forest? As far as possible, please fill out the table below

Species	Weight (kg)	Size/dimension of firewood

3. Household water supply:

3.1 How big is your household's water collecting vessel?

a) 5L ____ b) 10L____ c) 20L____ d) Both b and c____

3.2 How much water does your household need per day?

a) 10L to 15L_______b) 16L to 25L_______ c) 25L_______ d) Others (specify) ____

3.3 How many (minutes/hours) does your household spend collecting water each day?

a) 15 to 30 minutes_______ b) 31 to 59 minutes_______ c) Over minutes_______

3.4 Who is in charge (person) of water collection? _______________

3.5 Where does your household get water?

____

3.6 What is the distance from your household to water source?

____

3.7 What difficulties do you face to get water?

____

3.8 How does your household store the water? _________________________

3.9 How often does your household collect water?

a. Once a day
b. Twice a day
c. Three times a day
d. Others (specify)

3.10 What is the main source of water for your household? (please tick one for each activity)

Source	Drinking water	Water for cooking and washing
Piped water into house		
Piped water to yard/plot		
Public tap/standpipe		
Tube well/borehole		
Protected dug well		
Unprotected dug well		
Protected spring		
Rainwater collection		
Bottled water		
Cart with tank/drum		
Tanker truck		
Surface water (river/lake)		
Other (please specify)		

3.11 Do you use any other water source (apart from the main source identified above) for drinking or cooking? (**Yes/No**) If so, what sources?

____

4. Feedstock:

4.1 How do you deal with animal waste?

____

4.2 Does your family own animals? (Yes/No) If Yes, please complete the following

Species	Number	Are they free to roam around Village?	Are they penned on a tree around the home?	Are they free to roam around your home?
		Yes / No	Yes/No	Yes / No
		Yes / No	Yes/No	Yes / No
		Yes / No	Yes/No	Yes / No
		Yes / No	Yes/No	Yes / No
		Yes / No	Yes/No	Yes / No

4.3 Do your neighbors' animals come onto your land? (Yes/No) If Yes, please complete the following

Species	Number

4.4. Does your household grow crops around the house?

a) Yes b) No

4.5. Does your household graze more animals away from the house?

a) Yes b) No

4.6. Do you give additional feed to your animals?

A) Yes B) No

If Yes, What kind and amount?

…………………………………………………………………………………………………
…………………………………………………………………………………………………
………………………………………………………………………………….

4.7. How much money do you spend per day for buying commercial feeds to your animals?

4.8. Does your household grow crops away from the house?

a) Yes b) No

4.10. What does your household currently do with crop wastes?

a) Compositing b) Mulching c) Animal feed d) burning as fuel
e) Burning as waste f) Dumping

4.11. What does your household currently do with animal wastes?

a) Compositing b) Mulching c) Animal feed d) burning as fuel
e) Burning as waste f) Dumping

5. Community meetings and Finance:

5.1. Have you heard of or seen biogas before? Yes/No

5.2. What information would you like to have before installing a biogas digester?

____

5.3. Do you think men and women from this community would take part in training and installation of biogas digesters and then go on to train others?

____

5.4. What are the biggest problems faced by a) women and b) men that could affect their ability to participate in workshops

____

5.5. Would your farmers' group finance a biogas digester? Yes/No

Appendix B: Temperature and rainfall distribution of Doliyo Village

Months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
T.max(C^0)	23.5	23.7	24.2	24.0	24.6	23.0	20.1	19.8	20.6	22.4	22.9	23.2
T.min(C^0)	3.8	6.9	7.2	8.6	8.2	8.0	9.4	9.6	8.0	4.4	2.3	2.3
T. Av. (C^0)	13.7	15.3	15.7	16.3	16.4	15.5	14.8	14.7	14.3	13.4	12.6	12.8
R.fall	12.4	31.7	67.5	58.2	40.9	95.4	252.6	270.2	182.7	8.9	4.8	37.4

Appendix C: Temperature and rainfall distribution of Kumbursa Village

Months	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
T.max(C^0)	26.5	28.0	28.3	28.3	29.0	27.5	24.5	24.1	25.3	26.4	26.1	25.9
T.min(C^0)	9.3	10.6	13.5	14.5	14.2	13.0	13.6	13.7	12.6	10.1	8.8	8.5
T. Av.(C^0)	17.9	19.3	20.9	21.4	21.6	20.3	19.1	18.9	19.0	18.3	17.5	17.2
R.fall(mm)	7.9	16.3	50.0	53.4	38.2	97.7	205.3	206.0	110.5	23.4	4.8	4.9

Appendix D: Nitrogen and phosphorus content of bioslurry and bioslurry compost on dry weight basis

Bioslurry			Bioslurry compost		
Sample code	N (%)	P (%)	Sample code	N (%)	P (%)
BS1	1.78	0.91	BSC1	1.65	0.75
BS2	1.76	0.94	BSC2	1.63	0.76
BS3	1.79	0.92	BSC3	1.65	0.77
BS4	1.77	0.93	BSC4	1.63	0.76
BS5	1.80	0.91	BSC5	1.64	0.77

Appendix E: Biomass consumption rates by the different stove types based on observations from kitchen performance test

No	Three stone open fire	Mud-stoves	Fuel saving	Three stone open fire	Mirt stove	Fuel saving	Three stone open fire	Mud-stove + Biogas stove	Fuel saving	Three stone open fire	Mirt + Biogas stove	Fuel saving
1	8909	6193	2716	9007	4875	4132	8978	4530	4448	8709	3841	4868
2	8917	6028	2889	8669	4591	4078	8984	4741	4243	8731	4070	4661
3	8723	5892	2831	9055	5127	3928	8761	4566	4195	9121	4414	4707
4	8770	5864	2906	8793	4944	3849	8801	4378	4423	8963	4076	4887
5	8967	6137	2830	8859	4908	3951	8771	4281	4490	8976	4247	4729
6	8668	5887	2781	8927	4850	4077	8929	4659	4270	8746	3974	4772
7	9120	6219	2901	8787	4713	4074	8943	4655	4288	8926	4017	4909
8	8675	5912	2763	8987	5027	3960	8747	4372	4375	9003	4255	4748
9	9071	6182	2889	8953	4905	4048	8945	4475	4470	8841	3989	4852
10	8870	6047	2823	9087	5119	3968	8811	4493	4318	8966	4139	4827
11	8962	6029	2933	9005	5103	3902						

Appendix F: Daily fuel consumption rates for the different cookstoves based on observation using controlled cooking test during second week of May, 2016

	Three stone Open fires			Mud-stoves			Mirt stoves		
Day	1	2	3	1	2	3	1	2	3
Monday	19.5	17.4	17.6	12.1	12.3	12.1	10.3	10.4	10.6
Tuesday	18.8	19	19.6	11.7	11.8	11.8	10.4	10.6	10.6
Wednesday	18.7	17.6	17	12.3	12	12.3	10.2	10.5	10.3
Thursday	19.6	18.5	19.3	11.5	12	12	10.5	10	10.4
Friday	17.7	19.2	17.9	12.3	12.4	12.2	10.5	10.6	10.7
Saturday	19.4	17.1	20.2	12	11.9	12.3	10.3	10.4	10.6
Sunday	20.3	17.2	17.4	11.9	12.4	11.9	10.5	10.5	10.5

Appendix G: Post-treatment results of soil parameters for Doliyo trial plots

Trial rep.	Soil Parameters				Trial rep	Soil Parameters			
	TN (%)	P(ppm)	OC (%)	BD (gcm^3)		TN (%)	P(%)	OC (%)	BD (g cm^{-3})
R1-T1	0.135	12.24	1.48	1.29	R1-T1	0.136	12.25	1.50	1.29
R1-T2	0.134	12.19	1.45	1.31	R1-T2	0.135	12.21	1.43	1.31
R1-T3	0.136	12.25	1.51	1.29	R1-T3	0.137	12.27	1.50	1.28
R1-T4	0.135	12.30	1.53	1.27	R1-T4	0.136	12.29	1.52	1.28
R1-T5	0.135	12.24	1.47	1.30	R1-T5	0.135	12.26	1.48	1.30
R1-T6	0.138	12.27	1.56	1.26	R1-T6	0.139	12.32	1.59	1.26
R1-T7	0.135	12.09	1.42	1.30	R1-T7	0.134	12.15	1.44	1.31
R1-T8	0.133	12.14	1.39	1.31	R1-T8	0.133	12.11	1.42	1.30
R1-T9	0.134	12.15	1.47	1.31	R1-T9	0.132	12.19	1.49	1.28
R1-T10	0.134	12.26	1.48	1.30	R1-T10	0.135	12.25	1.48	1.32
R1-T11	0.134	12.27	1.47	1.30	R1-T11	0.136	12.29	1.51	1.31
R1-T12	0.135	12.26	1.49	1.29	R1-T12	0.138	12.28	1.51	1.29
R1-T13	0.134	12.26	1.50	1.28	R1-T13	0.136	12.26	1.49	1.30
R1-T14	0.135	12.28	1.48	1.27	R1-T14	0.137	12.29	1.53	1.29
R1-T15	0.136	12.31	1.52	1.27	R1-T15	0.137	12.32	1.56	1.29
R1-T16	0.134	12.12	1.43	1.31	R1-T16	0.133	12.14	1.39	1.32
R2-T1	0.136	12.21	1.52	1.30					
R2-T2	0.134	12.25	1.43	1.31					
R2-T3	0.137	12.27	1.54	1.28					
R2-T4	0.136	12.28	1.52	1.29					
R2-T5	0.134	12.21	1.45	1.31					
R2-T6	0.142	12.30	1.54	1.26					
R2-T7	0.134	12.13	1.44	1.30					
R2-T8	0.134	12.16	1.41	1.31					
R2-T9	0.133	12.18	1.44	1.30					
R2-T10	0.134	12.23	1.47	1.30					
R2-T11	0.134	12.29	1.49	1.29					
R2-T12	0.135	12.27	1.51	1.28					
R2-T13	0.134	12.27	1.49	1.30					
R2-T14	0.135	12.31	1.51	1.28					
R2-T15	0.136	12.33	1.55	1.27					
R2-T16	0.132	12.08	1.41	1.34					

Appendix H: Post-treatment results of soil parameters for Kumbursa wheat trial plots

Trial rep.	Soil Parameters				Trial rep	Soil Parameters			
	TN(%)	P(ppm)	OC (%)	BD (gcm^3)		TN (%)	P (ppm)	OC(%)	BD(gcm^3)
R1-T1	0.118	3.83	1.33	1.44	R1-T1	0.119	3.83	1.34	1.43
R1-T2	0.117	3.79	1.32	1.45	R1-T2	0.116	3.80	1.31	1.45
R1-T3	0.118	3.85	1.34	1.43	R1-T3	0.119	3.87	1.34	1.43
R1-T4	0.120	3.86	1.34	1.41	R1-T4	0.121	3.82	1.34	1.42
R1-T5	0.117	3.80	1.33	1.45	R1-T5	0.116	3.88	1.33	1.44
R1-T6	0.120	3.87	1.35	1.40	R1-T6	0.121	3.91	1.35	1.41
R1-T7	0.116	3.89	1.31	1.44	R1-T7	0.116	3.86	1.30	1.44
R1-T8	0.117	3.85	1.30	1.45	R1-T8	0.115	3.84	1.31	1.45
R1-T9	0.116	3.86	1.32	1.45	R1-T9	0.116	3.95	1.32	1.45
R1-T10	0.115	3.84	1.31	1.45	R1-T10	0.117	3.85	1.32	1.45
R1-T11	0.118	3.88	1.32	1.45	R1-T11	0.118	3.90	1.33	1.44
R1-T12	0.117	3.90	1.33	1.44	R1-T12	0.117	3.92	1.33	1.45
R1-T13	0.118	3.87	1.32	1.44	R1-T13	0.116	3.86	1.32	1.44
R1-T14	0.115	3.90	1.33	1.44	R1-T14	0.117	3.92	1.34	1.43
R1-T15	0.116	3.91	1.33	1.43	R1-T15	0.120	3.94	1.34	1.43
R1-T16	0.115	3.80	1.30	1.45	R1-T16	0.115	3.77	1.30	1.44
R2-T1	0.116	3.84	1.33	1.44					
R2-T2	0.115	3.79	1.31	1.46					
R2-T3	0.119	3.84	1.33	1.43					
R2-T4	0.121	3.87	1.32	1.44					
R2-T5	0.116	3.83	1.32	1.45					
R2-T6	0.122	3.89	1.35	1.41					
R2-T7	0.116	3.84	1.31	1.46					
R2-T8	0.117	3.81	1.30	1.45					
R2-T9	0.115	3.87	1.32	1.46					
R2-T10	0.117	3.87	1.32	1.45					
R2-T11	0.116	3.89	1.33	1.44					
R2-T12	0.117	3.92	1.33	1.44					
R2-T13	0.117	3.86	1.32	1.44					
R2-T14	0.119	3.92	1.33	1.45					
R2-T15	0.118	3.93	1.34	1.44					
R2-T16	0.117	3.78	1.31	1.45					

Appendix I: Post-treatment results of soil parameters for Kumbursa teff trial plots

Trial rep.	Soil Parameters				Trial rep	Soil Parameters			
	TN (%)	P(ppm)	OC (%)	BD (gcm^3)		TN (%)	P(%)	OC (%)	BD (g cm^{-3})
R1-T1	0.118	3.78	1.30	1.36	R1-T1	0.119	3.81	1.30	1.37
R1-T2	0.113	3.73	1.27	1.39	R1-T2	0.115	3.77	1.28	1.38
R1-T3	0.121	3.85	1.33	1.36	R1-T3	0.120	3.83	1.31	1.36
R1-T4	0.123	3.87	1.34	1.35	R1-T4	0.122	3.84	1.33	1.36
R1-T5	0.117	3.77	1.29	1.39	R1-T5	0.118	3.79	1.29	1.38
R1-T6	0.125	3.91	1.36	1.33	R1-T6	0.125	3.88	1.34	1.34
R1-T7	0.107	3.72	1.27	1.41	R1-T7	0.110	3.72	1.28	1.41
R1-T8	0.105	3.73	1.24	1.41	R1-T8	0.110	3.77	1.26	1.40
R1-T9	0.111	3.75	1.28	1.42	R1-T9	0.112	3.74	1.27	1.41
R1-T10	0.113	3.74	1.29	1.40	R1-T10	0.114	3.78	1.29	1.39
R1-T11	0.114	3.78	1.31	1.38	R1-T11	0.116	3.79	1.30	1.37
R1-T12	0.117	3.80	1.31	1.38	R1-T12	0.120	3.83	1.30	1.37
R1-T13	0.115	3.76	1.28	1.39	R1-T13	0.115	3.78	1.28	1.38
R1-T14	0.117	3.79	1.30	1.37	R1-T14	0.117	3.81	1.31	1.37
R1-T15	0.119	3.81	1.32	1.36	R1-T15	0.119	3.84	1.33	1.36
R1-T16	0.110	3.72	1.25	1.42	R1-T16	0.109	3.74	1.25	1.41
R2-T1	0.116	3.79	1.31	1.37					
R2-T2	0.115	3.76	1.28	1.40					
R2-T3	0.120	7.84	1.31	1.37					
R2-T4	0.122	3.89	1.32	1.35					
R2-T5	0.116	3.76	1.30	1.37					
R2-T6	0.124	3.89	1.35	1.34					
R2-T7	0.110	3.77	1.25	1.41					
R2-T8	0.106	3.78	1.26	1.40					
R2-T9	0.110	3.76	1.28	1.40					
R2-T10	0.114	3.78	1.28	1.40					
R2-T11	0.115	3.79	1.30	1.37					
R2-T12	0.118	3.81	1.32	1.37					
R2-T13	0.116	3.79	1.29	1.38					
R2-T14	0.116	3.80	1.30	1.38					
R2-T15	0.121	3.83	1.31	1.37					
R2-T16	0.108	3.74	1.26	1.41					

Appendix J: Post-treatment result of different soil parameters for Doliyo wheat trial plots

Code	Soil Parameters							Code	Soil Parameters						
	Ca^{2+}	Mg^{2+} meq/100g	K^{+}	Na^{+}	CEC	%BS	PH		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH
R1-T1	12.50	2.38	.31	.16	31.99	47.98	5.13	R1-T1	12.50	2.38	.31	.17	32.02	47.97	5.12
R1-T2	12.50	2.38	.30	.16	31.98	47.97	5.12	R1-T2	12.51	2.37	.30	.16	31.98	47.97	5.12
R1-T3	12.50	2.38	.31	.17	32.01	47.99	5.13	R1-T3	12.50	2.39	.31	.17	32.00	48.03	5.13
R1-T4	12.51	2.39	.31	.17	32.01	48.05	5.14	R1-T4	12.51	2.39	.31	.17	32.02	48.03	5.12
R1-T5	12.50	2.38	.30	.17	31.98	48.00	5.13	R1-T5	12.50	2.38	.29	.16	32.01	47.89	5.12
R1-T6	12.52	2.39	.32	.17	32.03	48.08	5.14	R1-T6	12.51	2.40	.33	.17	32.04	48.10	5.15
R1-T7	12.50	2.38	.30	.16	31.99	47.95	5.11	R1-T7	12.49	2.37	.30	.16	31.98	47.90	5.10
R1-T8	12.50	2.37	.30	.16	31.99	47.92	5.12	R1-T8	12.48	2.37	.29	.17	31.96	47.90	5.11
R1-T9	12.49	2.37	.29	.16	31.98	47.87	5.11	R1-T9	12.49	2.37	.29	.16	31.96	47.90	5.10
R1-T10	12.50	2.38	.31	.16	32.01	47.95	5.12	R1-T10	12.50	2.37	.31	.16	31.97	47.98	5.11
R1-T11	12.50	2.38	.31	.17	32.00	48.00	5.11	R1-T11	12.51	2.39	.31	.17	32.00	48.03	5.11
R1-T12	12.51	2.38	.31	.17	32.01	48.02	5.13	R1-T12	12.50	2.39	.31	.17	32.01	48.02	5.13
R1-T13	12.50	2.37	.31	.16	31.99	47.95	5.13	R1-T13	12.50	2.38	.30	.16	31.99	47.95	5.12
R1-T14	12.50	2.38	.31	.17	32.02	47.97	5.13	R1-T14	12.50	2.39	.30	.16	32.00	47.97	5.12
R1-T15	12.51	2.39	.32	.17	32.00	48.09	5.13	R1-T15	12.51	2.39	.31	.17	32.03	48.02	5.13
R1-T16	12.49	2.37	.30	.16	31.97	47.92	5.12	R1-T16	12.50	2.37	.29	.16	31.96	47.93	5.12
R2-T1	12.51	2.39	.30	.17	32.01	48.02	5.12								
R2-T2	12.50	2.38	.30	.17	31.97	48.01	5.12								
R2-T3	12.50	2.38	.31	.17	32.02	47.97	5.12								
R2-T4	12.51	2.38	.31	.17	32.00	48.03	5.13								
R2-T5	12.49	2.37	.31	.16	31.98	47.94	5.12								
R2-T6	12.51	2.40	.32	.17	32.05	48.05	5.14								
R2-T7	12.49	2.37	.31	.17	32.00	47.94	5.10								
R2-T8	12.50	2.38	.29	.16	31.98	47.94	5.11								
R2-T9	12.49	2.37	.30	.16	31.98	47.90	5.10								
R2-T10	12.50	2.37	.29	.17	31.98	47.94	5.12								
R2-T11	12.49	2.38	.31	.16	32.01	47.92	5.12								
R2-T12	12.51	2.38	.31	.17	32.02	48.00	5.12								
R2-T13	12.49	2.37	.29	.16	31.98	47.87	5.11								
R2-T14	12.51	2.38	.31	.17	32.01	48.02	5.12								
R2-T15	12.51	2.38	.31	.17	32.01	48.02	5.14								
R2-T16	12.49	2.38	.30	.16	31.99	47.92	5.10								

Appendix K: Post treatment result of different soil parameters for Kumbursa wheat trial plots

Code	Soil Parameters							Code	Soil Parameters						
	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH
R1-T1	12.50	2.39	.32	.17	32.02	48.03	6.91	R1-T1	12.50	2.40	.31	.17	32.02	48.00	6.90
R1-T2	12.49	2.39	.31	.16	31.99	47.98	6.90	R1-T2	12.50	2.39	.30	.17	31.99	48.02	6.89
R1-T3	12.50	2.40	.32	.17	32.02	48.06	6.91	R1-T3	12.50	2.40	.31	.17	32.02	48.03	6.90
R1-T4	12.50	2.40	.31	.17	32.02	48.03	6.91	R1-T4	12.50	2.40	.32	.17	32.02	48.06	6.92
R1-T5	12.49	2.39	.31	.16	32.04	47.91	6.90	R1-T5	12.50	2.38	.31	.16	32.01	47.95	6.88
R1-T6	12.51	2.41	.33	.17	32.05	48.11	6.93	R1-T6	12.51	2.41	.33	.17	32.07	48.08	6.93
R1-T7	12.49	2.38	.30	.17	31.98	47.97	6.88	R1-T7	12.49	2.39	.31	.17	31.98	48.03	6.88
R1-T8	12.49	2.38	.31	.16	31.99	47.95	6.88	R1-T8	12.49	2.39	.29	.17	31.99	47.95	6.90
R1-T9	12.49	2.39	.30	.17	32.00	47.98	6.88	R1-T9	12.48	2.38	.31	.16	31.97	47.95	6.88
R1-T10	12.49	2.38	.31	.16	31.97	47.98	6.88	R1-T10	12.50	2.39	.31	.16	31.98	47.97	6.90
R1-T11	12.49	2.39	.31	.17	32.01	47.99	6.90	R1-T11	12.49	2.39	.32	.17	32.02	48.00	6.91
R1-T12	12.49	2.39	.31	.17	32.01	47.99	6.90	R1-T12	12.49	2.40	.32	.17	32.02	48.03	6.90
R1-T13	12.49	2.39	.30	.16	31.99	47.95	6.90	R1-T13	12.49	2.38	.31	.17	31.98	47.94	6.89
R1-T14	12.50	2.40	.31	.17	32.03	48.02	6.91	R1-T14	12.49	2.39	.32	.17	32.00	48.03	6.91
R1-T15	12.50	2.40	.32	.17	32.02	48.06	6.91	R1-T15	12.50	2.40	.32	.17	32.02	48.06	6.92
R1-T16	12.48	2.39	.30	.16	31.99	47.92	6.88	R1-T16	12.49	2.39	.30	.16	31.98	47.97	6.89
R2-T1	12.48	2.40	.32	.17	32.02	48.00	6.90								
R2-T2	12.49	2.38	.31	.16	31.99	47.95	6.87								
R2-T3	12.50	2.40	.31	.17	32.02	48.03	6.91								
R2-T4	12.51	2.40	.32	.17	32.03	48.08	6.91								
R2-T5	12.49	2.39	.30	.17	31.98	48.00	6.88								
R2-T6	12.51	2.40	.33	.17	32.05	48.08	6.92								
R2-T7	12.50	2.38	.31	.16	32.00	47.97	6.89								
R2-T8	12.50	2.39	.30	.16	31.99	47.98	6.90								
R2-T9	12.48	2.38	.30	.17	31.99	47.92	6.89								
R2-T10	12.49	2.39	.30	.17	32.01	47.95	6.90								
R2-T11	12.50	2.39	.32	.17	32.03	48.02	6.90								
R2-T12	12.50	2.41	.32	.17	32.03	48.08	6.91								
R2-T13	12.50	2.39	.31	.17	32.01	48.02	6.89								
R2-T14	12.50	2.41	.32	.17	32.03	48.08	6.90								
R2-T15	12.50	2.40	.32	.17	32.03	48.05	6.90								
R2-16	12.49	2.38	.31	.17	31.98	48.00	6.88								

Appendix L: Post-treatment results of the different soil parameters for Kumbursa wheat trial plots

Trial rep.	Soil Parameters							Trial rep	Soil Parameters						
	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH
R1-T1	12.53	2.41	0.33	0.17	32.58	48.31	5.28	R1-T1	12.92	2.43	0.32	0.16	32.76	48.32	5.26
R1-T2	12.49	2.35	0.30	0.16	32.14	46.73	5.17	R1-T2	12.38	2.36	0.31	0.15	32.21	47.19	5.18
R1-T3	12.53	2.43	0.34	0.16	33.81	49.10	5.42	R1-T3	13.59	2.47	0.34	0.18	32.94	50.33	5.39
R1-T4	12.57	2.42	0.36	0.17	33.82	49.79	5.53	R1-T4	14.13	2.40	0.37	0.18	33.77	50.58	5.48
R1-T5	12.52	2.38	0.32	0.16	33.27	45.12	5.23	R1-T5	12.28	2.39	0.33	0.16	32.85	46.15	5.19
R1-T6	12.59	2.49	0.39	0.18	34.62	49.97	5.57	R1-T6	14.25	2.51	0.34	0.18	34.75	49.73	5.61
R1-T7	12.43	2.32	0.30	0.17	31.51	46.05	4.92	R1-T7	11.97	2.31	0.30	0.16	31.42	46.91	4.58
R1-T8	12.44	2.33	0.28	0.16	31.47	46.33	4.95	R1-T8	11.68	2.33	0.28	0.16	31.28	46.20	5.03
R1-T9	12.40	2.30	0.30	0.16	31.35	43.48	4.89	R1-T9	11.05	2.31	0.31	0.17	31.35	44.15	4.86
R1-T10	12.49	2.38	0.32	0.17	31.94	46.46	5.08	R1-T10	12.16	2.38	0.32	0.16	31.89	47.10	5.09
R1-T11	12.53	2.40	0.33	0.16	32.07	46.80	5.16	R1-T11	12.37	2.39	0.34	0.17	32.36	47.19	5.12
R1-T12	12.55	2.42	0.35	0.17	32.86	46.50	5.24	R1-T12	12.64	2.45	0.35	0.17	32.84	47.53	5.19
R1-T13	12.51	2.39	0.34	0.17	32.56	46.56	5.14	R1-T13	12.51	2.44	0.33	0.17	33.27	46.44	5.16
R1-T14	12.52	2.44	0.37	0.17	32.91	47.89	5.27	R1-T14	13.23	2.46	0.34	0.17	32.93	49.20	5.29
R1-T15	12.56	2.47	0.37	0.18	32.97	48.89	5.36	R1-T15	13.37	2.49	0.35	0.18	33.15	49.44	5.34
R1-T16	12.43	2.31	0.29	0.16	31.41	46.26	4.91	R1-T16	11.54	2.30	0.27	0.16	31.48	45.33	4.96
R2-T1	13.22	2.41	0.34	0.16	32.74	49.27	5.26								
R2-T2	12.35	2.33	0.30	0.16	32.26	46.93	5.12								
R2-T3	13.43	2.42	0.35	0.18	33.92	48.29	5.38								
R2-T4	13.61	2.44	0.37	0.17	34.12	48.62	5.49								
R2-T5	12.08	2.39	0.32	0.16	32.28	46.31	5.27								
R2-T6	13.86	2.48	0.40	0.18	34.85	48.55	5.61								
R2-T7	11.81	2.28	0.29	0.16	31.37	46.35	4.92								
R2-T8	11.79	2.31	0.28	0.15	31.19	46.58	4.98								
R2-T9	11.02	2.30	0.31	0.17	31.14	44.32	4.85								
R2-T10	12.27	2.38	0.31	0.17	31.73	47.68	5.05								
R2-T11	12.51	2.39	0.34	0.17	32.38	47.59	5.17								
R2-T12	12.68	2.44	0.36	0.18	32.47	48.23	5.21								
R2-T13	12.49	2.37	0.34	0.17	32.34	47.53	5.15								
R2-T14	12.82	2.45	0.35	0.17	32.69	48.30	5.29								
R2-T15	13.13	2.47	0.35	0.18	32.88	49.06	5.32								
R2-16	11.19	2.30	0.29	0.15	31.42	44.33	4.92								

Appendix M: Post-treatment results of the different soil parameters for Kumbursa teff trial plots

Code	Soil Parameters							Code	Soil Parameters						
	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CEC	%BS	PH
R1-T1	12.52	2.39	.33	.17	32.02	48.13	7.01	R1-T1	12.51	2.40	.32	.17	32.03	48.08	6.99
R1-T2	12.52	2.39	.31	.17	32.01	48.08	7.00	R1-T2	12.50	2.39	.31	.16	32.03	47.96	6.99
R1-T3	12.53	2.40	.33	.17	32.03	48.17	7.01	R1-T3	12.52	2.40	.32	.17	32.02	48.13	7.00
R1-T4	12.53	2.40	.34	.18	32.03	48.24	7.01	R1-T4	12.53	2.40	.32	.17	32.03	48.14	7.00
R1-T5	12.51	2.39	.33	.17	32.03	48.08	7.00	R1-T5	12.50	2.38	.30	.16	32.03	47.89	7.00
R1-T6	12.54	2.41	.34	.18	32.05	48.27	7.01	R1-T6	12.53	2.41	.33	.17	32.04	48.20	7.02
R1-T7	12.51	2.38	.31	.17	32.00	48.03	6.98	R1-T7	12.49	2.39	.30	.17	32.01	47.95	6.99
R1-T8	12.51	2.38	.32	.16	32.01	48.02	6.99	R1-T8	12.48	2.39	.30	.17	32.02	47.91	7.00
R1-T9	12.52	2.39	.31	.17	32.01	48.08	6.99	R1-T9	12.49	2.38	.30	.16	32.02	47.89	6.98
R1-T10	12.51	2.38	.32	.17	32.02	48.03	6.99	R1-T10	12.51	2.39	.31	.16	32.01	48.02	6.99
R1-T11	12.51	2.39	.32	.17	32.03	48.05	7.00	R1-T11	12.52	2.39	.32	.17	32.02	48.09	6.99
R1-T12	12.52	2.39	.33	.18	32.03	48.14	7.00	R1-T12	12.51	2.40	.33	.17	32.03	48.11	7.00
R1-T13	12.50	2.39	.31	.16	32.02	47.97	6.99	R1-T13	12.50	2.38	.31	.16	32.00	47.97	6.99
R1-T14	12.52	2.40	.33	.17	32.03	48.14	7.00	R1-T14	12.51	2.39	.32	.17	32.03	48.05	6.99
R1-T15	12.53	2.40	.33	.18	32.03	48.20	7.01	R1-T15	12.52	2.40	.33	.17	32.03	48.14	7.00
R1-T16	12.50	2.39	.31	.17	32.02	48.00	6.99	R1-T16	12.50	2.39	.31	.17	32.01	48.02	6.99
R2-T1	12.51	2.40	.32	.16	32.02	48.06	7.00								
R2-T2	12.50	2.38	.32	.17	32.02	48.00	7.00								
R2-T3	12.52	2.40	.33	.17	32.03	48.14	7.01								
R2-T4	12.52	2.40	.33	.16	32.03	48.11	7.01								
R2-T5	12.50	2.39	.31	.17	32.02	48.00	6.99								
R2-T6	12.53	2.40	.33	.17	32.04	48.16	7.01								
R2-T7	12.52	2.38	.32	.17	32.02	48.06	6.99								
R2-T8	12.51	2.39	.31	.17	32.01	48.05	6.99								
R2-T9	12.48	2.38	.32	.17	32.02	47.94	6.98								
R2-T10	12.49	2.39	.31	.17	32.02	47.97	7.00								
R2-T11	12.51	2.39	.32	.16	32.02	48.03	6.99								
R2-T12	12.52	2.41	.33	.16	32.03	48.14	7.01								
R2-T13	12.51	2.39	.31	.17	32.02	48.03	6.99								
R2-T14	12.52	2.41	.32	.18	32.03	48.17	6.99								
R2-T15	12.52	2.40	.33	.17	32.05	48.11	7.01								
R2-16	12.51	2.39	.32	.18	32.02	48.09	6.99								

Appendix N: Average nutrients and carbon concentrations of crop residues and dung cakes Samples

Sample	Farm wealth group	Average nutrient concentration (%)			Organic carbon
		Nitrogen	Phosphorus	Potassium	
Teff	Rich	1.14 (±0.03)	0.18 (±0.02)	1.04 (±0.05)	55 (±1)
	Medium	1.06 (±0.02)	0.15 (±0.01)	0.85 (±0.04)	52 (±0.9)
	Poor	1.04 (±0.02)	0.13 (±0.01)	0.82 (±0.03)	49 (±0.8)
	Mean	1.08 (±0.02)	0.16 (±0.01)	0.90 (±0.04)	52 (±0.9)
Chickpeas	Rich	1.18 (±0.03)	0.15 (±0.02)	3.16 (±0.1)	57 (±0.7)
	Medium	1.14 (±0.02)	0.14 (±0.02)	2.84 (±0.09)	54 (±0.7)
	Poor	1.07 (±0.01)	0.11 (±0.02)	2.61 (±0.08)	54 (±0.7)
	Mean	1.13 (±0.02)	0.13 (±0.01)	2.87 (±0.08)	55 (±0.6)
Wheat	Rich	1.04 (±0.03)	0.13 (±0.02)	1.16 (±0.02)	52.5 (±0.4)
	Medium	0.96 (±0.03)	0.12 (±0.01)	1.14 (±0.01)	51.4 (±0.4)
	Poor	0.84 (±0.02)	0.09 (±0.01)	1.13 (±0.01)	50.5 (±0.4)
	Mean	0.95 (±0.03)	0.11 (±0.01)	1.15 (±0.01)	51.5 (±0.4)
Dung cakes	Rich	2.5 (±0.1)	0.67 (±0.05)	2.89 (±0.04)	48.4 (±0.4)
	Medium	2.1 (±0.1)	0.58 (±0.03)	2.73 (±0.04)	47.2 (±0.3)
	Poor	1.7 (±0.1)	0.42 (±0.02)	2.64 (±0.03)	46.5 (±0.3)
	Mean	2.1 (±0.1)	0.56 (±0.04)	2.75 (±0.04)	47.4 (±0.4)

Note: standard errors are shown in brackets.

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