Sokoine University of Agriculture

PhD Dissertation

# Agroforestry for Sustainable Bioenergy and Improved Soil Fertility in Two Agro-Ecological Zones, Rwanda

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# AGROFORESTRY FOR SUSTAINABLE BIOENERGY AND IMPROVED SOIL FERTILITY IN TWO AGRO- ECOLOGICAL ZONES, RWANDA

***PhD Dissertation Submitted to Sokoine University of Agriculture in Fulfilment of the Requirement for the Degree of Doctor of Philosophy***

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## EXTENDED ABSTRACT

In Rwanda, the demand for food and energy is high and rising due to population growth. Furthermore, in rural households, the primary energy supply is from fuelwood combusted in inefficient cookstoves, resulting in fuel wastage and health issues associated with smoke in the kitchen. Biochar produced in cooking stoves can contribute to negative carbon emissions through sequestration of biomass Carbon while also providing other benefits for sustainable development, including provision of clean renewable energy and increased yields in tropical agriculture. In addition, B has low nutrient content and is recalcitrant to biodegradation; supplementing B with a fast-releasing nutrient source may contribute to improving soil fertility and physical conditions and lead to increased crop productivity. The reported research aimed to assess the impact of introducing Biochar-producing cooking stoves on household energy access and vegetable production, both on smallholder farms and experimental stations, in two agro-ecological zones (AEZs) of Rwanda. Participatory research on B production and use was conducted with 60 smallholder farmers selected purposively to evaluate the potential of Biochar – producing cooking stoves to address the interconnected challenges of household energy access and low vegetable productivity in Rwanda. The study compared two top-up lift draft (TLUD) gasifier types (Gastov and Karundura) with a three-stone fire (TSF) cookstove, using a standardized cooking test (SCT) and a household survey. Key indicators included cooking time, firewood usage and Biochar yield while the survey collected information

about fuel availability, frequency of use, gasifier design, benefits and challenges. In addition, a three-season field study was done in two AEZs to assess the Biochar effects on vegetable yields after application to soil, where Biochar from gasifier stoves was applied in furrows (2-3 cm deep) in the gardens of French beans (*Phaseolus vulgaris*) at a rate of 3 tons per hectare (t/ha) using randomized paired design. Yield and the soil's physical and chemical properties were analyzed. Concurrently, another, three-season field study (on station trials) was conducted in two AEZs to assess the synergistic effect of five types of Biochar (from *S. sesban, G. sepium*, *A. angustissima, Eucalyptus,* and *Grevillea* sp.) alone or mixed with livestock manure (LM) and applied at 1 and 3 t/ ha using French bean as a test crop. The key indicators were French bean yields, and soil chemical properties of soils. The study utilized descriptive statistics, one-way analysis of variance (ANOVA) using a generalized model in R, linear fixed effect model and the difference between means was examined using Tukey's test at $p<0.05$. The study revealed that the TSF stove cooked a standardized meal faster than the gasifier stove did but the later reduced fuelwood consumption by 25-50% and produced biochar. The household survey responses revealed low firewood availability, but with the ability of firewood, savings when using gasifier stove. Gasifier stoves provided benefits through temperature control, reduced need for constant supervision, Biochar production, and reduced time needed for fuelwood collection, more hygienic and attractive appearance cooking. Most household cooks reported that the gasifier stoves produced less smoke and were safer for children and women's health. The findings from on-farm trials

showed a consistently positive response in French bean yield following a one-time application of B in both sites. The B-treated plots were significantly ($P<0.05$) higher in pH, plant available nutrients (available Phosphorus (P), total Nitrogen (TN) and exchangeable bases), and soil nutrient retention capacity (high cation exchange capacity (CEC)). Soil porosity, plant available water (PAW), were significantly increased by B application while reducing soil bulk density (BD). The B produced by the TLUD gasifiers was perceived as positive as it combines B production and bioenergy, reduces off-farm biomass gathering, improves energy security and produces sufficient B to improve soil productivity in home gardens. For the on-station trials, the seasonal increase in yield has been recorded in combined plots with the high yield found in B-LM, each at the level of 3 t/ha, compared to the sole application of LM or B and the control treatment. The main factors for the increase of the French bean yield in the study areas are improved soil properties, including high pH; high nutrients content (Avail P, TN), soil OC and soil CEC. The application of B, either alone or in combination with LM, positively increased soil nutrients and French bean yield. The improvement became better as the B rate increased and when mixed with LM than sole application of B or LM. Increased vegetable yield enables enhanced nutrition and/or market opportunities and the adoption of the TLUD stoves may contribute to energy sustainability through the reduction of fuel use. The study recommends considering the combination of B with LM as an effective land rehabilitation strategy to improve soil fertility and increase vegetable yield in Rwanda. This technology of using B and LM is a low-cost technology for managing acidic sandy soils of Rwanda. The technology offers significant contributions in terms of improving soil fertility, increasing bioenergy output, mitigating climate change by sequestering atmospheric carbon in the soil and reducing greenhouse gas emissions associated with traditional cooking methods, particularly for women and children, thus improving the overall well-being and socio-economic stability of rural communities.

**Keywords:** TLUD, three-stone fire cookstove, fuel saving, cooking time, *Biochar, soil properties, French bean yield,* smallholder farmer, Rwanda.

## MUHTASARI KUU

Mahitaji ya nishati na chakula yanaongezeka Rwanda kutokana na kuongezeka kwa idadi ya watu. Katika maeneo ya vijijini ambayo ni wazalishaji wa chakula, nishati inayotumika kwa kiasi kikubwa kwa matumizi ya nyumbani ni kuni. Hivyo, majiko ambayo ni banifu kwa ajili ya kupunguza matumizi ya kuni, na ambayo yanatoa mkaa hai kwa ajili ya kurutubisha ardhi ni ya muhimu katika mazingira ya kijijini. Mfano wa majiko haya ni yale yanayobadilisha kuni au mkaa kuwa gesi ambayo inaweza kutumika kwa kupikia nyumbani. Katika utafiti huu, tulitahmini namna majiko haya yanayobadilisha kuni au mkaa kuwa gesi, Gastov na Karundura, yanavyoweza kuokoa kuni na kuzalisha mkaa hai. Pia tuliangalia namna mkaa huu hai unavyoboresha rutuba katika udongo.

Utafiti huu ulifanyika kwenye mashamba ya wakulima wadogo katika kanda mbili za kilimo nchini Rwanda. Utafiti ulikuwa shirikishi kwa kuhusisha wakulima wadogo 60 waliochaguliwa kimakusudi kuzalisha na kutumia mkaa hai uliotokana na majiko ya Gastov na Karundura. Katika utafiti huu, tulilinganisha majiko ya Gastov na Karundura na jiko la mafiga matatu. Vigezo vya ulinganifu vilikuwa muda wa kupika, nishati iliyotumika, na mkaa hai uliozalishwa. Pia, data juu ya upatikanaji wa nishati, utumiaji wa majiko, muundo wa jiko, faida na changamoto katika utumiaji wa majiko zilikusanywa toka kwa kaya. Pamoja na haya, majaribio yalianzishwa shambani na kwenye stesheni kwenye kila kanda ya kilimo kutathmini athari za mkaa hai katika uzalishaji wa mboga mboga kwa misimu mitatu.

Katika kulinganisha majiko, utafiti ulitumia njia ya ANOVA kapata utofauti katika ya majiko. Baada ya hapo utafiti ulitumia kipimo cha Tukey kujua chanzo cha utofauti. Njia hii ya ANOVA ilifanyakia katika programu ya R. Tuligundua kuwa jiko la mafiga matatu lilipika chakula kwa haraka kuliko majiko ya Gastov na Karundura, ingawa majiko ya Gastov na Karundura yalipunguza matumizi ya kuni kwa asilimia 25 mpaka 50, na yalitoa mkaa hai.

Data zilizopatikana toka kwenye kaya zilichakatwa kupata takwimu zinazoelezea hali ilivyo katika jamii. Takwimu hizi zilidhihirisha kuwa upatikanaji wa kuni ulikuwa wa shida. Majiko ya Gastov na

Karundura yalikuwa na faida ya kutotoa joto na moshi mwingi, matumizi banifu ya kuni hivyo kupunguza muda wa kukusanya kuni, kutohitaji usimamizi mkubwa, kutoa mkaa hai, na usalama kwa afya ya watoto na kina mama.

Katika kutathmini athari za mkaa hai katika uzalishaji wa mboga mboga kwa misimu mitatu katika kanda mbili za kilimo, majiribio ya shambani (on-farm trials) yalianzishwa katika kila kanda kwa kutumia muundo wa "randomized pair". Katika muundo huu, mkaa hai uliwekwa kwenye mitaro yenye kina cha sentimeta 2 mpaka 3, kwa kiwango cha tani 3 kwa hekta katika mashamba ya maharagwe (*Phaseolus vulgaris*). Data za tabia ya udongo pamoja na mavuno yaliyopatikana yalichakatwa. Sambamba na majaribio ya shambani, majaribio ya stesheni (on station trials) yalianzishwa pia kutathmini athari ya kutumia mkaa hai toka spishi za *S. sesban, G. sepium*, *A. angustissima, Eucalyptus,* and *Grevillea* sp. pekee na zinapochanganywa na mbolea ya samadi katika uzalishaji wa maharagwe.

Matokeo kutokana na majaribio ya shambani yalionyesha kuongezeka kwa uzalishaji wa maharagwe baada ya kutumia mara moja mkaa hai katika kanda zote mbili za kilimo. Ploti zilizorutubishwa na mkaa hai zilikuwa na kiwango cha juu cha pH, cha virutubisho vya Fosforasi (P), Naitrojeni (N) na besi; na uwezo mkuwa wa kuhifadhi virutubisho hivyo

Hali ya udongo ya kupitisha hewa, na uhifadhi wa maji yanayopatikana kwa mimea (PAW), yaliongezeka kwa kiasi kikubwa kufuatia uwekaji wa mkaa hai. Matumizi ya Gastov na Karundura yalionekana chanya kwa sababu yalipunguza matumizi ya kuni shambani, na yalizalisha mkaa hai ambao ulitumika kurutubisha udongo.

Kwa majaribio ya stesheni, mavuno yaliongezeka katika ploti zilizorutubishwa na mkaa hai pamoja na mbolea ya samadi kulinganisha na ploti zilizorutubishwa kwa mkaa hai pekee au mbolea ya samadi pekee, na ploti ambazo hazikurutubishwa. Sababu za kuongezeka kwa mavuno kulitokana na kuongezeka kwa viwango vya pH na virutubisho kama ilivyonekana kwenye majaribio ya shambani.

Mbinu hii ya kutumia majiko banifu yanayozalisha mkaa hai itapunguza hitaji la chokaa na mbolea za viwandani kwa ajili kuboresha hali ya udongo na kuongeza mavuno. Kuongezeka kwa mavuno ya mboga mboga kutaimarisha lishe na kuongeza kipato kitakachotokana na mauzo ya mboga mboga. Pia, matumizi ya majiko haya, Gastov na Karundura, kutachangia kwenye uendelevu wa nishati ya kuni kwa sababu ya upunguaji wa matumizi ya nishati hii. Utafiti unapendekeza kuzingatia mchanganyiko wa mkaa endelevu na mbolea ya samadi kama mkakati madhubuti wa kuboresha rutuba ya udongo na kuongeza mavuno ya mboga mboga nchini Rwanda. Teknolojia hii ya kutumia mkaa hai na mbolea ya samadi ni rahisi katika kukabiliana ardhi ya Rwanda yenye kiwango cha juu cha tindikali.
Maneno muhimu: *TLUD, Jiko la mawe matatu, kuokoa nishati, Muda wa kupikia, Hali ya udongo, Mavuno ya maharagwe ya Kifaransa mkulima mdogo, Rwanda*.

**Maneno muhimu**: *TLUD, Jiko la mafiga matatu, uokoaji nishati, Muda wa kupikia, Tabia ya udongo, Mavuno ya maharagwe ya aina na French, mkulima mdogo, Rwanda*

## DECLARATION

I, **Solange Uwingabire**, do hereby declare to the Senate of Sokoine University of Agriculture that this PhD Dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

Solange Uwingabire Date
(PhD Forest Sciences Candidate)

The above declaration is confirmed by:

Prof. Shabani A. Chamshama Date
(Main Supervisor)

Prof. Gert Nyberg Date
(Co-Supervisor)

Prof. Jean Nduwamungu Date
(Co-Supervisor)

## LIST OF MANUSCRIPTS

***Paper I***: **S. Uwingabire,** S. A. O. Chamshama, G. Nyberg & J. Nduwamungu. Gasifier cookstove use and biochar production in smallholder farmers in Rwanda.

**Status: Published in Biofuels, 1-8.**
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***Manuscript 2***: **S. Uwingabire,** S. A. O. Chamshama, G. Nyberg & J. Nduwamungu. Farmer-managed French bean biochar trials in Rwanda: Effects on yield and soil nutrients.

**Status:** Published in Rwanda Journal of Agricultural sciences 2024, 106-122.
https://www.ajol.info/index.php/rjeas/article/view/279087

***Paper 3****: French bean production as influenced by* Biochar and Biochar blended manure application in two agro-ecological zones of Rwanda.

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## COPYRIGHTS

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# DEDICATION

First and foremost, to my adoptive parents for their unfailing support throughout my life. To my family and friends for having my back throughout this study. To each of you from whom I have obtained academic and professional experience, I dedicate this work.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AEZs | Agro-Ecological Zones |
| AF | Agroforestry |
| ANOVA | Analysis of Variance |
| ASTM | American Society for Testing and Materials |
| BD | Bulk Density |
| B-LM | Biochar mixed with Livestock manure |
| CEC | Cation Exchange Capacity (Cmol$_{+}$/kg) |
| ENEDOM | Energy Domestique sarl |
| *et al* | and others |
| FC | Field Capacity |
| Fig | Figure |
| Ha | Hectare |
| HSD | Honest Significance Differences |
| ICT | Information and Communication Technology |
| IEA | International Energy Agency |
| K | Hydraulic Conductivity |
| LM | Livestock Manure |
| LPG | Liquid Petroleum Gas |
| NSS | National Soil Service |
| PAW | Plant Available Water |
| pH | Soil acidity or alkaline |
| PWP | Permanent Wilting Point |
| REFOREST | Regional Research School in Forest Sciences |
| REG | Rwanda Energy Group |
| SCT | Standardized Cooking Tests |
| SSA | Sub-Saharan Africa |
| SWCC | Soil Water Characteristic Curves |
| TLUD | Top-lit Updraft draft |
| TN | Total Nitrogen |
| TSF | Three-Stone Fire |
| & | and |
| > | Greater than |
| °C | Degree Celsius |

# CHAPTER ONE

## 1.0 General Introduction

This chapter explores the critical challenges of rising population pressure, land degradation, and energy demands in Rwanda, with a focus on sustainable solutions. It examines the environmental impacts of over-cultivation, deforestation, and unsustainable land use practices, particularly in the context of declining soil fertility and wood fuel scarcity. The chapter highlights the potential of integrated approaches, such as biochar and agroforestry systems, to enhance both soil productivity and bioenergy generation. Additionally, it reviews the benefits of innovative technologies like gasifier cookstoves for addressing energy shortages while improving environmental and agricultural outcomes.

## 1.1 Background

The world's population is increasing rapidly and is predicted to surpass 9 billion people by 2050, with Africa, particularly Sub-Saharan Africa (SSA), expected to provide the majority of the increase, leading into considerable increase in energy and food demand (Desai, 2018; IEA, 2021). This has led to high forest degradation and soil fertility deterioration due to over-cultivation without effective nutrient management (Leblois *et al*., 2017). In SSA, bioenergy accounts for over 60% of total energy (Jianguo *et al*., 2021). Additionally, soil fertility degradation is one of the major causes of high yield gaps and nutrient deficiencies in East African highlands, including Rwanda (Uwiragiye *et al*., 2022; Mulualem *et al.,* 2021).

Land degradation is a common environmental problem facing Rwanda, largely driven by the rising population density, which currently stands at 535.11 people per km$^2$and an annual population increase of 2.28% in 2023) (Worldometer, 2023). This degradation is characterized by soil erosion and declining soil fertility

(Mukurarinda *et al.,* 2016; Kabirigi *et al*., 2017). The main drivers are unsustainable land use practices such as deforestation, over cultivation (two seasons per year) on steep slopes (>60%) without adequate soil conservation measures and overgrazing. Soil infertility is aggravated by soil nutrient depletion, soil acidity, organic matter depletion, and low CEC of soils (Nduwumuremyi *et al*., 2017). In Rwanda, nutrient depletion ranged from 14 to 35 kg N /ha/year, 1 to 3 kg P /ha/year, and 1 to 27 kg K /ha/yr in selected AEZs using only soil nutrient inputs from fertilizers and nutrient outputs from crop products (Bucagu *et al*., 2014 and Kabirigi *et al*., 2017; Uwiragiye *et al*., 2022). It is estimated that acid soils comprise two-thirds of the cultivated soils of Rwanda and about half of these soils have low pH (Musahara and Herman, 2001; Kabirigi *et al*., 2017). These soils related problems have challenged the crop/vegetable production such as French bean (*Phaseolus vulgaris L.*) in which this study is focusing on (MINAGRI annual report, 2021).

In Rwanda, about 90% of rural households use woodfuel (charcoal and firewood) for cooking (Hakizimana *et al*., 2020). This leads to large gap between supply and demand as the population continues to increase due to overexploitation and degradation of trees/shrub resources (forest and crop/agroforestry (AF) shrubs) with consecutive exposure of soils to erosion (Nahayo *et al*., 2013; Hakizimana *et al*., 2020). Moreover, energy conversions are carried out in traditional TSF that escalate the demand for firewood and results in poor health among users due to excessive products of incomplete combustion and smoke emissions in poorly ventilated houses common in rural area that harm people's health especially women and children (Hakizimana *et al*., 2020; Champion and Grieshop, 2019; Jetter *et al.,* 2012). Wood scarcity costs women and children time and body energy and can cause serious long-term physical damage without sufficient time to recover (Champion and Grieshop, 2019).

Regarding the problems of wood scarcity and soil fertility, an integrated approach focusing on high-quality land management, is needed to improve agricultural productivity and wood supply while minimizing environmental degradation. The integrated approach through biochar (B) use and on farm wood supply that increases the efficiency of energy generation (sustainable bioenergy) and agricultural inputs can be a good opportunity. This approach focuses on-farm tree planting and Top-lit Updraft draft (TLUD)/gasifier cookstoves as strategies to mitigate woodfuel scarcity. Gasifier cookstove is a cooking appliance that produces heat through the gasification of dry solid biomass at temperatures between $700^0$C and $1000^0$C (Anderson and Schoner, 2016). It also produces charcoal as a by-product. The charcoal can be used as a fuel or as a soil amendment (B) for improving soil productivity and sequestering Carbon (Sundberg *et al*., 2020).

Livestock manure (LM) is a black, fine particulate matter obtained from organic material consisting primarily of more or less homogenous mix of animal faeces and urine and bedding material (Rayne and Aula, 2020; Sutton *et al.,*2022). LM has a large specific surface area, high drainage, high-water-holding capacity, and good aeration, which increases the number and activity of microorganisms in the soil, easily forming granular structures, reducing the soil BD, and increasing the TP (Wang *et al*., 2021).This effect is for short period of time as this decompose rapidly in the soils, specifically sandy textured soils.

Gasifier cookstoves have been reported to be cleaner and more efficient options when utilizing solid biomass fuel for cooking, compared with open-air combustion of fuelwood (Njenga *et al*., 2017). In Kenya for example, a gasifier cookstove was shown to save up to 41% of fuel by galvanized gasifier cookstove (Njenga *et al.,* 2016). In addition, Duguma *et al*. (2014) have reported 20-56% reduction for firewood in Ethiopia. In Kenya, another study carried out in a rural area showed that the use of a rocket mud stove reduced fuel consumption by 34%, compared with the traditional

TSF (Ochieng *et al.,* 2013). In Khairatpur village in rural India, an improved cook stove was found to reduce the annual consumption of fuel by 41% compared with the traditional cook stove (Singh *et al.,* 2015). On the other hand, cooking with gasifier produces B. B is a Carbon-rich material produced by the thermal decomposition of organic matter in low-Oxygen settings (Zemanova *et al.,* 2017). Many studies have proved the role of B in improving soil fertility, including raising soil pH (Mandal *et al*., 2019), increasing water holding capacity and thus reducing irrigation demand, enhancing root penetration, and changing microbial reactions in soil (Wang *et al.,* 2020). It improves soil physical properties, soil sorption capacity, and thereby increasing crop production (Meena and Prakasha, 2020).

**1.2 Problem Statement and Justification**

The major soil constraints in Central plateau and Eastern Savanna AEZs of Rwanda include nutrient depletion in combination with low permanent charge (0.5 to 2.45 cmol (+)/kg), soil acidity (pH below 5.5), Aluminum (Al) toxicity, and soil organic matter (SOM) depletion (Nabahungu, 2015; Nduwumuremyi *et al.,* 2017). Concurrently, increasing population, along with inadequate land use management practices, and premature cutting, has resulted in a significant wood scarcity problem. The shortage was anticipated to be 4.3 million tons (oven dry weight) in 2017, with a forecast of 7.5 million tons by 2026 (Ministry of Land and Forestry, 2017).

To alleviate the fertility problem and boost crop yields, significant measures have been proposed, including liming acidic soils, increasing the use of inorganic or organic fertilizers, and promoting AF (Nduwumuremyi *et al.,* 2017). On the other hand, inorganic fertilizers are problematic due to their high cost and negative environmental effects (Nduwumuremyi *et al.,* 2017). For manure, despite its high nutrient content, it cannot be entirely absorbed once it is applied to soils, resulting in nutrient leaching and rapid nutrient release. Manure also needs to be applied annually because of microbial decomposition processes (Ndambi *et al.,* 2019). The government of Rwanda has proposed that the wood deficit problem be remedied by more efficient alternative methods (biogas, pellets, briquettes, and liquid petroleum gas (LPG)), as well as the building of modern kilns for charcoal manufacturing and improved cookstoves (Ministry of Land and Forestry, 2017). Not enough effort has been made and an increasing gap in woodfuels scarcity problem has been reported (Hakizimana *et al*., 2020).

As a result, there is a need at the global and local levels to protect the environment without compromising sustainable agriculture. As government of Rwanda is currently promoting the use of AF to provide potential restoration solution to land degradation, the use of biomass cookstoves known as TLUD or gasifiers can be key. The Top-lit updrafts (TLUD) that pyrolyze biomass to generate heat for cooking and B for soil improvement could be a promising alternative to enhance fuel efficiency while reducing the demand on existing biomass supplies (Jeffery *et al*., 2017). This integrated system can provide affordable, reliable, sustainable and modern energy for rural communities in rural areas while contributing to the achievement of other SDGs.

Biochar has a porous nature and high surface area that increases soil water retention and nutrient holding capacity, potentially reducing the need for inorganic fertilizers and irrigation (Razzaghi *et al*., 2020). While Biochar has been shown to have a positive conditioning effect on soil, it is limited as a nutrient supplier alone, due to its relatively low nutrient content and its recalcitrance to biodegradation (Partey *et al*., 2014). When combined with organic manure, Biochar could potentially enhance nutrient availability to plants through its intermediate nutrient holding capacity and through improving soil physical and biological properties. Recent studies have demonstrated that bulking livestock manure (LM) with Biochar reduces nitrogen loss through leaching while simultaneously improving humification and producing manure with a high fertilizer value (Adekiya *et al*., 2019), thus increasing the yield of crops. Adekiya *et al.* (2019) reported that B alone due to its recalcitrant nature was unable to positively increase the yield of radish in the first year of application. Wisnubroto *et al*. (2017) reported that the highest yield of red chili (*Capsicum annum* L.) was obtained from plots with B and manure. In Nigeria, the results revealed that B+ poultry manure and B+inorganic fertilizer (NPK) improved soil physical and chemical properties, growth, and ginger yield compared to their sole forms (Adekiya *et al*., 2020). However, B technology using gasifier stoves has been given less attention in Rwanda and less studied considering local social technical aspects or in a way that is relevant to small-scale farmers. Despite the potential advantages of B-LM amendments, there is a lack of a comprehensive understanding of their effectiveness in the tropical soil context, particularly regarding their effect on soil properties (chemical and hydro-physical properties) and vegetable yield in Rwanda.

In the present study, the results of a research project designed to assess the effect on household cooking energy, soil quality and vegetable yield in kitchen gardens of smallholder farmers from the introduction of TLUD stoves in two AEZs of Rwanda (on- farms) are reported. Moreover, the synergistic effect of B when mixed with LM on soil properties and on French bean yield were studied (On-station).

## 1.3 Research Objectives

### 1.3.1 General objective

The overall objective of this research is to evaluate energy efficiency of cookstoves, production of B and effects of B and LM on soil fertility and vegetable production.

### 1.3.2 Specific objectives

i. To estimate the effects on household cooking energy access and farmers user perception from introduction of B-producing cookstoves on smallholder farms in Rwanda.
ii. To assess the effect of Biochar from agroforestry specie on French bean yield and soil nutrients (on- farm trials)

iii. To assess the synergistic effect of B blended with LM on chemical properties and vegetable production in Central plateau and Eastern savanna AEZs of Rwanda.

### 1.3.3 Hypotheses

The study will test the following hypotheses:

a) B from cookstove increases the household cooking energy access and is appreciated by most of the household farmers.
b) B from gasifier stove increases French bean yield, plant available nutrients, amount of plant-available water, CEC, and pH and these effects should sustain over several growing seasons.
c) The combined application of B and LM induces a synergistic and persistent effect on soil health and French bean yield.

# CHAPTER TWO

## PAPER I

## 2.0 Gasifier Use for Cooking and Biochar Production by Smallholder Farmers in Rwanda[1]

[1] The material contained in this chapter has been published in **Biofuels 2024, 1-8;** https://doi.org/10.1080/17597269.2024.2381164

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# Gasifier use for cooking and biochar production by smallholder farmers in Rwanda

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# Gasifier use for cooking and biochar production by smallholder farmers in Rwanda

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**ABSTRACT**

Rwanda's rural households primarily use biomass fuel, leading to fuel waste and air quality related issues. The study compared two-top-up lift draft (TLUD) gasifier types (Gastov and Karundura) with a three-stone fire (TSF) cookstove in Bugesera and Huye Districts, Rwanda, using standardized cooking tests (SCT) and a qualitative survey. Key indicators included cooking time, fuel usage and biochar yield while the survey collected information about fuel availability, frequency of use, gasifier design, benefits and challenges. The study utilised descriptive statistics and ANOVA for analysis. The study revealed that the TSF cooked a standardised meal faster than the gasifier did, but the gasifiers reduced fuelwood consumption by 25–50% and produced biochar. The survey responses revealed low fuelwood availability, with fuel savings, temperature control, reduced need for constant supervision, biochar production, and reduced time needed to gather fuelwood, more hygienic and attractive appearance cooking have been revealed. Most household cooks reported that the gasifier stoves produced less smoke and were safer for women and children's health. The biochar produced by the TLUD gasifiers was perceived as positive as it combines biochar production and bioenergy, reduces off-farm biomass gathering, improves energy security and produces sufficient biochar to improve soil productivity.

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TLUD; three-stone fire cookstove; fuel saving; cooking time; smallholder farmer; Rwanda

## Background

Globally, 2.4 billion people depend on wood and other solid fuels for cooking and heating. Bioenergy accounts for >60% of total energy use in Sub-Saharan Africa [1]. In Rwanda, biomass represents 85% of final energy consumption, with rural households being responsible for 91% of energy consumption [2]. Population growth in Rwanda is leading to wood scarcity and unsustainable harvesting of wood biomass, hindering forest regeneration [3, 4]. Moreover, biomass is combusted in traditional TSF cookstoves with a high demand for firewood that produce high emissions, which affect air quality, particularly for women and children [5]. Lack of wood causes women and children to spend more time and energy collecting fuel, which can lead to long-term physical damage if they do not have sufficient time to recover [5].

The government of Rwanda believes that the current wood scarcity problem could be overcome through the introduction of more efficient fuel combustion methods (biogas, pellets, briquettes, liquid petroleum gas, modern kilns for charcoal production and improved cookstoves [6]. However, despite efforts by government to address the problem of wood scarcity, the gap between demand and supply of wood fuels in Rwanda is reported to be increasing [4]. A potential solution is to introduce affordable biomass cookstoves, known as TLUD gasifiers, which were first developed by Anderson and Reed (2004) [7]. Gasifiers produce energy through the process of gasification of dry biomass at the temperature ranging between 700 and 1000 °C while at the same time produce biochar as by–product [8]. Biochar can be used as a fuel (charcoal) or as a soil amendment (biochar) for improving soil productivity and sequestering Carbon [9].

A TLUD gasifier is a cleaner and more efficient biomass-based cookstove than open-air combustion of fuelwood in traditional TSF [9]. The higher efficiency means that the gasifier reduces fuel use compared with TSF, with studies in *e.g.* Kenya and Ethiopia; Njenga et al. [10] reported fuel savings of up to 41% and 56% of fuel, respectively. In a similar study by Singh et al. [11] in rural India, they reported reduced annual fuel consumption by 41% when using gasifiers compared with traditional TSF cookstoves. The present study aimed to compare TLUD gasifier and traditional TSF cookstoves in terms of fuel use and time required for cooking under realistic household conditions in Rwanda. An additional aim was to investigate biochar yield and perceptions of the TLUD gasifier among rural householders in Huye and Bugesera Districts, Rwanda.

## Material and methods

### *Study areas*

The study was conducted among smallholder farmers in Tumba Sector, in Huye District and Rusagara Village, Nyamata Sector, in Bugesera District. Huye District is characterized by a sub-equatorial temperate climate, with mean

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annual temperature of approximately 20 °C and a mean annual rainfall of 1160 mm. Bugesera District is regarded as a drought-prone region that experiences frequent rainfall deficits, a significant number of dry spells and mean annual rainfall of 943 mm. The maximum temperature in Bugesera District is 26–29 °C and the minimum is 13–15 °C (ICT-Environment Linkage 2007).

### *Sampling design and data collection*

Purposive sampling design was used to select voluntary thirty households in each district, following the criteria that the households were rural smallholders, available for the study and willing to test the new technology (*i.e.* TLUD gasifiers). The selected farmers were provided with a TLUD stove free of charge, with 15 households in each district receiving a Karundura gasifier and the other 15 households a Gastov gasifier. This sample size was dictated by expected high variation as well as by the available number of gasifier cookstoves. The participating farmers got trainings on fuel preparation, fuel arrangement in the canister, lighting the gasifier, using it for cooking, and harvesting and cooling the charcoal produced, using a standard manual provided with the stove. Follow-up visits were made every three weeks by trained male or female field assistants to support its use or address the challenges that may arise. In addition, they were asked to save biochar after cooking for upcoming field trials with French beans (*Phaseolus vulgaris*). Trained males who were not stove users were urged to transfer the skills to female household members responsible for cooking. In Bugesera district, the cooking biomass used were wood of *Senna spectabilis* in gasifiers and TS.In Huye, wood of Eucalyptus together with maize cobs were used in gasifier and TSF (Table 1). The main target here is to assess the wood saving performance of gasifier stoves compared to TSF.These are the common species in both districts, where they provide shade, assist in soil conservation and meet local demand for domestic firewood and timber.

### *TLUD gasifier and traditional TSF stove*

Two TLUD gasifier models (one brand name Karundura) from the ENEDOM Company in Rwanda (Figure 1a) and one (brand name Gastov) from the Kenya Industrial and Research Development Institute (Figure 1b) were used in this study. Their performance was compared with that of a traditional TSF cookstove (Figure 2).

### *Quantification of biochar from TLUD cookstoves*

#### *Cooking test and type of meal*

SCT were conducted in rural kitchen settings to compare the wood-saving performance of the two TLUD gasifiers with that of the traditional TSF cookstove and to quantify biochar production by the gasifiers. Three SCTs were performed in each household, giving 30 sets of tests in each study district. The kitchen settings are common and traditional in the area, but with considerable room for variation between households. Hence, the relative large number of

**Table 1.** Biomass used and its associated properties.

| Biomass used | Moisture content % | Volatile matter % | Ash content% | Fixed Carbon % |
|---|---|---|---|---|
| *Eucalyptus sp* | 9.87 | 28.5 | 0.7 | 60.93 |
| Maize cobs | 9.85 | 76 | 3.2 | 10.95 |
| *Senna spectabilis* | 8.5 | 6.5 | 5.5 | 86.5 |

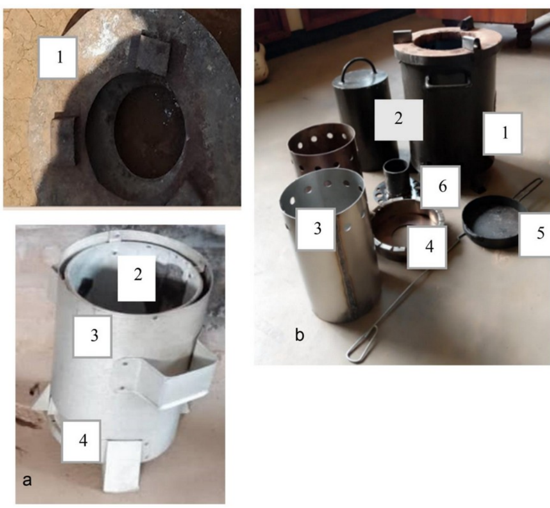


**Figure 1.** **(a)** Karundura gasifier, (a1 = top plate, a2 = inner canister, a3 = outer cylinder, a4 = ash collector). Stove parts (a2, a3 and a4) are connected together. **(b)** Gastov gasifier (b1 = outer cylinder, b2 = extinguisher, b3 = inner fuel canister 4 = top plate, b5 = ash collector, b6 = pellet bed). It has higher heat concentration, lower fuel consumption and produces less smoke than the TSF.

Figure 2. Traditional three-stone fire cookstove. It is exposed from all its sides to the surrounding environment, hence lower heat concentration and high amount of smoke.

households included. The type of food cooked in SCT was a traditional meal for five people consisting of five components (2 kg cassava, 450 g amaranth, 400 g tomatoes, 33 g onions, 150 g groundnuts), which were mixed and cooked in one pot. Food preparation involved washing, peeling and chopping the cassava, amaranth, tomatoes, and onions into small pieces before adding them to the pot. The meal was cooked for dinner (16.00–18.00 h) in each household. Before each test, available fuel to be used in the stove was weighed and biomass for use in the gasifier was cut into 20 cm pieces. The gasifier was lit outdoors, using small pieces of biomass, as it is portable and has a canister that holds the fuel in place (see Figure 1a,b), while the TSF stove was lit inside the house following common practice. In SCT, the households used various forms of biomass normally used in their daily life. Female members of the household, in the presence of the research assistants, carried out the cooking experiment. The remaining charcoal/biochar was harvested after the flame had been quenched using the extinguisher on the gasifier (see Figure 1b). In all SCT, the quantity of fuel used, the quantity of biochar produced, and the time taken to cook the meal was measured. Standard cooking instructions were provided (*e.g.* covering the pot during cooking, keeping doors and windows open during all cooking tests) to reduce operator bias [12]. The moisture content (%-wet basis) of each type of biomass fuel used in SCT was determined using a standardized oven-drying method [13].

### *Biochar yield*

Percentage biochar yield was calculated according to Sadaka et al. (2014) [14]

$$m_{biochar}/m_{raw} \times 100, \quad (1)$$

Where $m_{biochar}$ is the total quantity of biochar obtained
$m_{raw}$ is the total quantity of raw biomass used

### *User perceptions of the gasifier cooking technique in the study areas*

A Likert scale questionnaire with close-ended questions was used to collect data on household demographics, fuel availability, use frequency (weekly basis) of the gasifier stove, daily use frequency (three times per day), gasifier design, and perceived benefits and challenges with the gasifier cooking technique.

### *Statistical analysis*

The data were subjected to analysis of variance (ANOVA) to check for significant differences in mean fuel use, time taken to cook the food and biochar yield and Tukey test at 5% probability to find means that are significantly different from each other. This statistical analysis was performed with R Studio [15]. For the user perception survey, the questionnaire responses were crosschecked for completeness and the data were entered into Microsoft Excel. Descriptive statistics on the data were then calculated using SPSS software. The significance level was set at $p < 0.05$.

## Results

### *Quantification of biochar production by TLUD gasifiers*

#### *Burning time (stove lighting and cooking time)*

The results of SCT conducted on the TLUD gasifiers (Karundura and Gastov) in rural households in Bugesera District and Huye District are presented in Table 2. The ANOVA results indicated that TLUD gasifiers had a longer burning time (stove lighting plus cooking time) than the TSF cookstove, while the difference between Karundura and Gastov models was not statistically significant.

#### *Fuel use*

The ANOVA results revealed that the gasifiers used significantly ($p < 0.05$) less fuel than the traditional TSF cookstove. A post hoc test showed that the Karundura model consumed 75% and 71% of the fuel consumed by the TSF in Huye and Bugesera Districts, respectively, while the Gastov model consumed 48-61%. However, lighting and total cooking time were significantly shorter with the TSF stove than with the gasifier cookstoves (Table 2).

#### *Biochar yield*

There was a notable difference in biochar yield between the Karundura and Gastov gasifiers in both districts, with the Karundura model consistently producing a greater amount of biochar. The Karundura gasifier also gave a higher biochar yield in Bugesera District compared with Huye District (Table 3).

### *User perceptions of the TLUD gasifier*

#### *Demographic characteristics*

Household size was similar in both districts (mean 5 members, range 1–12). Women represented 63.3% of respondents, as the survey focused on women due to their greater

**Table 2.** Burning time and amount of fuel consumed by the two types of top-up lift draft (TLUD) gasifier (Gastov, Karundura) and the three-stone fire (TSF) cookstove in standardized cooking tests (SCT) in rural households in Bugesera District and Huye District, Rwanda.

| | Stove lighting (min) | | Cooking meal (min) | | Specific fuel consumption (g) | | % wood fuel consumed | |
|---|---|---|---|---|---|---|---|---|
| Stove type | Bugesera | Huye | Bugesera | Huye | Bugesera | Huye | Bugesera | Huye |
| Gastov | $3.9 \pm 0.2^{b}$ | $2.1 \pm 0.2^{b}$ | $41.8 \pm 0.1^{b}$ | $41.6^{a} \pm 0.19^{b}$ | $880.9 \pm 84.5^{c}$ | $875.8 \pm 62^{c}$ | 61 | 48 |
| Karundura | $4.9 \pm 0.2^{a}$ | $3.9 \pm 0.05^{a}$ | $40.9 \pm 0.01^{a}$ | $41.2^{a} \pm 0.44^{b}$ | $981.8 \pm 26^{b}$ | $1327.2 \pm 16.4^{b}$ | 71 | 75 |
| TSF (Control) | $1.8 \pm 0.02^{c}$ | $1.8 \pm 0.05^{c}$ | $35.5 \pm 0.01^{c}$ | $36.4^{b} \pm 0.16^{a}$ | $1453.1 \pm 105.7^{a}$ | $1755.1 \pm 8.6^{a}$ | 100 | 100 |
| SE | 0.1 | 0.42 | 0.7 | 1.14 | 25.4 | 146.6 | | |
| Tukey's HSD | 0.08 | 0.38 | 0.6 | 1.01 | 22.5 | 130.07 | | |

SE: standard error; Tukey's HSD: turkey's honestly significant difference. Means within columns with different superscript letters are significantly different ($p < 0.05$, HSD test). Small letters (a, b and c) are used to compare means significantly within treatments.

**Table 3.** Biochar yield of the two types of top-up lift draft (TLUD) gasifier (Gastov, Karundura) in standardized cooking tests (SCT) in rural households in Bugesera District and Huye District, Rwanda.

| | Amount of biochar produced (g) | | Biochar yield (%) | |
|---|---|---|---|---|
| Model | Bugesera | Huye | Bugesera | Huye |
| Gastov | $202.9^{b} \pm 6.8$ | $196.9^{b} \pm 6.4$ | $24.3^{b} \pm 1.01$ | $23.4^{b} \pm 0.8$ |
| Karundura | $298.5^{a} \pm 2.8$ | $260.5^{a} \pm 5.6$ | $30.2^{a} + 0.7$ | $26.2^{a} \pm 1.1$ |
| SE | 8.7 | 12.4 | 13.3 | 23.4 |
| Tukey's HSD | 14.6 | 16.8 | 2.4 | 2.8 |

SE = Standard error; Tukey's HSD = turkey's honestly significant difference. Means within columns with different superscript letters are significantly different $p < 0.05$, HSD test).

involvement in kitchen tasks. Around one-third of the respondents (38.3%) were above 50 years old, while 31.7% were in the age range 30–40 years. Approximately 51.7% had primary education, 30% had secondary education and 18.3% had no formal education.

### *Fuel availability and cost savings with the gasifier*

The survey responses indicated that low firewood availability was a constraint for all respondents. Most respondents agreed that using a gasifier for cooking could save costs when biomass is not freely available (Table 4).

### *Daily use frequency of the gasifier and weekly use frequency*

The surveyed households were asked how frequently they used the TLUD gasifier provided. The results showed that only one-third used their gasifier three times per day (for breakfast, lunch and dinner). Around half of the participants stated that they used the TLUD stove often in a week (Table 4).

### *Characteristics of the TLUD gasifiers and TSF cookstove*

Respondents in the study districts were also asked questions related to stove design, which might affect their perceptions. Both types of gasifier reduce the risk of injury from a hot flame while cooking, according to all respondents. A majority (90%) stated that the TLUD gasifier does not heat the surrounding room/kitchen, as opposed to the TSF. Temperature control during cooking on the TLUD gasifier is easy according to almost 90% of the respondents. All respondents agreed that cooking with a gasifier does not require constant supervision (Table 4).

All (100%) of the respondents agreed that the TLUD gasifier saves fuel, 98.4% agreed that the gasifier produces biochar as a useful by-product and 96.7% agreed that it is easy to handle a gasifier during cooking. However, approximately 75.8% disagreed that the gasifier cooks faster than the TSF. The majority agreed that a gasifier reduces the time needed to gather fuelwood and is stable, hygienic and has an attractive appearance compared with TSF (Table 4).

### *Benefits and challenges*

In addition to appreciating the above-mentioned gasifier characteristics, the respondents also agreed that the gasifier produces less smoke and is better for women and children's health. Approximately 85% reported some difficulties in lighting the TLUD gasifier and two-thirds found that it did not fit all their cooking vessels (Table 4). Approximately 74% of the respondents agreed that fuel preparation for the gasifier is a challenge, as biomass has to be chopped into shorter lengths, and 83.9% agreed with the statement that cooking with fuel that chars before the food is ready requires reloading.

## Discussion

### *Quantification of biochar from TLUD cookstoves*

Both gasifier models tested saved fuel compared with the traditional TSF cookstove. Similar fuel savings by gasifier stoves have been reported previously. For example Gitau et al. (2019) [16], found that since starting to use a gasifier, 94% of households observed a decrease in the amount of firewood used, while Duguma et al. [17] reported 38% fuel saving after switching from TSF to a gasifier. A recent study by Sundberg et al. [18] found that compared with traditional cooking, the gasifier stove can save 20–43% of fuel depending on the fuel type. Due to reduced fuel consumption, the time spent on firewood collection is reduced, as shown by Gitau et al. [16]. In the present study, the Karundura gasifier showed higher fuel consumption than the Gastov model, probably due to differences in design.

There were significant differences in the cooking process between the gasifiers and TSF ($p = 0.05$), with both gasifier models (Karundura and Gastov) having a longer burning time than TSF. This contradicts findings by Gitau et al. [16] and Njenga et al. [10] that the use of a larger TLUD gasifier by rural households in Kenya reduced the cooking time by 18% compared with using the TSF cookstove. The difference was attributed to the unrestricted airflow through the TSF cookstove, which allows heat to escape to the open air. The longer burning time for the gasifiers in the present study could be attributable to longer lighting time because it is lit from the top, while the TSF is lit from below, and to the lighting material used, arrangement of fuel in the canister, and the blowing effort spent on lighting. In some cases, improper arrangement of biomass, especially packing

**Table 4.** Perceptions of rural householders in Rwanda about top-up lift draft (TLUD) gasifiers compared with the traditional three-stone fire (TSF) cookstove, as assessed in a Likert scale questionnaire.

| | Statement | SD (%) | D (%) | N (%) | A (%) | SA (%) |
|---|---|---|---|---|---|---|
| Fuel availability | I have easy access to firewood | 28 (46.7) | 32 (53.3) | – | – | – |
| | The gasifier saves cost if biomass is not freely available | – | – | – | 40 (66.7) | 20 (33.3) |
| Daily and weekly use frequency of the gasifier stove | I use the TLUD gasifier 3 times per day (breakfast, lunch, dinner) | 20 (33.3) | 21 (35) | – | 19 (31.7) | – |
| | I often use the TLUD gasifier in a week | 12 (20) | 21 (35) | – | 27 (45) | – |
| Beneficial characteristics of the gasifier compared with the TSF cookstove | The TLUD gasifier reduces the risk of injury from a hot flame during cooking | – | – | – | 1 (1.7) | 59 (98.3) |
| | The TLUD gasifier can heat the kitchen space | 25 (41.7) | 30 (50) | – | 1 (1.7) | 4 (6.7) |
| | Temperature control during cooking is easy with a TLUD gasifier | 6 (10) | – | 1 (1.7) | 31 (51.7) | 22 (36.6) |
| | The TLUD gasifier requires constant supervision | 59 (98.3) | 1 (1.7) | – | – | – |
| | The TLUD gasifier saves fuel | – | – | – | 34 (56.7) | 26 (43.3) |
| | The TLUD gasifier produces charcoal as a byproduct | 1 (1.7) | – | – | 31 (51.7) | 28 (46.7) |
| | It is easy to handle a gasifier | | – | – | 21 (33.9) | 39 (66.1) |
| | The TLUD gasifier cooks food faster | 23 (38.3) | 22 (36.6) | – | 14 (23.3) | 1 (1.7) |
| | The TLUD gasifier reduces the time taken to gather fuelwood | – | – | – | 7 (11.7) | 53 (88.3) |
| | When cooking with a TLUD gasifier, there is stability and the pot does not risk toppling over when stirring | – | – | – | 31 (51.7) | 29 (48.3) |
| | The TLUD gasifier is more hygienic and has an attractive appearance | 6 (10) | – | – | 23 (38.3) | 31 (51.7) |
| | The TLUD gasifier is suitable for all my cooking vessels | 13 (21.7) | 27 (45) | – | 20 (33.3) | – |
| Challenges with the functionality of the gasifier | Fuel preparation is a challenge, as I have to chop the biomass | 13 (21.7) | 3 (5) | – | 21 (35) | 23 (38.3) |
| | Cooking with fuel that chars before the food is ready requires reloading | 2 (3.3) | 6 (10) | – | 35 (58.3) | 17 (28.3) |
| | It was difficult to light the gasifier | 7 (11.7) | – | – | 30 (50) | 23 (38.3) |
| Health benefits | The TLUD gasifier is smoke-free and better for women's and children's health | – | – | – | 13 (21.7) | 47 (78.3) |
| | The TLUD gasifier reduces the physical burden on women and children (wood collection) | – | – | – | – | 60 (100) |

Note n = 60; SD = strongly disagree; D = disagree; N = neither agree nor disagree; A = agree; SA = strongly agree. The numbers represent a number of responses, while the number in parentheses represent percentage.

in more fuels and leaving no air spaces, was observed, resulting in the gasifier taking longer to light.

The yield of biochar is defined as the final weight of charred fuel as a percentage of the initial fuel mass [19]. There was a significant difference between Karundura and Gastov gasifiers in terms of biochar yield in both districts in this study, but the biochar yield of both was consistently higher in Bugesera district. Farmers in the more drought-prone Bugesera District mostly use wood biomass, as this has low moisture, low ash, high calorific value, and high bulk density [20]. The lower biochar yield in Huye District may be attributable to more frequent use of non-woody biomass with high moisture and ash content, lower calorific value, and low bulk density [20].

### *User perceptions of gasifiers in the study areas*

This study confirmed that fuelwood availability is a major challenge for rural small-scale farmers in Rwanda. Some households reported using local agricultural waste, such as maize stovers or cobs, banana roots, and rice husks, which are affected by seasonal variability. Rural householders in Rwanda generally use fuelwood from the bush or forest, the collection of which hurts the physical well-being of women and children and on forest regeneration. Due to low access to firewood, most of the respondents in both study districts appreciated the fuel-saving ability of gasifiers. This is in line with findings by Ganewo et al. [21] and Njenga et al. [10] that the fuel-saving ability of the gasifier reduces the time spent collecting firewood. From that free time, women can increase their income, advance their skills, work on their farms (thereby increasing production), improve their health, support the community and benefit from rare leisure time [10].

The survey results indicated that participating households in the study districts continued to rely on TSF stoves for cooking despite being given a gasifier. This is probably due to other factors such as the need for chopping wood into small pieces (20 cm), difficulty in arranging fuel in the canister, harvesting and cooling char, and the need to reload or change the canister when fuel chars before the food is cooked. Eltigani et al. [22], Njenga et al. [9], and Gitau et al. [16] have reported inconsistent use of gasifiers by rural households previously. There was no significant effect of the education level of survey respondents on the frequency of use of gasifiers, indicating that the education/training provided in regular visits by researchers and/or research assistants was sufficient in addressing any challenges encountered in gasifier use.

Previous research in Kenya has shown that women often suffer burns from open fire flaring during cooking [23]. In the present study, the majority of the respondents reported less exposure to hot flames while cooking with a gasifier because the flames from the burning biomass in the gasifier fuel canister are all directed to the pot through the single opening on the burner. The flames may be also blocked by skirting that concentrates the flames in the pot and the outer casing insulated with a clay lining that retains heat (see Figure 1b), so very little heat escapes to the surroundings. However, the outer surface of the Karundura gasifier becomes hot when cooking and can cause burns during cooking.

The majority of the respondents agreed that heat adjustment during cooking is easier with the gasifier than with a TSF stove. This is attributed to the user's need to simple move the ash collector up or down to increase or decrease the heat, while with the TSF stove the firewood has to be pushed in or pulled out, which can cause flaring and fill the kitchen with smoke. The majority of the respondents in both study districts also agreed that there is no need for constant supervision when using a gasifier to cook. This is because the TLUD stove once catches fire, the flame burns until the pyrolysis process is complete and reloading occurs when the charring is complete before the food is ready.

All of the respondents strongly agreed that the TLUD gasifier saves fuel. Person et al. [23] revealed that women viewed the fuel-saving ability of TLUD gasifiers, as a benefit resulting in cost savings and firewood collection reduction. Reduced time requirement for firewood collection has been reported in a study in Kenya, where women needed to walk four hours per week to collect firewood in forest, but by using a TLUD gasifier for cooking, this was reduced to half [10]. In a study by Njenga et al. [24], in Idifu, Tanzania, a 32% reduction in annual time, spent collecting firewood was achieved using a gasifier cookstove rather than TSF.

Gasifiers produce charcoal as a by-product and all households surveyed appreciated this characteristic. Similarly, in rural Kenya and Tanzania, the households appreciated the biochar produced by gasifiers [10], (Lotter et al. 2015) [25]. Gasifier users in both districts of Rwanda included in the present study were happy and interested, as this was the first charcoal-producing stove they had ever seen. The charcoal produced was used in a charcoal stove to cook a meal that took a long time, such as beans, or was used in a clothes iron. It may also be used as a soil amendment (biochar) to improve soil health and crop productivity and increase Carbon sequestration [18, 26, 27]. Participating households in the present study were asked to save the biochar produced for upcoming participatory trials in kitchen gardens.

Households appreciated the physical stability of the gasifiers during cooking, as they are fitted with stands. The respondents explained that there is less risk of the stove tilting and spilling the food being cooked. For example, when cooking ugali (cassava flour), a local dish that involves adding cassava flour to boiling water and stirring vigorously until a solid mass develops. With the traditional TSF, the adjustment of the stone to the size of the pot is necessary, and pushing wood into the TSF can easily nudge the pot, spilling the contents. The study by Palit and Bhattacharyya [28] identified stove stability as an essential feature of cookstoves in Kenya, especially when cooking meals that require continuous and vigorous stirring.

Respondents appreciated the gasifier because the food cooked on it did not smell of smoke and less ash got into the pot because there was no need to blow the fire. This meant that households found the gasifier more hygienic. Similarly, the women interviewed in the study by Person et al. [23] reported that soot and ash no longer contaminated cooked food once they started using the gasifier stove. In addition, both models of gasifiers tested in this study were reported to keep the kitchen and pots clean better compared to the TSF stove. Some respondents reported that since they started using the gasifier, it took them less time to clean pots that had less soot on the outside. According to Palit and Bhattacharyya [28], features such as the ability to keep dishes clean, thereby reducing cleaning time, can increase the adoption of gasifier stoves.

In addition to the beneficial cooking-related features of the gasifier, such as the ability to save fuel, reduced time needed to collect firewood, and stability of the stove, all households reported that the gasifier produced less smoke than the TSF stove. The gasifier is lit outdoors, similar to other portable biomass stoves, and only comes inside when it is well lit and smoke has stopped [10]. This instruction was given to participating households during training and if followed, smoke in the kitchen will be reduced. The report of less gasifier smoke production during cooking is a sign that smoke is a problem in the kitchen and that women would like a stove that produces less smoke. Uckert et al. [29] reported similar findings for the village of Idifu in Tanzania, where local households reported reduced smoke from gasifiers as their main benefit compared to TSF stoves. Laboratory experiments by MacCarty et al. (2010) [30] showed that a well-functioning gasifier can reduce particulate matter emissions by an average of 90% compared to a TSF digester. In field studies in Kenya, Njenga et al. [10] achieved a 45% reduction in carbon monoxide (CO) emissions and a 90% reduction in fine particulate matter (PM2.5) emissions due to the use of a cooking gasifier instead of period after TSF.

Challenges encountered when using the gasifier in this study were mainly related to work such as cutting firewood into smaller pieces (20 cm), more time consuming to light the stove, the need to refuel when the fuel ran out before the food was ready and harvesting charcoal/biochar. Previous studies have also identified fuel preparation, such as cutting wood into smaller pieces, as a challenge as it requires additional work compared to TSF stove preparation [16, 18, 22]. Njenga et al. [10] concluded that the need for fuel preparation is a limitation of the gasifier compared to the TSF cooker as it involves extra labor and a lengthy process. Most respondents in our study agreed that cooking food, especially large amounts of food, requires a gasifier to reload. Respondents who used the Karundura model also mentioned that the canister got hot and that the fuel arrangement within it was complicated and posed a risk of burns. Respondents using the Gastov

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gasifier were given a second canister to replace the hot canister.

## Conclusions

In SCTs conducted in rural households in Bugesera District and Huye District, Rwanda, with two gasifier models tested performed well regarding fuel savings and ability to produce biochar. User perceptions of both gasifiers were very positive concerning cooking benefits, agricultural uses, and air quality. The main challenges that may hinder the wider adoption of gasifiers in the region are labor-related activities and device design. To facilitate the adoption of TLUD gasifiers, creating awareness about their wider benefits is important, *e.g.* use of TLUD stoves can improve health at household and community levels and reduce tree felling, which in turn has positive effects on climate change. The lower fuel requirement of TLUD gasifiers can also increase fuelwood sustainability and contribute to solving the problem of fuelwood scarcity.


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## Authors' contributions

All authors contributed to the conceptualization of the study. SU performed the analysis and wrote the original draft of the article. All authors contributed to the final draft, read, and approved the final manuscript.

## Disclosure statement

No potential conflict of interest was reported by the author(s).


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## Availability of data and materials

The datasets during and/or analysed during the current study available from the corresponding author on reasonable request.

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# CHAPTER THREE

## Paper II

## 3.0 Farmer-Managed French bean Biochar Trials in Rwanda: Effects on Yield and Soil Nutrients[2]

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## Farmer-managed French bean biochar trials in Rwanda: Effects on yield and soil nutrients

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**Abstract**

In pursuing sustainable and environmentally friendly agricultural practices, using biochar derived from Top-Lit Up-Draft (TLUD) stoves in agriculture has gained significant interest. Biochar (B) from TLUD was applied in furrows in 60 kitchen gardens of French beans (*Phaseolus vulgaris*) using randomized paired design at a rate of 3 tons/ha in Rwanda's Huye and Bugesera districts. Data on yield and the soil properties were collected and analyzed using One-way analysis of variance (ANOVA) within a generalized model in R, followed by Tukey's test ($P<0.05$). The results showed a consistently positive response in French bean yield following a one-time biochar application in both sites. In Bugesera, yields were 21.6 t/ha in season 1, 24.1, and 28.8 t/ha in season 3. In Huye, yields were slightly lower with 21.6t/ha, 24.3t/ha and 27.3 t/ha for season 1,2 and 3 respectively. The soil's chemical properties in treated and control plots ranged as follows: pH 4.9–7.4, available phosphorus 1.3–8.3 ppm, total nitrogen 0.1–0.4%, calcium 3.3–7.6 $cmol_+/kg$, magnesium 0.04–1.7 $cmol_+/kg$, potassium 0.02–0.7 $cmol_+/kg$, and cation exchange capacity 7.3–13.3 $cmol_+/kg$. Biochar application significantly increased soil porosity by 15.2% and plant-available water by 24.1%, while reducing soil bulk density by 15.3% compared to the control. It is evident from the results that biochar improves soil fertility, boosts french bean yield, and support sustainable farming and energy practices. This technology promotes the use of biochar in soil management and suggests that adopting TLUD stoves can enhance energy sustainability by reducing fuel consumption.

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**Keywords:** *TLUD stoves, soil properties, French bean yield, biochar, smallholder farmers, Rwanda*
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## Introduction

Soil fertility degradation is one of the root causes of low yields and nutrient deficiencies in the highlands of East Africa, including Rwanda (Uwiragiye *et al.*, 2022; Mulualem *et al.*, 2021). In Rwanda, soil nutrient depletion, acidity, organic matter depletion, and low CEC increase soil infertility. This is due to soil erosion from intensive agriculture (two seasons per year), high altitude (>60 m asl), poor management practices, and high nutrient removal in the tropics (Kabirigi *et al.*,2017). All these are mainly the effects of high population density (more than 400 inhabitants/km$^2$) (Bucagu *et al.*,2014).

The increasing use of fertilizers (inorganic and organic), liming of acidic soils (Nduwumuremyi *et al.*,2017), and the promotion of agroforestry systems (Mukurarinda *et al.*,2016) have been proposed to alleviate the soil fertility challenge and boost crop/vegetable yields. However, inorganic fertilizers are still challenging due to their high cost and adverse environmental effects (Tittonell *et al.*, 2016; Nduwumuremyi *et al.*, 2017). Despite the high nutrient content in organic amendments such as chicken manure or compost, they mineralize rapidly in the tropics' humid soils (Bol *et al.*,2000). Yet for crop nutrient requirements to be sustained, manure or compost must be applied every season, and this increases labor and costs (Ndambi *et al.*,2019). Furthermore, manure is a limited resource for most small-scale farmers, and they do not have enough to apply to the whole farm.

Biochar is a carbon (C) rich material that can be used as a soil amendment in agricultural soils. Biochar is produced by the thermal decomposition of organic matter in low oxygen settings (Zemanova *et al.*,2017), such as in TLUD stoves, where the gases from wood or other organic materials are used for cooking, and biochar remains a by-product. Applying biochar on farmlands can ensure long-term benefits for soil fertility and crop production improvement. Both positive and negative yield responses have been reported for a wide variety of crops as a result of biochar application to soils (Meena and Prakasha, 2020, Agegnehu *et al.*,2017, Agegnehu *et al.*,2016a, 2016b, Deenik *et al.*,2010). For instance, the addition of manure biochar increased maize yield by 98–150% and water use efficiency by 91–139% (Uzoma *et al.*,2011); the use of oil mallee biochar increased wheat grain yield by 18% (Solaiman *et al.*,2010); and the applications of bio-char and co-composted biochar-compost increased peanut yield by 23% and 24% (Agegnehu *et al.*,2015a). Moreover, biochar has potential benefits in improving the biophysico-chemical properties of soils. According to Van Zwieten *et al.*,2010), the application of paper-mill biochar at a rate of 10 t/ha in a Ferrosol resulted in considerable increases in pH, CEC, exchangeable Ca, and total C, as well as a reduction in Aluminium availability. In addition, biochar has increased soil fertility, including raising soil pH (Mandal *et al.*,2019), increasing water holding capacity and thus reducing irrigation demand, enhancing root penetration, and changing microbial reactions in soil (Wang *et al.*,2020). Due to the long-lasting stability of biochar in the soil, it requires one application only every 10 to 50 years, depending on the amounts applied (Greenberg *et al.*,2019).

However, to produce enough biochar for all agricultural soils in East Africa or on a small-scale farm may be difficult. In addition, biochar has been extensively studied in crops such as maize (Mensah and Frimbong, 2018; Šimansky *et al.*,2019), Kamara *et al.*,2015), its application in vegetable production systems, particularly in smallholder farming context remains relatively limited. For our study, we have concentrated on biochar application to higher value (from a nutritional and economic perspective) vegetables in smaller areas. Hence, we assessed the effect of biochar from household TLUD stoves on vegetable yield and soil quality in different kitchen gardens of smallholder farmers in two agro-ecological zones (AEZs) of Rwanda. We hypothesized an increase in French bean yield, a highly nutritious and marketable agricultural product in Rwanda, and plant available nutrients upon adding biochar. In addition, we hypothesized an increased amount of plant-available water, CEC, and pH by adding biochar and that these effects should be sustained over several growing seasons.

**Materials and methods**

**Description of Study Sites**

The farmer-managed field trials were conducted at 120 farmers' kitchen gardens in the Huye and Bugesera districts (Fig. 1). Huye District is characterized by a sub-equatorial temperate climate with an average temperature of approximately 20°C with an average annual rainfall of 1160 mm (Huye District report 2013). The soils in Huye are generally acidic in nature and are saturated with Aluminium ($Al^{3+}$) cations, suggesting low agricultural production unless fertilizers (organic or mineral) are added (Huye District report 2013). Bugesera District is regarded as a drought-prone region that experiences frequent rainfall deficits, a significant number of dry spells, and an average annual rainfall of 943 mm; it has an average temperature of approximately 27°C (Benimana *et al.*,2015). The soils in the Bugesera region are shallow to reasonably deep, clayey, sandy clay, or sandy silt (Mikwa *et al.*, 2014).

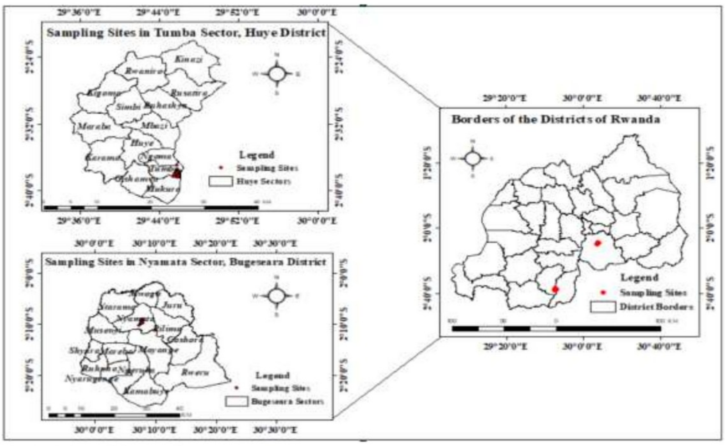


*Fig 1. Map of the study areas*

**Experimental Setup**

The field experiment was run over three seasons from September 2022 – September 2023. The trials were conducted at 60 farms (kitchen gardens) in each district, with a single vegetable French beans (*Phaseolus vulgaris*) being grown. French beans are crucial for smallholder farmers due to its economic and nutritional benefits. They can be grown on small plots of french been may be grown on small land where farmers may use limited resources such biochar at low rate of application, yet they benefit with good yield. At each field, the treatments were arranged in a randomized paired design, and the plot size was 3 m$^2$, where one plot received biochar while the other plot was considered a control. The biochar was applied in furrows (2-3 cm deep) one week before sowing at 3 tons/ha, weeding activities were carried out after two weeks, and pests and diseases were controlled using the recommended pesticides.

**Biochar preparation and analysis**

The TLUD gasifier cookstoves were provided to smallholder farmers in the Huye and Bugesera districts (Fig. 2). Based on the principle of TLUD technology (McLaughlin 2010), farmers received training on how to use the stove and were required to save the biochar produced for use in participatory on-farm field experiments in the next planting season (French beans in kitchen gardens). *Eucalyptus* fuelwood was used as feedstock. Random sampling design has been used to collect biochar across 30 different kitchen gardens in each site, and 15 samples have been collected, grounded and sieved at <0.154 mm for their chemical analyses. The properties of the biochar were evaluated using the American Society for Testing and Materials methods (ASTM, 2018).


*Figure 1. (a) Top Lit UpDraft gasifier stove. (b)stove parts: b1 =outer cylinder, b2 =extinguisher, b3 =inner fuel canister 4=top plate, b5 =ash collector, b6 =pelle*

**Soil sampling and analysis**

Four random soil samples per plot (0-20 cm depth) were mixed to make a composite and collected for further analysis. Soil pH was measured potentiometrically in water and 1N Potassium chloride (KCl) at 1:2.5 soil: water and KCl (Okalebo, 2002). The Total Nitrogen (TN) was determined using the Kjeldahl method (Bremmer and Mulvaney, 1982), while available P was measured using the Bray 1 method (Okalebo, 2002). Exchangeable bases were extracted using one molar of Ammonium acetate ($NH_4OAc$) (Thomas, 1982), with its concentration being measured using the Atomic Absorption Spectrophotometer. Organic C was determined through the Walkley and Black wet oxidation method (Nelson and Sommers, 1982). Particle size analysis was determined using the Bouyoucos hydrometer method after dispersion with 5% Sodium hexametaphosphate (NSS, 1990), and textural classes were determined using the United States Department of Agriculture (USDA) textural class triangle (USDA, 1975). Bulk density was determined through the core method (Black and Hartge, 1986). Available water was determined using a sand kaoline box and pressure apparatus (NSS,1990).

**Determination of Yield of French Beans**

Green pods were harvested from each unit plot at regular intervals, and their weight was recorded. As harvesting was done at different intervals, the total weight of pods per season was recorded for each unit plot and was expressed in kilograms (kgs). The green pod yield per plot was converted to yield per hectare (ha) and was expressed in tons (t/ha). The total number of pods per plant was counted and noted from 5 randomly selected plants. The weight of 5 pods and the average weight per pod was calculated.

**Data analysis**

We tested for outliers using the Gibs test, removing data larger than two standard deviations. The normality test was done using Shapiro-Wilk's test. The Analysis of Variance (ANOVA) was performed to test for differences in soil parameters across the study treatments and yield across the three successive seasons. Tukey Honest Significance Differences (HSD) post hoc analysis implemented in Tukey (HSD) function at $p < 0.05$ was further performed on the study treatments. All statistical tests were performed using R Studio (Ludecke *et al*., 2021).

**Results**

**Biochar properties**

The results of the biochar properties of *Eucalyptus* are summarised in Table 1. *Eucalyptus* biochar indicated a moderately basic pH level, low electrical conductivity (EC), high C, and a low level of basic cations and soil nutrients, such as P and TN.

**Table 1.** ***Eucalyptus biochar properties (n= 15)***

| pH | EC | TC | TN | C/N | P | K | Ca | CEC | VM | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| 1:10($H_2$0) | µs/cm | % | % | ratio | ppm | ppm | ppm | Cmol+/kg | % | % |
| 8 | 115.9 | 71.8 | 0.33 | 217.6 | 0.09 | 0.35 | 0.57 | 26.4 | 27.5 | 0.7 |

*TC: total organic Carbon, EC: electrical conductivity, CEC: Cation Exchange Capacity, TN: total Nitrogen, VM: volatile matter, P: Phosphorus, K: Potassium, Ca: Calcium, Mg: Magnesium.*

**Yield as induced by biochar application**

Green pod yield (the number of green pods and weight per plant of French beans) as influenced by biochar application is shown in Tables 2 and 3. All the biochar treatments showed significantly enhanced total yield (Table 2) and a greater number and weight of pods per plant (Tables 3) than control plants grown in untreated soils. Yields also significantly increased over three consecutive seasons with biochar amendments, while they significantly decreased over the seasons in control plots at both sites (Table 2).

**Table 2.** *Green pod yield (t/ha) to biochar input for all growing seasons at each site (Mean±SE) (n=30)*

| Treatment code | Bugesera site | | | Huye site | | |
|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S1 | S2 | S3 |
| BC | 21.6±0.1[aC] | 24.1±0.1[aB] | 28.3±0.09[aA] | 21.6± .14[aC] | 24.3±0.1[aB] | 27.3±0.09[aA] |
| C | 14.4 ±0.1[bA] | 12.3±0.05[bB] | 8.8±0.02[bC] | 13.8 0.11[bA] | 11.5±0.05[bB] | 8.5±0.02[bC] |

*Small letters are used to compare means between the treatments; Capital letters are used to compare seasons; s1, s2, s3: growing season of French beans (45-60 days), BC: biochar plot, C: control plot. SE: Standard Error*

**Table 3.** ***The number of green pods per plant and green pod weight per plant due to biochar input for all growing seasons at each site (Mean±SE) (n=30)***

| | **Trt code** | **Bugesera site** | | | **Huye site** | | |
|---|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | S1 | S2 | S3 |
| **Pods number** | BC | 10.4+0.19 [aC] | 12.4±0.16[aB] | 15.1±0.18[aA] | 5.3±0.13[bC] | 12.7±0.1[aB] | 16.7±0.1[aA] |
| | C | 7.4±0.1[aA] | 5.9±0.15[bB] | 5.3±0.13[bC] | 6.5±0.1[bA] | 5.5±0.04[bB] | 5.4±0.03[bB] |
| **Pod weight (g)** | BC | 65.9±0.4 [aC] | 67.7±0.43[aB] | 68.9±0.29[aA] | 62±0.13 [aC] | 66.1±0.06[aB] | 69.8±0.1[aA] |
| | C | 43.7 ±0.2[bB] | 44.6±0.39[bA] | 45.3±0.15[bA] | 43.4 ±0.1[bA] | 42.3±0.04[bA] | 42.6±0.03[bA] |
| **Weight/pod** | BC | 6.3±0.4 [aA] | 5.5±0.43[bB] | 4.6±0.29[bC] | 11.7±0.13[aA] | 5.2±0.04[bB] | 4.2±0.03[bC] |
| | C | 5.9±0.2[cC] | 7.6±0.39[aB] | 8.6±0.15[aA] | 6.7±0.1[bB] | 7.7±0.06[aA] | 7.9±0.1[aA] |

Small letters compare means between treatments; Capital letters are used to compare seasons; s1, s2, s3: growing season of French beans (45-60 days), BC: biochar plot, C: control plot. SE: Standard Error, Trt: treatment

**Soil properties as induced by biochar application**

Table 4 shows the increase in the soil's chemical properties after three successive seasons since biochar application. A significant effect has been observed in soil pH, organic C, and available P and TN (Table 4).

**Table 4.** *Chemical properties of soils after biochar application in the Huye and Bugesera districts (Mean±SE) (n=30)*

| Sites | Trts codes | pH water | %OC | %TN | C/N ratio | Av. P (ppm) |
|---|---|---|---|---|---|---|
| Bugesera | BC | 7.4±0.1[a] | 4.06±0.03[a] | 0.3±0.003[a] | 13.9±0.1[a] | 8.3±0.08[a] |
| | C | 5.9±0.06[b] | 1.5±0.13[b] | 0.1±0.003[b] | 11.5±0.1[b] | 3.5±0.09[b] |
| Huye | BC | 6.5±0.14[a] | 2.7±0.03[a] | 0.4±0.001[a] | 12.2±0.6[a] | 5.4±0.09[a] |
| | C | 4.9±0.06[b] | 1.4±0.13[b] | 0.1±0.003[b] | 11.3±0.4[b] | 1.3±0.01[b] |

OC: Organic Carbon; TN: total Nitrogen; AV. P: available Phosphorus. Values followed by similar letters under the same column are not significantly different at $p < 0.05$ according to the Tukey test, Trts: treatments. SE: Standard Error

Table 5 shows a significant increase in base cations such as Calcium ($Ca^{2+}$), Magnesium ($Mg^{2+}$), and Potassium (K+) due to biochar application in both sites. Sodium ($Na^{+1}$) was not significantly influenced by biochar application in either site.

**Table 5.** *Exchangeable bases and CEC of the studied soils after biochar application (Mean±SE) (n=30)*

| Sites | Trts codes | Exchangeable bases $cmol_+/kg$ $Ca^{2+}$ | $Mg^{2+}$ | $K^{1+}$ | $Na^{1+}$ | CEC ($cmol_+/kg$) |
|---|---|---|---|---|---|---|
| Bugesera | BC | 7.6±0.2[a] | 1.7±0.1[a] | 0.72±0.01[a] | 0.04±0.0[a] | 12.7±0.2[a] |
| | C | 3.6±0.1[b] | 0.04±0.0[b] | 0.02±0.0[b] | 0.03±0.0[a] | 7.6±0.2[b] |
| Huye | BC | 4.9±0.1[a] | 0.9±0.01[a] | 0.3±0.02[a] | 0.05±0.01[a] | 13.3±0.1[a] |
| | C | 3.2±0.02[b] | 0.04±0.01[b] | 0.02±0.02[b] | 0.04±0.01[a] | 7.3±0.2[b] |

$Mg^{2+}$: exchangeable Magnesium, $Ca^{2+}$: exchangeable Calcium, $K^{1+}$ exchangeable Potassium; $Na^{1+}$: exchangeable Sodium. Values followed by similar letters under the same column are not significantly different at $p < 0.05$ according to the Tukey test, Trts: treatments. SE: Standard Error

Table 6 shows no significant difference in soil textural classes (clay, sand, and silt) in either site. Soil bulk density has changed from 1.5 g/cm$^3$ (moderate) to 1.3 g/cm$^3$ (low). In addition, soil porosity and plant available water were both influenced by biochar.

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**Table 6.** *The physical soil properties of studied soils before and after biochar application in the Huye and Bugesera districts (Mean±SE) (n=30)*

| | | Soil textural classes (%) | | | | | |
|---|---|---|---|---|---|---|---|
| **Sites** | **Trts codes** | **Clay** | **Sand** | **Silt** | **BD ($g/cm^3$)** | **% Porosity** | **Available water(mm/m)** |
| Bugesera | BC | 22.5±1.3[a] | 65.5±0.5[a] | 13.2±0.2[a] | 1.3±0.6[a] | 47.6±0.2[a] | 115.8±0.1[a] |
| | C | 22.5±0.2[a] | 65.5±0.5[a] | 10.1±0.1[a] | 1.5±0.5[b] | 41.3±0.1[b] | 93.3±0.1[b] |
| Huye | BC | 22.5±0.1[a] | 60.5±0.2[a] | 14.1±0.2[a] | 1.3±0.02[a] | 47.3±0.4[a] | 102.5±0.1[a] |
| | C | 21.9±0.1[a] | 60.4±0.2[a] | 12.9±0.1[a] | 1.5±0.01[b] | 41.3±0.1[b] | 97.5±0.1[b] |

BD: Bulk density, Values followed by similar letters under the same column are not significantly different at p = 0.05 according to the Tukey test. SE: Standard Error, Trts: Treatments

## Discussion

### Biochar properties

It is realistic for smallholder farmers to produce enough biochar for application to kitchen gardens while saving much fuelwood (Munoz, (2014); Sundberg *et al.* (2020)). The high pH observed in the biochar used is related to ash enrichment and the rapid charring or carbonization rate that involves high temperatures and limited Oxygen availability. This aids the release of volatile acidic compounds from biomass; by driving off these volatile acids, such as acetic acid and formic acid, the overall acidity of the biochar is reduced, leading to an increase in pH (Yargicoglu *et al.*, 2014). The low EC value in the biochar could be due to increased highly soluble and exchangeable base cations. The high CEC value in biochar produced from Eucalyptus may be due to the high oxygen-containing functional group (Dejene *et al.*, 2019). The high P content could be due to the charring of organic materials, which can highly enhance P availability from plant tissue through the cleaving of organic P bonds, as well as to the P content of the ash (Yargicoglu *et al.*, 2014).

### Biochar effect on yield of french beans

Given that a large amount of biochar is required to effectively cover large areas and achieve a reasonable yield, which can be challenging, it would be more beneficial to focus biochar applications on smaller, and targeted areas. Concentrate biochar use on plots where a farmer grow higher-value crops or vegetables is a good strategy that may allow him/her to apply biochar in manageable, realistic amounts while maximizing its benefits and improving the productivity and profitability of his or her farm. Typically, the kitchen gardens of smallholder farmers are nutrient-rich soils due to the continuous application of household wastes such as ash from the kitchen and food scraps, among others. In our study, biochar has proven to enhance soil pH, thereby making soil nutrients more accessible and consequently increasing French bean yields. Moreover, biochar increases porosity (Table 6) with micropores, which increases water retention, acts as a habitat for microorganisms, and increases soil biological activity, thereby enhancing soil aggregation. The higher activity of soil microorganisms can increase the availability of nutrients in the soil, which enables plants to absorb adequate nutrients better and increase plant production (Widowati, 2010; Akhil *et al*., 2021). In addition, the yield increase in our study areas was likely partly due to a fertilization effect with the ash as a source of nutrients (Tables 1, 4, and 5), specifically, basic cations and P and the liming effect of biochar. The increase in crop/vegetable yield with biochar application has been reported in the literature (Das *et al. 2020;* Singh *et al., 2019*; Jeffrey *et al*., 2019; Danso and Agyare, 2021). Singh *et al*. (2019) reported that applying rice husk biochar in wheat crops improved the yield and water-holding capacity. El-Naggar (2019) also reported that the number of pods per plant (*Phaseolus vulgaris*) increased with biochar application. Significant horticultural responses to biochar were observed not only in acid soils (Jeffrey *et al*. 2017; Bolan *et al*., 2022) but also in neutral and alkaline tropical soils, as found in other vegetable crops (William *et al*., 2023).

**Biochar effect on soil properties**

The amended plots showed a significant increase in pH compared to the control plots. The increase in soil pH caused by biochar application may be due to the high surface area and porosity of biochar, which increases the CEC of the soils. This will increase Al (Aluminium) and Iron (Fe) binding to soil exchange sites. Additionally, the ash (e.g., alkaline oxides, carbonates) can increase soil pH by providing greater alkalinity (Vassilev *et al.,* 2013a). The ability of biochar to neutralize acidity has been confirmed in several studies (Zhao *et al*., 2015; Paz-Ferreiro *et al*., 2020), stating that biochar can increase the pH of acidic soils, reducing Al toxicity and increasing nutrient availability. Shetty *et al*. (2020) and Martinsen *et al*. (2015) reported that soil pH increased from 4.7 to 8.5 by adding biochar. Moreover, in tropical Kenya, where biochar was used at 50+50 Mg/ha in the first two seasons, soil pH increased significantly, from 4 to 7, in the following years (Kätterer *et al*., 2019).

The increase in exchangeable bases and CEC was due to the high CEC of biochar (Table 1), which favors nutrient retention, mainly Ca, Mg, K, Fe, and Manganese (Mn), against leaching loss, thus increasing their efficient use by plants. The non-significance of Na in the soil treated with biochar is most likely because biochar doesn't contain Na, and once applied to soils, all the Na is adsorbed, which increases the exchangeable Mg and Ca, to replace Na in the soil and makes it less alkaline. Using (30 t/ha) of coffee husk biochar to degraded sandy loam soil in Nigeria doubled the soil CEC from 19.1 to 40.4 cmol/kg (Adekiya *et al.*,2020).

The findings show a significant influence of biochar on soil TN in the biochar-treated soils (Table 4). Biochar does not provide many nutrients to the soils; instead, it increases their availability by increasing pH. Another reason could be the ability of French beans to fix N. N-fixation from beans and N kept available by biochar (an-ion binding) avails N to plants (Singh *et al.*, 2023).

The increase in available P (Table 4) from biochar application could be attributed to the presence of soluble and exchangeable phosphate in the biochar ash component and the soil pH improvement (Mensah *et al.*, 2017). In agreement with this, Agegnehu *et al.* (2015) and Naeem *et al.* (2018) have reported more significant available P contents in biochar-amended soils than in unamended soils. This improvement was attributed to biochar's ability to retain and exchange phosphate ions due to its positively charged surface sites.

The increase in organic C in both sites following biochar application is due to high amounts of C in the biochar used (Table 1). The soil microorganisms do not as readily degrade compounds found in biochar (it can be sequestered in the soil in the long-term, i.e.,>100 years), as happens for organic material that is not pyrolyzed (Weng *et al.*, 2017; Wijitkosum *et al.*, 2019; Tisserant *et al.*,2019; Ajayi *et al.*, 2016).

The improvement of soil bulk density after biochar application is due to the low density of biochar itself (<0.6 g/ $cm^3$ for biochar and ~1.5 g / $cm^3$ for soil), which reduces the density of the bulk soil through the mixing or dilution effect (Humberto Blanco-Canqui (2017), and to increased soil aggregation (Burell *et al.*, 2016). As expected, the decrease in soil bulk density caused by biochar application directly increased soil porosity (Table 6). Biochar particles have a 70 to 90% porosity, and adding this porous material to the soil can concomitantly increase soil porosity.

Biochar has significantly increased plant available water compared to control plots (Table 6). This is due to the particular surface area of biochar (>3000 $m^2/g$), which is much higher than soil (10 to 40 $m^2/g$ for sandy loam soils, 5 to 150 $m^2/g$ for silt loam soils, and 150 to 250 $m^2/g$ for clayey soils). Hence, adding biochar to soil can alter total porosity, pore size distribution, water transmission, and water retention characteristics (Githinji, 2013; Uwase, 2022).

## Conclusion

Biochar increases soil organic C and can do so over extended periods, making it pertinent to the international carbon sequestration and climate change discourse. Biochar also raised soil pH, increased CEC and nutrient availability (mostly P, which has strong interactions in acidic soils), and decreased soil bulk density; it increased soil porosity and plant available water, which could be a good sign for water use efficiency. The technology reduces the need for lime and inorganic fertilizers through improved soil properties. Our results show a significant increase in the yield of French beans over three consecutive seasons. The increased vegetable yield can improve nutrition and farm economics in local communities and eventually enhance the adoption of the TLUD stoves, which will ensure energy sustainability. Therefore, biochar application can be recommended, especially to smallholder farmers, for sustainable agriculture/agroforestry. There is potential for concentrating biochar to produce nutrients/high-value crops/vegetables. Longer-term effects shall be investigated to assess the effect of B on soil quality and crop/vegetable production using diverse feedstocks available in the Rwandan landscape to produce Biochar. Sustainability of biomass availability may be strengthened throught the promotion of agroforestry adoption among smallholder farmers.

## Data Availability

Data will be made available on request

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## Declaration of competing interests

The authors declare that they have no known competing interests.

## Credit Authorship Contribution Statement

US conceptualized the study, conducted fieldwork and laboratory analyses, and wrote manuscript drafts. JN, GN, and SAOC conceptualized the study, commented on drafts, and contributed to the writing. All the authors contributed to the final manuscript.

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# CHAPTER FOUR

## Paper III

## 4.0 Synergistic Effect of Biochar and Livestock Manure on Soil Health and French bean Yield in Two Agro-ecological Zones of *Rwanda*[3]

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# French Bean Production as Influenced by Biochar and Biochar Blended Manure Application in Two Agro-Ecological Zones of Rwanda

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**Abstract:** Biochar (B) has low nutrient content and is recalcitrant to biodegradation. Supplementing B with a fast-releasing nutrient source may improve soil fertility and physical conditions and increase crop productivity. A three-season field study was conducted on sandy loam and sandy clay loam textured soils to investigate the effect of B mixed with livestock manure (LM) on soil properties (pH, organic carbon (OC), cation exchange capacity (CEC), total Nitrogen (TN), available Phosphorus (Avail P)), and French bean yield (*Phaseolus vulgaris* L.) in Rwanda. The study used a factorial randomized block design with four replications. Treatments comprised three levels of B (0, 1, and 3 t/ha) and three levels of LM (0, 1, and 3 t/ha). Biochar was used from *S. sesban*, *G. sepium*, *A. angustissima*, *Eucalyptus*, and *Grevillea* sp., prepared using a drum kiln, while LM was prepared using the pit method. The Analysis of Variance (ANOVA), Tukey (HSD) function at $p < 0.05$, and linear mixed-effects model were performed in R software version 4.3.3 (R Core Team, 2024). The analysis showed that the treated plots significantly increased French bean yield compared to the control plots, with the highest value found in plots treated with 3 t/ha. The combined plots showed an increased yield compared to sole Biochar or manure. The seasonal increase has been observed, with percentage increases recorded as follows: 16%, 33.56%, 173.06% in sole B plots; 40.28%, 14.43%, and 11.76% in sole LM plots and 125%, 156%, and 209.8% in B + LM plots for season 1, 2, and 3, respectively. Furthermore, the results indicated that the application of B alone or combined with LM significantly enhanced soil pH, OC, TN, avail P, and CEC with the pH ranging from 6.77 to 5.43 for B alone, 6.7–5.35 for LM alone, 8.53–6.06 for B-LM plots, and 4.34–3.78 for control plots. Applying Biochar, either alone or in combination with LM, at a low rate demonstrated positive effects on French bean yield and soil nutrients in smallholder farmers. This study encourages using natural materials such as B and LM to improve soil fertility and increase vegetable production while reducing chemical fertilizers that can cause pollution and damage the environment.

**Keywords:** Biochar; livestock manure; French bean yield; soil properties; Rwanda



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## 1. Background

Soil nutrient mining is the most common form of soil degradation; it threatens future soil productivity, especially in Sub-Saharan Africa [1–3]. In Rwanda, liming of acidic soils, increasing the use of inorganic or organic fertilizers [4], and promoting agroforestry systems [5] have been proposed as solutions to soil fertility problems. However, the use of inorganic fertilizers is problematic due to their adverse environmental effects and high

**Table 1.** The characteristics of the studied areas and soil properties at the start of the experiments.

| | Tonga Station | Rusagara Station |
|---|---|---|
| Latitude | 1°33′37″ S | 2°12′19″ S |
| Longitude | 30°05′28″ E | 30°13′04″ E |
| Temperature (°C) | 20 | 27 |
| Annual rainfall (mm) | 1160 | 943 |
| Soil classification | Gleyic Acrisols | Ferralic Cambisols |
| Land use/vegetation | Follow | Agriculture/maize |
| Texture | Sand clay loam | Sandy loam |
| Soil pH | 4.34 ± 0.4 | 4.01 ± 0.75 |
| Soil Organic Carbon (S.OC) % | 0.74 ± 0.39 | 0.68 ± 0.47 |
| Cation Exchange Capacity (CEC) ($col_{(+)}$/kg) | 4.63 ± 1.43 | 3.84 ± 1.07 |
| Available Phosphorus (P) | 3.08 ± 1.15 | 3.71 ± 1.04 |
| Total Nitrogen (T.N.) % | 0.06 ± 0.02 | 0.04 ± 0.02 |

In the study areas, the soil was classified as sandy clay loam (65.4% sand, 26% clay, and 9.03% silt) and sandy loam (63.4% sand, 16.1% silt, and 20% clay) in Huye and Bugesera, respectively (U.S. textural classification triangle [23]). The soil was acidic in nature. Soil OC, TN, available P, Potassium ($K^+$), Calcium ($Ca^{2+}$), and Magnesium ($Mg^{2+}$) were rated as very low according to the critical levels of 3% soil OC, 0.2 0% TN, 10 mg/kg available P, 0.20 cmol/kg $K^+$, 2.0 cmol/kg $Ca^{2+}$, and 0.40 cmol/kg $Mg^{2+}$ [24]. The low soil CEC (<5 $cmol_{(+)}$/kg) has been recorded [25] in both sites, indicating poor soil fertility (Table 1). Consequently, the soil will be unable to sustain crop yield without the addition of external inputs. The chemical composition of LM and B is characterized by a relatively high TN, available P, K, Ca, Mg, organic C (OC), and CEC at the level required for the growth of French beans [26] (Table 2).

**Table 2.** Properties of livestock manure and Biochar used.

| Soil Parameters | BE | BGr | BGl | Bses | BAc | LM |
|---|---|---|---|---|---|---|
| pH | 9.33 | 9.05 | 9.87 | 7.96 | 7.26 | 9.00 |
| EC ds/m | 1.35 | 2.42 | 2.86 | 3.45 | 3.79 | 2.51 |
| Total OC (%) | 71.80 | 79.7 | 65.00 | 70.89 | 68.00 | 50.82 |
| TN (%) | 0.68 | 0.38 | 1.00 | 1.52 | 1.32 | 2.40 |
| Total P (%) | 0.09 | 0.03 | 0.04 | 0.07 | 0.04 | 0.90 |
| CEC(cmol+/kg) | 26.40 | 24.00 | 28.1 | 45.7 | 45.8 | 67.25 |
| Total Ca (ppm) | 0.12 | 0.27 | 0.44 | 0.42 | 0.39 | 0.35 |
| Total K (ppm) | 0.15 | 1.36 | 4.35 | 4.67 | 5.78 | 2.82 |
| Total Mg (ppm) | 0.19 | 0.17 | 0.12 | 0.15 | 0.19 | 0.21 |
| Ashes (%) | 0.78 | 0.65 | 2.10 | 0.60 | 0.20 | - |

BE: Biochar from Eucalyptus wood; BGr: Biochar from Grevillea wood; BGl: Biochar from Gliricidia wood; BSes: Biochar from Sesbania wood; BAc: Biochar from Acacia wood; LM: livestock manure; EC: electrical conductivity.

Eighteen treatments with four replicates were placed in plots in a randomized block design. Treatments consisted of a factorial combination of three levels of B (0, 1, and 3 tons/hectare (t/ha) and three levels of LM (0, 1, and 3 t/ha). The treatments were set up assuming all kinds of B were equal (Table 3). The B was crushed and incorporated alone or with LM into a seedbed and stayed for 7 days before sowing. French bean seeds obtained from the local market were directly sown into seedbeds with a depth of 15 cm, maintaining a 30 × 20 cm spacing within plots measuring 2 × 3 m. Except for in the control plots, decomposed LM and B were uniformly applied at specified rates (Table 2). The crushed Biochar and mature were incorporated in the soil, 1 week before seed plantation. The hoe-weeding activities were carried out manually for 2 weeks post-sowing to avoid competition and to reduce insect pest infestation.

**Table 3.** Treatments of the field experiments with the dose of Biochar and manure.

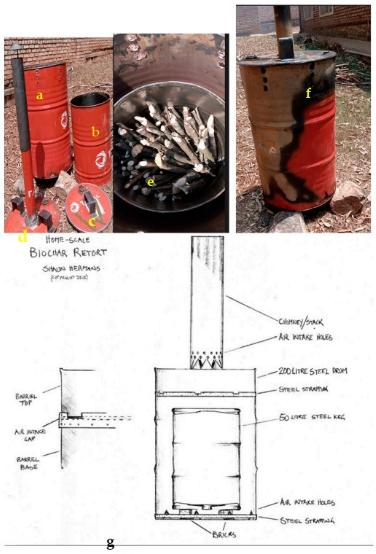
| Trt Code | Biochar Application (t/ha) | Manure Application (t/ha) | N |
|---|---|---|---|
| B0 + MO (Control) | 0 | 0 | 4 |
| B1E | 1 | 0 | 4 |
| B1Gl | 1 | 0 | 4 |
| B1Ses | 1 | 0 | 4 |
| B1Gr | 1 | 0 | 4 |
| B3E | 3 | 0 | 4 |
| B3Ses | 3 | 0 | 4 |
| B3Ac | 3 | 0 | 4 |
| LM1 | 0 | 1 | 4 |
| LM3 | 0 | 3 | 4 |
| B1E + LM1 | 1 | 1 | 4 |
| B1Ses + LM1 | 1 | 1 | 4 |
| B1E + LM3 | 1 | 3 | 4 |
| B1Ses + LM3 | 1 | 3 | 4 |
| B3E + LM1 | 3 | 1 | 4 |
| B3Ses + LM1 | 3 | 1 | 4 |
| B3E + LM3 | 3 | 3 | 4 |
| B3Ses + LM3 | 3 | 3 | 4 |

B0 + MO: control; B1E: Biochar from Eucalyptus ssp; B1Gl: Biochar from Gliricidia sepium; B1Ses: Biochar from Sesbania sesban; B1Gr: Biochar from Grevillea sp; B3Ac: Biochar from Acacia angustissima; LM: livestock manure; Trt: treatment.

### *2.2. Biochar and Manure Preparation*

To produce B, *S. sesban*, *G. sepium*, *A. angustissima*, *Eucalyptus* sp., and *Grevillea* sp. were collected from a local farmer's field and pyrolyzed using a drum kiln method (slow pyrolysis) (Figure 1A,B). Each species was manually cut into appropriate sizes (average 20–25 cm length and 10–15 mm diameter) to load the kiln with feedstocks in a uniform manner and for the uniform heat transfer during the pyrolysis process. The drum kiln method utilizes indirect heating, in which the feedstock is heated by burning fuel outside the drum. This indirect heat helps sustain a relatively stable temperature inside the drum, typically around 4000 °C, suitable for Biochar production. The wood from the various species was sun-dried separately to reduce the moisture content below 10%. All B samples were ground and sieved at <0.154 mm for their chemical analyses.

The pit method was used to prepare LM, which lasted 3 weeks to allow mineralization. Detailed information on B and LM properties is provided in Table 2.




(**A**)

(**B**)

**Figure 1.** (**A**). (a) Biochar drum kiln, (b) inner kiln, (c) drum kiln lid with chimney column, (d) inner kiln lid, (e) loaded fuel in the inner drum kiln, (f) ignited fuel, (g) drum kiln design. (**B**). produced Biochar from the kiln.

### *2.3. Soil, Biochar, and Livestock Manure Analysis*

In September 2022, before the experiments began and after the harvest of French beans in December 2023, the samples of soils were collected from the top 0–20 cm depth using a random sampling design, with four soil samples taken per plot. These individual samples were combined to create a composite sample for subsequent analysis. Soil pH was measured potentiometrically in water and 1N Potassium chloride (KCl) at 1:2.5 soil: water and KCl [27]. Soil TN was determined using the Kjeldahl method [28], while available P was extracted using Bray 1 solution and determined by spectroscopy at 882 nm wavelength following color development by the molybdenum bleu method [27]. OC was determined by the Walkley and Black wet oxidation method [29]. Soil CEC and exchangeable bases were extracted by saturating soils with neutral 1M $NH_4OAc$ (ammonium acetate [30] and the absorbed $NH_4^+$) by $K^+$ using 1M KCl and then determined by Kjeldahl distillation method for the estimation of CEC of $NH_4^+$ were measured by atomic absorption spectrophotometer [30]. The properties of B were calculated using the American Society for Testing and Materials (ASTM) methods [31].

The LM properties were analyzed using the same methods as for soil analysis. To determine ash content, we first measured moisture content by drying a 5 g sample in an oven at 103 °C for 12 h and expressed as the percentage loss of weight of the original sample. Secondly, we measured volatile matter, where the oven-dried sample was incinerated in a muffle furnace for 7 min at 900 °C and weighed after cooling. Volatile matter was expressed as the percentage of weight loss in the original sample. Then, the ash content was determined using the cooled incinerated sample, which was returned to the muffle furnace at 900 °C for 1.5 h, and the weight was expressed as a percentage of the weight of the original sample.

### *2.4. Determination of French Bean Yield*

After 45 days, green pods were harvested at regular intervals (three times) from each unit plot, and their weight was recorded. The total weight of pods per season was recorded for each unit plot and was expressed in kilograms (kgs). The pod yield per plot was converted to yield per ha and was expressed into t/ha.

### *2.5. Statistical Analysis*

The Analysis of Variance (ANOVA) was performed to test for differences in soil parameters across the four study treatments (B, B + LM, LM, and control no additions). Tukey Honest Significance Differences (HSD) post hoc analysis implemented in Tukey (HSD) function at $p < 0.05$ was further performed on the study treatments. The linear mixed-effects model was applied to generate the relationship between the dependent variable (green pod yield (t/ha) and fixed effects (site and seasons), while treatments were the random effect [32]. Statistical analyses were performed in R software (version 4.3.3) (R Core Team; 2024).

## 3. Results

### *3.1. The Effect of Co-Applying Biochar with Manure on French Bean Yield*

Generally, the yield of French beans in the treatment plots significantly differed ($p < 0.05$) from that in the control plots (Figure 2), with the highest values (31.02, 36.1, and 40.93 t/ha for seasons 1, 2, and 3) observed in plots amended with combined B3 + LM3 plot. Across the three growing seasons, plots treated with B or LM at 3 t/ha exhibited significantly higher French bean yields than plots treated with the same amendments at a 1 t/ha rate. In addition, during the first growing season, plots treated with LM alone yielded higher than those treated with B alone. However, in subsequent seasons, the yields in plots treated with LM decreased while the ones in B plots increased, as depicted in Figure 2. In addition, in the plots treated with B alone or combined with LM, there was a pronounced seasonal effect on yields, with the peak values recorded during the third growing season.in the first season, the green pod yield was 7.2, 7.7, and 13.9 for B alone; 8.7, 6.6, and 5.7 t/ha for LM alone; 13.9, 14.9, and 15.8 t/ha for B + LM plots; and 6.2, 5.8 and 5.1 t/ha for control plots.

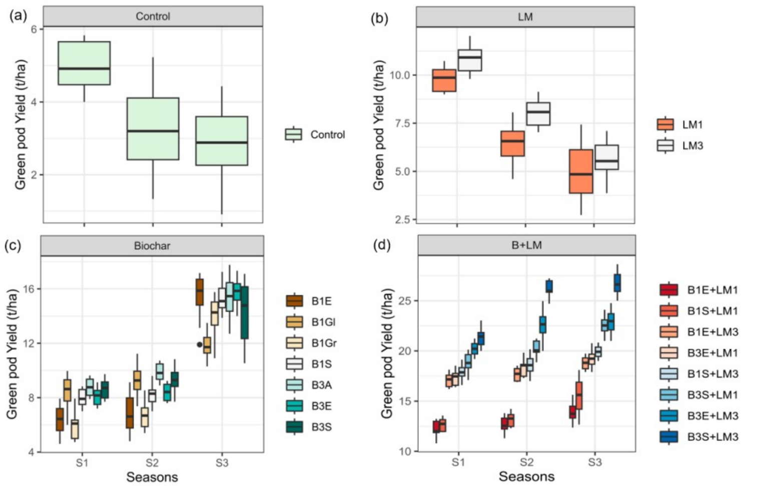



**Figure 2.** Effect of B amendments and LM on green pod yield, within (**a**) control, (**b**) LM plots, (**c**) B alone, and (**d**) B-LM. Bars represent values of four replicates and contain a standard error of means (n = 4). Bars with different letters differ significantly from each other at $p < 0.05$. B1E/B3E: Biochar produced from Eucalyptus wood and applied at 1 or 3 tons/ha. B1Gl: Biochar produced from Gliricidia wood and applied at 1 or 3 tons/ha. B1S/B3S: Biochar produced from Sesbania wood and applied at 1 or 3 tons/ha. B1Gr: Biochar produced from Grevillea wood and applied at 1 or 3 tons/ha. B3A: Biochar produced from Acacia wood and applied at 1 or 3 tons/ha.

### *3.2. The Effect of Biochar and Biochar + Manure on Soil Chemical Properties*

The results obtained on soil pH influenced by B and B-LM were presented in Supplementary Table S1 and Figure 3. The site factor was not significantly different for soil pH. The statistical analysis revealed a significant ($p < 0.05$) increase in pH following sole and combined applications of LM and B in both soils (Figure 3). The soil pH ranged from 6.77 to 5.43 for B plots, 6.7–5.35 for LM plots, 8.53–6.06 for B-LM plots, and 4.34–3.78 for control plots. Plots with 3 t/ha showed higher pH values than those amended with 1 t/ha (Supplementary Table S1).

The findings showed that Huye District was significantly high in soil OC but low compared to the Bugesera site (Figure 4). Compared to the control or sole treatment plots, the combined plots showed the highest value of OC ranging between 5.5 and 4.58 for B3Eucalptus + LM3 plots and 4.59 and 4.04 for B3Sesbania + LM3 plots (Table S1).

The Huye site was significantly ($p \leq 0.05$) high in soil T.N. but low in available P compared to the Bugesera site (Figure 5). The TN content ranged from 0.04 to 0.24% for B alone, 0.05–0.12% for LM alone, 0.4–0.11% for B + LM, and 0.43–0.41% for control plots. The available P ranged from 6.77 to 5.6 mg/kg, 6.7–5.34 mg/kg, 8.5–6.6 mg/kg, and 4.34–3.78 ppm for B alone, LM alone, B + LM, and controls plots, respectively. Furthermore, applying a higher level of 3 t/ha showed a significant increase than 1 t/ha.

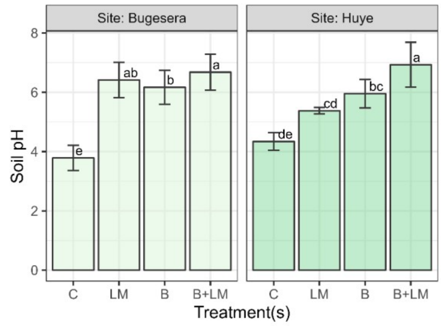



**Figure 3.** Effect of Biochar amendments and LM on Soil pH and Bars represents values of four replicates and contain a standard error of means (n = 4). Bars with different letters differ significantly from each other at $p < 0.05$.

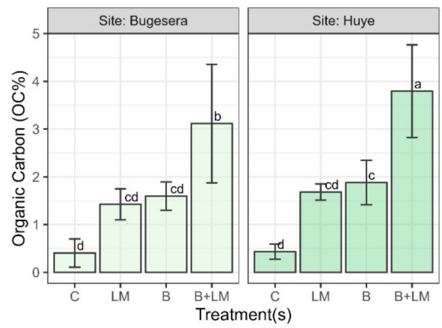



**Figure 4.** Effect of B amendments and LM on soil OC (percentage). Bars represent values of four replicates and contain a standard error of means (n = 4). Bars with different letters differ significantly from each other at $p < 0.05$.

The effect of B addition on CEC (Figure 6) and the contents of exchangeable bases (Table S1) in studied soils are in Figure 6. The analysis of variance showed that CEC and exchangeable bases including $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$ were significantly ($p < 0.05$) increased by application of B with the highest increase recorded in the soil amended with B and LM at 3 t/ha (Table S1) and this increase in CEC results in increment of basic cations. On the other hand, B addition did not significantly affect Sodium ($Na^{+}$). The soil CEC ranged between 17.89 and 8.1, 13.23 and 9.38, 24.05 and 11.42, and 6.42 and 5.51 cmol+/kg for B alone, LM alone, B + LM, and controls plots, respectively.

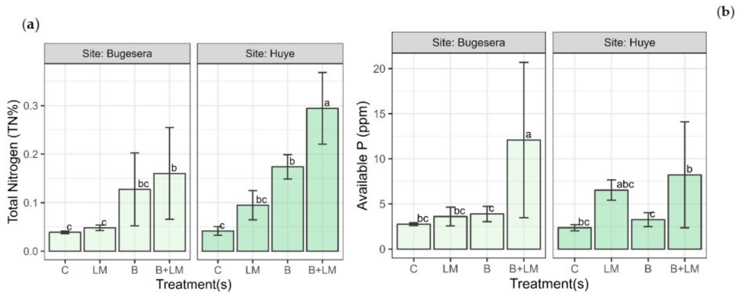



**Figure 5.** Effect of B amendments and LM on (**a**) soil TN (%) and (**b**) available P (ppm). Bars represent values of four replicates and contain a standard error of means (n = 4). Bars with different letters differ significantly from each other at $p < 0.05$.

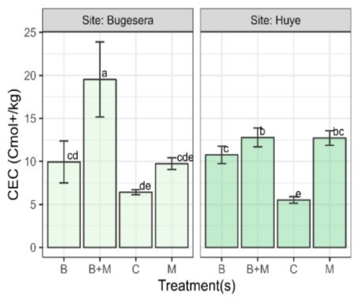



**Figure 6.** Effect of B amendments and LM on EC. Bars represent values of four replicates and contain a standard error of means (n = 4). Bars with different letters differ significantly from each other at $p < 0.05$.

## 4. Discussion

*Biochar and Biochar + Manure Effect on Yield of French Beans in the Studied Soils*

French beans are essential for smallholder farmers; therefore, concentrating limited resources such as LM and B on valuable vegetables like French beans can raise soil fertility by improving soil structure and water retention capacity, increasing yield [14]. Economically, this approach may increase income by focusing on crops with better market prices while reducing the need for inorganic inputs, lowering production costs, and promoting sustainability [33]. B's C sequestration capabilities help combat climate change, enhancing crop resilience to extreme weather. Efficient nutrient use through targeted application minimizes waste and optimizes resource benefits [34] (present study, the high seasonal yield was found in the B-LM plots where the maximum significant values were recorded in B + LM at a 3 t/ha application level). The higher yields may be due to the increased activity of meristematic tissues of plants at optimum fertility levels as B + LM plays a role in cell differentiation, meristematic division, and higher translocation of food materials in plants, thereby resulting in higher production of yield [35]. Furthermore, the application of B led to enhanced N-fixing organism activity and subsequently improved total crop biomass, indicating that B's resistance to chemical and biological processes promotes its long-term agronomic and environmental advantages with a residence period that could reach up to hundreds to thousands of years [36]. The yield increase was attributed to the integrated use of B along with LM improved soil health, creating a favorable environment for the growth and development of the crop [37–39]. This is in line with the study by Agbede et al. [40], reporting that the application of sole poultry manure did not enhance the growth and yield of cucumber but resulted in a substantial decrease in output after 1 month of application.

We observed a continuous increase in yield throughout three seasons, which may be attributed to the residual effect caused by the co-application of B and LM in the study areas. In the first growing season, the plots with LM alone showed a higher yield than those with B alone. Manure provides readily available nutrients for early-season plant growth, decomposes quickly (with declining nutrient release over time), and contributes SOM to enhance soil fertility. On the other hand, B has a gradual nutrient release, persists in the soils for an extended period, enhances SOM content, and reduces nutrient leaching through its porous structure [40]. The substantial decrease in the control plots was attributed to soil acidity that adversely affects synergistic interaction amid the legume crops and their linked rhizobia [34]. The residual effect revealed the sustainability of French bean production using B mixed with LM. The results obtained here are promising as they support the integrated soil nutrient management technology [40]. In addition, the results support that B was recalcitrant (i.e., stays longer in the soil), as reported by other authors [20,39]. Several authors [12,19,21] reported that combining B and M resulted in the highest radish yield and improved soil microbial community richness. According to Shifa et al. [19], B co-applied with LM at total rates showed the highest soil property and plant growth improvements relative to control. Ayito et al. [38] concluded that fruit length, weight, and yield were significantly improved by B treatments, with the combination of palm kernel husk B and poultry manure yielding the highest fruit weight. Increasing crop yield and performance due to the co-application of B with organic amendments have also been reported for crops including lettuce [9], maize [12], soya bean [19], tomatoes [10], mung bean [14], and radish [20].

The findings show that soil properties, at the end of three consecutive seasons, were improved, as showed by a higher yield of French beans in the areas of study (Section Biochar and Biochar + Manure Effect on Yield of French Beans in the Studied Soils). The Huye site was statistically significantly higher in soil OC, TN, pH, and CEC but low in available P (Table S1) compared to the Bugesera site. This was probably because the site was dominated by fine-textured soils (sandy clay loam), which contain a high percentage of clay and silt and tend to have naturally higher amounts of organic matter. The increase in soil pH in the B + LM plots can be attributed to the synergistic effect between B and LM. This was due to the high pH from B's inherent capacity to increase pH, alongside LM's contribution facilitated by the complexation of its organic anions released into the soil exchange sites [15]. The pH values recorded in this study were consistent with those reported by Habieb et al. [15], who concluded that the application of B + LM could improve soil quality by increasing soil pH.

The combined plots showed higher values of OC, TN, and available P content than the sole application plots. For OC, it was because of the C added by the B and the additional C from the organic matter through the LM addition [17]. For TN and available P, B improves the capacity of LM to improve acidic soil, increase CEC, and supplement the soil with nutrients released from their organic matter. Shifa et al. [19] also revealed the higher organic C and total N at the ancient terra preta compared with adjacent soils. The findings of Antonangelo et al. [22] confirmed that B-amended soils have more readily available P contents than soils without treatment. Similar results reported by Nguyen et al. [9] and Huang et al. [34] indicated that soil amended with B has a higher available P than unamended soil. The increase in the OC or other nutrients observed after the B and LM application agrees with the findings of Adekiya et al. [12,14] and de la Rosa et al. [17]. In addition, B addition to LM showed a significantly higher ($p < 0.005$) CEC content than the control or other treatments. This was due to the high surface area of B and highly porous, variable charge organic material from LM that could potentially increase CEC, surface sorption capacity, and base saturation when added to the soil. Within combined plots, high values of exchangeable bases might be attributed to the presence of ash in B and the organic matter derived from LM. The ash content of B helps in the immediate release of occluded mineral nutrients like Ca, K, and N for crop use [38]. The results of the present study also agree with previous studies [33–35], which reported the highest exchangeable bases in B-applied soils. The low levels of Na in the studied soils do not present deficiencies as it was regarded as a beneficial nutrient needed in a low quantity to avoid damage to soil structure, permeability, and plant growth.

## 5. Conclusions

Degraded tropical soils have low total OC, available P, N, and soil pH; hence, they have low crop yield. Therefore, restoration of degraded tropical soil was needed to ensure crop productivity. This study showed that the application of B, either alone or in combination with LM, significantly increased the green pod yield compared to control plots, with the highest values found in B + LM plots at 3 t/ha. LM plots yielded higher in the first growing season but decreased in subsequent seasons, with peak values recorded in the third season. The high yield was attributed to improved soil quality indicators and the residual effect caused by combining B + LM Biochar alone or combined with LM has improved chemical properties such as soil pH, soil OC, CEC, and soil nutrients (TN and avail P). The results of this study confirmed that the use of B together with LM for amending soils for vegetable cultivation could be an economically reasonable and environmentally justified way to enhance both agricultural productivity and soil quality, especially with coarse-textured soils. These findings showed that the co-application of B and LM could restore degraded soil in the tropics and increase the productivity of crops/vegetables. In addition, this integrated approach, which concentrates on limited resources such as B and LM, can benefit smallholder farmers when applied to their farms. This study recommends developing and promoting integrated soil fertility management programs that include B production and application and training of farmers on producing and using Biochar effectively. Longer-term effects shall be investigated to assess the effect of B on soil quality and crop production considering soil environment and using diverse feedstocks available in the Rwandan landscape to produce Biochar.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14092020/s1, Table S1: Soil properties as induced by biochar alone or combined with livestock manure in study areas.

**Author Contributions:** S.U. conceptualized the study, conducted fieldwork and laboratory analyses, and wrote manuscript drafts; J.N., G.N. and S.A.O.C. conceptualized the study, commented on drafts, and contributed to the writing. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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# CHAPTER FIVE

## 5.0 General Discussion, Conclusions and Recommendations

### 5.1 Discussion

This PhD Dissertation provides an integrated approach where TLUD stove that pyrolyse biomass (from AF trees) to generate heat for cooking and Biochar for soil improvement, could be a promising alternative to enhance fuel efficiency while reducing demand on existing biomass supplies (20-50%). Promoting the use of efficient cooking technologies as TLUD stoves not only reduce the demand for fuelwood by improving fuel efficiency but also produce B, which can enhance soil fertility. Encouraging the use of Biochar, as a soil amendment will address nutrient depletion, soil acidity, and organic matter depletion problems as B improves soil health, increases crop yields, and provides a use for biomass residues from AF.

Biomass (branches or sticks) from agroforestry species can be used for cooking in gasifier stove. Two cooking occasions per day annually require an estimated 679.886 kg of sticks or branches when cooking with gasifier stoves, while TSF stoves would consume 1281.223kg. The produced biomass (1059 kg of branches per year) would cover these cooking needs, and there would still be a surplus of fuel. Gasifier stoves also produced biochar of 91.51kg/year. In the context of Rwanda, where rural households heavily rely on biomass for cooking, the scenario of using agroforestry biomass in gasifier stoves offers a promising solution for sustainable energy consumption. Rwanda's smallholder farmers often face challenges with fuelwood scarcity and environmental degradation due to deforestation. Agroforestry, which integrates trees with crops and livestock, provides a renewable source of biomass (such as branches or sticks) that can be harvested without harming the ecosystem. Gasifier stoves, in particular, present an efficient alternative to traditional three-stone fires (TSF), which are commonly used in rural areas but have low fuel efficiency and contribute to indoor air pollution. Research findings showed that traditional TSF stoves required around 1,281 kg of biomass annually per household for cooking, while gasifier stoves reduced this demand to approximately 679 kg per year. This represents a significant fuel saving of nearly 50%, which not only alleviates the pressure on local forests but also reduces the time and labor spent on firewood collection, a task primarily undertaken by women and children (Gitau *et al.,* 2019). The use of agroforestry biomass, which can provide an estimated 1,059 (Garcıa Lopez *et al*.,2023) kg of branches annually, means that households using gasifier stoves would have surplus fuel available, which could either be used for additional energy needs or shared within the community, enhancing local energy security (Jafri *et al*., 2018).

Moreover, the adoption of natural draft gasifier stoves in Rwanda has additional benefits, particularly through the production of biochar. The findings showed that those gasifier stoves produced approximately 91.5 kg of biochar per year, which can be used as a soil amendment to improve soil fertility, water retention, and crop yields (Ren-yong *et al*., 2019). In Rwanda’s agricultural zones, where soil degradation and nutrient depletion are common, biochar application has been shown to enhance soil properties and support sustainable farming practices. This study demonstrated that biochar improved the nutrient availability and pH of acidic soils, leading to increased productivity in crops like French beans. Furthermore, gasifier stoves also offer environmental advantages by reducing carbon emissions and decreasing the demand for firewood. This aligns with Rwanda's commitment to environmental sustainability, as reflected in its National Strategy for Transformation (NST1), which emphasizes reducing biomass consumption and promoting alternative energy solutions to combat deforestation and greenhouse gas emissions (REMA, 2020). This integrated approach improves cooking energy access and addresses soil degradation, offering a sustainable model for smallholder farmers in regions facing fuelwood scarcity and soil fertility issues (Das *et al*., 2020; Singh *et al*., 2019; Jeffrey *et al.,* 2019). The research underscores the potential of biochar, especially when used alongside organic inputs like LM, to sustainably increase agricultural productivity and reduce the need for chemical fertilizers.

## 5.2 Conclusions

The integrated approach used in this study showed successful impact on cooking energy access among smallholder farmers. The gasifiers tested in SCTs performed well regarding fuel savings and ability to produce B with Gastov (Kenyan brand) performing better than Karundura (Rwandan brand). Additionally, user perceptions of both gasifiers were very positive concerning cooking benefits, agricultural uses, and air quality. The main challenges that may hinder the wider adoption of gasifiers in the region are costs, labour-related activities and device design. Regarding the fertility of soils and vegetable yield in various kitchen gardens, the results showed a significant increase in the yield of French beans over three consecutive seasons and an improvement of soil properties due to B application in Huye and Bugesera districts. Concurrently, the on-station study showed that co-application of B together with LM demonstrated positive effects on soil nutrients, soil acidity, soil Carbon, soil CEC properties and French bean yield over three consecutive seasons in Bugesera and Huye sites. This is due to the improvement of soil quality indicators and residual effect caused by combination of B and LM. This integrated approach can increase fuel sustainability due to the lower fuel requirement of TLUD gasifiers and contribute to solving the problem of fuelwood scarcity in rural areas of Rwanda. The increased vegetable yield can improve nutrition and/or farm economics in local communities and eventually enhance the adoption of the TLUD stoves, which will ensure energy sustainability. There is potential for the use of B in the production of high nutrients/high-value crops/vegetables. The results of this study confirmed that the use of B together with LM for amending soils for vegetable cultivation could be an economically reasonable and environmentally justified way to enhance both agricultural productivity and soil quality, especially with coarse textured soils. These findings showed that co-application of B and LM can restore degraded soil in the tropics and increase productivity of crops/vegetables. In addition, this integrated approach, which concentrate on limited (or locally available?) resources such as B and LM, can be highly beneficial for smallholder farmers when applied in their small farms.

**5.3 Recommendations**

Based on the findings of this study, the following recommendations can be made:

i. To facilitate the adoption of TLUD gasifiers in Rwanda, creating awareness about their wider benefits is important, e.g. use of TLUD stoves can improve health at household and community levels and reduce tree felling, which in turn has positive effects on climate change.
ii. Government and Non-Governmental Organizations should subsidize the cost of TLUD stoves to make them affordable for smallholder farmers. Additionally, educational campaigns should be conducted to demonstrate the benefits and usage of these stoves.
iii. Develop and promote integrated soil fertility management programmes that include B production and application. Provide training to farmers on how to produce and use biochar effectively.
iv. Future research on longitudinal studies on adoption rates and cost benefits analysis. In addition, long term studies on biochar alone or combined with other organic or inorganic shall be conducted.

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# APPENDICES

## Appendix 1: Table 2. Soil properties as induced by biochar alone or combined with livestock manure in study areas

| Treatment | Site | Soil pH | % OC | EC(ds/cm) | % TN | Available P (ppm) | CEC ($cmol_+$/kg) | $Ca^{2+}$($cmol_+$/kg) | $Mg^{2+}$($cmol_+$/kg) | $K^+$($cmol_+$/kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| B1Eucalptus | Bugesera | 6.24±0.35$^{cdefg}$ | 1.48±0.18$^{ghi}$ | 31.75±3.86$^{abc}$ | 0.04±0.01$^{l}$ | 6.2±0.4$^{cdefg}$ | 9.78±0.84$^{fghijkl}$ | 5.69±1.4$^{abcdefg}$ | 2.004±0.5$^{abcdefgh}$ | 0.83±0.5$^{mnop}$ |
| | Huye | 5.55±0.03$^{fgh}$ | 1.51±0.05$^{ghi}$ | 13.75±0.96$^{gh}$ | 0.15±0.01$^{hij}$ | 5.6±0.03$^{fgh}$ | 9.69±0.94$^{fghijkl}$ | 2.06±0.1$^{hi}$ | 0.41±0.04$^{k}$ | 0.17±002$^{p}$ |
| B1Gliricidia s. | Bugesera | 5.85±0.22$^{defg}$ | 1.37±0.12$^{hi}$ | 36.75±2.50$^{abc}$ | 0.14±0.00$^{ij}$ | 5.85±0.22$^{defg}$ | 8.1±0.54$^{jkl}$ | 4.56±0.6$^{bcdefghi}$ | 1.73±0.02$^{bcdefgh}$ | 0.39±01$^{op}$ |
| | Huye | 5.70±0.06$^{efg}$ | 1.51±0.09$^{ghi}$ | 16.75±0.96$^{defgh}$ | 0.17±0.01$^{ghi}$ | 5.7±0.06$^{efg}$ | 11.15±0.36$^{efghij}$ | 4.5±0.29$^{cdefghi}$ | 1.5±0.5$^{efghi}$ | 1.1±o.1$^{klmnop}$ |
| B1Sesbania s. | Bugesera | 6.11±0.58$^{cdefg}$ | 1.86±0.14$^{efgh}$ | 35.50±1.91$^{abc}$ | 0.14±0.02$^{ij}$ | 6.11±0.58$^{cdefg}$ | 11.41±1.52$^{efghij}$ | 5.22±0.8$^{abcdefgh}$ | 1.73±0.2$^{bcdefgh}$ | 0.56±0.38$^{nop}$ |
| | Huye | 5.76±0.02$^{defg}$ | 1.36±0.17$^{hi}$ | 15.00±1.15$^{fgh}$ | 0.16±0.01$^{hij}$ | 5.75±0.02$^{defg}$ | 11.69±1.43$^{efghij}$ | 3.65±0.1$^{efghi}$ | 1.42±0.09$^{efghi}$ | 0.42±0.03 |
| B1 Greveliria r. | Bugesera | 5.91±0.50$^{cdefg}$ | 1.38±0.05$^{hi}$ | 30.25±5.97$^{abcde}$ | 0.04[illegible]1$^{l}$ | [illegible]±0.5$^{cdefg}$ | 8.76±1$^{ijkl}$ | 4.25±0.4$^{defghi}$ | 1.45±0.2$^{efghi}$ | 0.64±0.6$^{nop}$ |
| | Huye | 5.43±0.08$^{gh}$ | 1.62±0.04$^{fghi}$ | 16.50±1.29$^{efgh}$ | 0.16[illegible]1$^{ghij}$ | 5.42±0.08$^{gh}$ | 11.49±0.77$^{efjhij}$ | 3.32±$^{fghi}$ | 1.19±0.2$^{hijk}$ | 0.33±0.03$^{op}$ |
| B3 Eucalyptus | Bugesera | 6.43±0.75$^{bcdefg}$ | 1.72±0.18$^{efghi}$ | 31.50±1.91$^{abc}$ | 0.08±0.01$^{kl}$ | 6.43±0.75$^{bcdefg}$ | 9.05±0.88$^{hijkl}$ | 5.37±1.1$^{abcdefgh}$ | 1.3±0.5$^{ghij}$ | 0.58±0.23$^{nop}$ |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Huye | 6.52±0.08$^{bcdefg}$ | 2.39±0.05$^{defgh}$ | 13.25±0.96$^{gh}$ | 0.18±0.02$^{ghi}$ | 6.52±0.08$^{bcdefg}$ | 10.76±0.84$^{fghij}$ | 4.49±0.2$^{cdefghhi}$ | 1.9±0.15$^{abcdefgh}$ | 0.38±0.04$^{op}$ |
| B3 Sesban s. | Bugesera | 6.29±0.60$^{cdefg}$ | 1.44±0.18$^{hi}$ | 40.00±2.94$^{ab}$ | 0.21±0.01$^{efg}$ | 6.29±0.59$^{cdefg}$ | 17.89±2.1$^{bcd}$ | 7.1±0.5$^{abcdefgh}$ | 2.3±0.32$^{abcde}$ | 0.96±0.7$^{lmnop}$ |
| | Huye | 6.77±0.17$^{bcde}$ | 2.29±0.03$^{defgh}$ | 14.50±1.29$^{gh}$ | 0.19±0.04$^{fgh}$ | 6.77±0.17$^{bcde}$ | 10.19±0.65$^{fghijk}$ | 3.38±0.2$^{fghi}$ | 1.16±0.02$^{hijk}$ | 0.88±0.1$^{mnop}$ |
| B3 Acacia a. | Bugesera | 6.37±0.94$^{bcdefg}$ | 1.94±0.46$^{efgh}$ | 35.50±3.11$^{abc}$ | 0.24±0.01$^{cdef}$ | 6.37±0.93$^{bcdefg}$ | 8.76±1.41ij$^{kl}$ | 5.15±0.5a$^{bcdefgh}$ | 1.38±0.2$^{fghi}$ | 1.20±0.5$^{jklmnop}$ |
| | Huye | 5.96±0.11$^{cdefg}$ | 2.50±0.07$^{defgh}$ | 17.00±1.41$^{defgh}$ | 0.20±0.02$^{fgh}$ | 5.96±0.11$^{cdefg}$ | 10.35±0.42$^{fghijk}$ | 2.74±0.2$^{ghi}$ | 1.38±0.2$^{fghi}$ | 0.15±0.01$^{p}$ |
| M1 | Bugesera | 6.13±0.42$^{cdefg}$ | 1.49±0.18$^{ghi}$ | 33.00±5.42$^{abc}$ | 0.05±0.01$^{l}$ | 6.13±0.42$^{cdefg}$ | 9.38±0.7$^{ghijkl}$ | 5.59±0.12$^{abcdefgh}$ | 0.5±0.1$^{jk}$ | 1.26±0.63$^{jklmnop}$ |
| | Huye | 5.35±0.12$^{gh}$ | 1.54±0.06$^{fghi}$ | 16.50±2.08$^{efgh}$ | 0.07±0.02$^{l}$ | 5.34±0.12$^{gh}$ | 12.23±0.6$^{efghij}$ | 6.65±0.5$^{abcdef}$ | 1.42±0.21$^{efghi}$ | 2.18±0.14$^{hijklmno}$ |
| M3 | Bugesera | 6.70±0.65$^{bcdef}$ | 1.36±0.45$^{hi}$ | 32.00±6.88$^{abc}$ | 0.05±0.01$^{l}$ | 6.7±0.65$^{bcdef}$ | 10.08±0.5$^{fghijk}$ | 5.96±1.5$^{abcdefg}$ | 2.57±0.3$^{ab}$ | 1.71±0.2$^{ijklmnop}$ |
| | Huye | 5.41±0.11$^{gh}$ | 1.83±0.08$^{efgh}$ | 14.50±0.58$^{gh}$ | 0.12±0.01$^{jk}$ | 5.4±0.11$^{gh}$ | 13.23±0.8$^{efgh}$ | 7.38±0.3$^{abcd}$ | 1.4±0.3$^{fghi}$ | 5.12±0.5$^{ab}$ |
| B1Eucalptus+ M1 | Bugesera | 6.81±0.52$^{bcde}$ | 2.37±0.74$^{defgh}$ | 30.25±7.14$^{abcde}$ | 0.0[illegible]1$^{l}$ | [illegible]14$^{bcde}$ | 12.91±1.4$^{efghi}$ | 7.69±1.4$^{abcd}$ | 2.01±0.03$^{abcdefg}$ | 2.41±0.7$^{ghijklmn}$ |
| | Huye | 6.69±0.11$^{bcdef}$ | 2.86±0.11$^{cdef}$ | 16.50±1.29$^{efgh}$ | 0.26±0.02$^{cd}$ | 6.69±0.11$^{bcdef}$ | 12.7±0.5$^{efghi}$ | 6.22±0.5a$^{bcdefg}$ | 2.1±0.2$^{abcdefgh}$ | 3.53±0.2$^{bcdefghi}$ |
| B1Sesbania +M1 | Bugesera | 6.16±0.41$^{cdefg}$ | 2.10±1.02$^{efgh}$ | 26.00±1.41$^{cdefgh}$ | 0.16±0.01$^{hij}$ | 6.78±0.14$^{bcde}$ | 15.37±2.15$^{cde}$ | 7.18±2.9$^{abcde}$ | 1.75±0.5$^{bcdefgh}$ | 2.91±0.6$^{efghijkl}$ |

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| | Huye | 6.79±0.14 bcde | 2.55±0.21 defgh | 16.00±0.82 fgh | 0.24±0.04 cdef | 6.16±0.41 cdefg | 11.42±0.4 efghij | 5.63±0.21 abcdefg | 1.9±02a bcdefgh | 2.67±0.3 fghijklm |
| B1 Eucalptus+M3 | Bugesera | 6.91± 0.73 bcd | 2.98±0.74 cde | 27.00±1.63 bcdefg | 0.05±0.01 l | 6.91±0.73 bcd | 18.83±0.76 bc | 6.39±1.9 abcdef | 2.5±0.5 abcd | 1.64±0.9 ijklmnop |
| | Huye | 6.06±0.13 cdefg | 3.51±0.21 bcd | 16.75±1.50 defgh | 0.26±0.02 cd | 6.06±0.12 cdefg | 12.96±1.3 efghi | 6.21±0.9 abcdefg | 1.6±0.2 defgh | 2.96±0.2 defghij |
| B1Sesbania+M3 | Bugesera | 6.30±0.12 cdefg | 2.07±1.43 efgh | 28.50±3.32 abcdef | 0.17±0.01 ghi | 6.29±0.12 cdefg | 17.89±2.1 bcd | 5.51±1.2 abcdefgh | 2.12±0.5 abcd | 3.14±2. 3cdefghij |
| | Huye | 6.65±0.23 bcdef | 3.01±0.33 cde | 15.25±0.96 fgh | 0.23±0.02 def | 6.65±0.23 bcdef | 13.67±1.26 defg | 8.3±1.7a | 2.01±0.17 abcdefgh | 4.89±0.6 abcd |
| B3 Eucalyptus +M1 | Bugesera | 6.75±0.71 bcdef | 4.01±0.81 bc | 33.75±7.14 abc | 0.13±0.01 ij | 6.75±0.71 bcdef | 21.75±1.11 ab | 7.19±2.18abcde | 2.21±0.55a bcdef | 4.09±0.7 abcdefgh |
| | Huye | 6.38±0.21 bcdefg | 4.38±0.20 ab | 16.75±1.26 defgh | 0.25±0.02 cde | 6.38±0.21 bcdefg | 12.12±0.9e fghij | 8.1±1.17ab | 2.52±0.14 abc | 4.84±0.4 abcde |
| B3Sesbania+M1 | Bugesera | 6.69±051 bcdef | 2.79±1.39 cdefg | 30.50±6.35 abcd | 0.26±0.01 cd[illegible] | [illegible]±0.51 bcdef | 22.1±0.71 ab | 5.8±2.3abcdefg | 1.9±0.73 abcdefgh | 1.92±0.94 ijklmnop |
| | Huye | 6.83±0.30 bcde | 3.96±0.20 bc | 12.25±0.50 h | 0.2[illegible]1 c | [illegible]±0.29 bcde | 12.96±1.02 efghi | 7.9±0.5abc | 1.82±0.13 abcdefgh | 4.22±0.32 abcdefg |
| B3Eucapltus +M3 | Bugesera | 7.12±0.63 bc | 4.58±0.41 ab | 30.50±11.73 abcd | 0.1[illegible]1 ij | 7.11±0.68 bc | 23.30±4.67 a | 7.12±3.5abcde | 1.62±0.4 defgh | 5.06±2.06 abcdefgh |
| | Huye | 7.53±0.19 ab | 5.50±0.25 a | 61.50±1.29 efgh | 0.42±0.03 a | 7.53±0.19 ab | 12.78±0.3 efghi | 8.1±0.4 a | 2.52±0.23 abc | 5.06±0.14 abc |

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| B3Sesbania + M3 | Bugesera | 6.72±0.83 $^{bcdef}$ | 4.04±0.44 $^{bc}$ | 31.75±5.91 $^{abc}$ | 0.34±0.02 $^{b}$ | 6.7±0.83 $^{bcdef}$ | 24.048±3.69 $^{a}$ | 5.37±0.9 $^{abcdefgh}$ | 1.67±0.3 $^{cdefgh}$ | 4.52±1.54 $^{abcdef}$ |
| | Huye | 8.53±0.25 $^{a}$ | 4.59±0.41 $^{ab}$ | 14.75±3.86 $^{fgh}$ | 0.40±0.04 $^{a}$ | 8.5±0.24 $^{a}$ | 13.67±1.21 $^{defg}$ | 8.08±0.9 $^{ab}$ | 2.66±0.17 $^{a}$ | 5.68±0. 07 $^{a}$ |
| Control | Bugesera | 3.78±0.43 $^{i}$ | 0.41±0.30 | 42.00±18.13 $^{a}$ | 0.04±0.00 $^{l}$ | 3.78±0.42 $^{i}$ | 6.42±0.3 $^{kl}$ | 3.05±0.9 $^{fghi}$ | 0.64±0.26i $^{jk}$ | 0.22±0.1 $^{p}$ |
| | Huye | 4.34±0.30 $^{hi}$ | 0.43±0.16 | 25.75±6.18 $^{cdefgh}$ | 0.04±0.01 $^{l}$ | 4.34±0.29 $^{hi}$ | 5.51±0.4 $^{i}$ | 1.45±0.25 $^{i}$ | 1.18±0.17 $^{hijk}$ | 0.14±0.01 $^{p}$ |