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Large Scale Nationwide Screening of Bioavailable Tetracyclines and Arsenic Using Whole-cell Bioreporter from Pangasius and Tilapia Aquaculture System in Bangladesh

Md. Emranul Ahsan[1], Mohammad Abdur Razzak[2], Seikh Razibul Islam[2], Ajmala Akter[1] & Md. Lokman Ali[2]

[1] Department of Fisheries Management, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh

[2] Department of Aquaculture, Patuakhali Science and Technology University, Patuakhali 8602, Bangladesh

Correspondence: Md. Emranul Ahsan, Department of Fisheries Management, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh. Tel: 880-171-509-3536. E-mail: meahsan@bsmrau.edu.bd

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Abstract

In this study, a large-scale screening of bioavailable tetracycline (TC) and arsenic (As) was carried out using Whole-Cell biosensor bacteria from the pond surface waters of selected pangasius and tilapia farms across Bangladesh. Bioavailability of Tetracyclines and Arsenic was detected using biosensor bacteria *E. coli* K12 pTetLux1 and *E. coli* DH5R (pJAMA-arsR), respectively. 62 samples were within the tetracycline detection limit; others were below the detection limit. The highest concentration 31.27µg/l was found in a pond of Jashore and the lowest concentration 2.57µg/l, was measured from Trishal, Mymensingh. Tetracyclines were detected in 19.57 % of all analyzed samples and varied from below the detection limit to a maximum of 31.27 µg/l. Khulna showed the maximum percentage of detected samples (90%), followed by Mymensingh (52%), Cumilla (27.5%), Jashore (14%), Bogura (14%), and Sathkhira (10%). Bioavailable As were detected in only 5.7% of all analyzed samples. Detectable as samples were higher in number among the collected samples at Madaripur and higher in percentage at Sathkhira (30%) followed by Madaripur (20%), Cumilla (5%), and Gopalgonj (3.2%). The pick level of Arsenic was found in Madaripur, which was 9.45 µg/l and the lowest figure was 2.35 µg/l, found in Cumilla. Though the concentrations of arsenic in groundwater (tube well water) were high in all studied regions, the concentrations of arsenic in pond water were low in every region. The concentration of as in the experimental ponds was neither very high nor in the danger limit. Use of shallow tube well water, fertilizers, drugs, pesticides, and herbicides possessed with as during fish culture might be the source of as contamination. However, extensive use of antibiotics results in the emergence and spread of antibiotic resistance in the aquatic environment.

Keywords: biosensor, bioavailability, tetracyclines, arsenic, aquaculture, Bangladesh

1. Introduction

Aquaculture is the largest sector of food production in the world, which has the potential to contribute to maintainable food production in the upcoming days (Hameed et al., 2022). In the most recent two decades, Bangladeshi aquaculture has improved expanded, and progressed innovatively with a growing trend to intensify cultural techniques in some regions in Bangladesh (Belton and Azad, 2012; Ali et al., 2013). With the extension and escalation of the aquaculture sector, there has been an increasing interest in using synthetic compounds and organic products (Faruk et al., 2008). Different natural and synthetic substances significantly contribute to treating and inhibiting various diseases, recovering water quality, upturning pond natural production, and growth promoters (Rico et al., 2013). Tetracycline antibiotics are the most important among them. Chlortetracycline and oxytetracycline, the naturally occurring antimicrobial agents were first discovered in the last part of the 1940s.

To improve growth rate and feed efficiency in animals, antibiotics are broadly used to treat and prevent infectious diseases in humans and livestock, and they are likewise utilized in agriculture and aquafarming (Cabello, 2006; FDA, 2009; McEwen and Fedorka-Cray, 2002; McManus et al., 2002). After applying antimicrobials, a substantial portion is discharged into various ecological sections (Zhou et al., 2013). About 30%

to 90% of all antimicrobials utilized in humans and livestock are released unaltered into the environment via domestic sewage (Jjemba, 2006; Lienert et al., 2007).

Groundwater has been utilized comprehensively as the principal wellspring of drinking and irrigation water availability in Bangladesh since the 1960s. It assumes a crucial part in making the nation independent in food production. Groundwater supplies about 90% of irrigation and 99% of drinking water in Bangladesh. However, this water asset is confronting issues remembering quality risk for some regions where the disclosure of contamination from cultivation and arsenic contamination in shallow aquifers makes the water unsafe for public use (Anwar et al., 2008). Groundwater and surface water tainting by arsenic happened normally or from human activities. Surface and groundwater are fundamentally utilized for aquaculture in Bangladesh. Some potential human health dangers are identified with domesticated animals and freshwater fisheries as these can be exposed to As through drinking water, lake water, and feeds.

Arsenic contamination and antimicrobial agents' utilization in aquaculture can be controlled by regular observation of arsenic and antibiotic deposits in various samples. In the present study, 325 farms were surveyed from different regions of Bangladesh where pangasius and tilapia are being cultured commercially to monitor or detect the bioavailable concentration of tetracyclines and arsenic using a whole-cell bacterial biosensor. One of the most important features of whole cell bioreporters (WCBs) is their capability to enumerate bioavailability that gives information associated with the effects of contaminants on living organisms and cannot be assessed by traditional instrumental analysis. The use of WCBs is more beneficial than any other chemical analysis since it is a stable, low-cost, high-throughput process and ideal for a large number of samples to be rapidly screened. This study aimed to provide information on the quantities of bioavailable arsenic and tetracyclines using whole cell bioreporters in pangasius and tilapia farms across Bangladesh and their interaction. To our knowledge, this is the first-ever large-scale monitoring of bioavailable tetracyclines and arsenic using whole-cell bioreporters of environmental samples across Bangladesh.

2. Materials and Methods

2.1 Sampling Sites and Collection of Samples

There are some distinct regions of Bangladesh where pangasius and tilapia aquaculture have been carried out at a large scale and dominated by other finfish. The major regions are Mymensingh, Cumilla, Bogura, and Jashore. Besides these areas, pangasius and tilapia are also being cultured in some other regions of Bangladesh on a medium scale (Figure 1). Arsenic contamination is dominant in some particular regions of Bangladesh. Jashore, Comilla, Feni, Chandpur, Madaripur, Shariatpur, and Sathkhira regions are highly affected by arsenic. 325 pond samples were collected for analysis of bioavailable tetracycline, and 212 samples were selected for the analysis of bioavailable arsenic from these regions. Besides these, 45 tube-well water samples from some arsenic sampling areas were collected to compare underground water arsenic concentration with pond water. A 100ml plastic water bottle was used to collect samples. High-resolution GPS coordinates were recorded for each pond. Water bottles were kept in the icebox with coolants to maintain the water temperature around 10-15˚C during transportation and to prevent direct exposure to light. After arrival in the lab, samples were stored in a freezer at -20˚C.

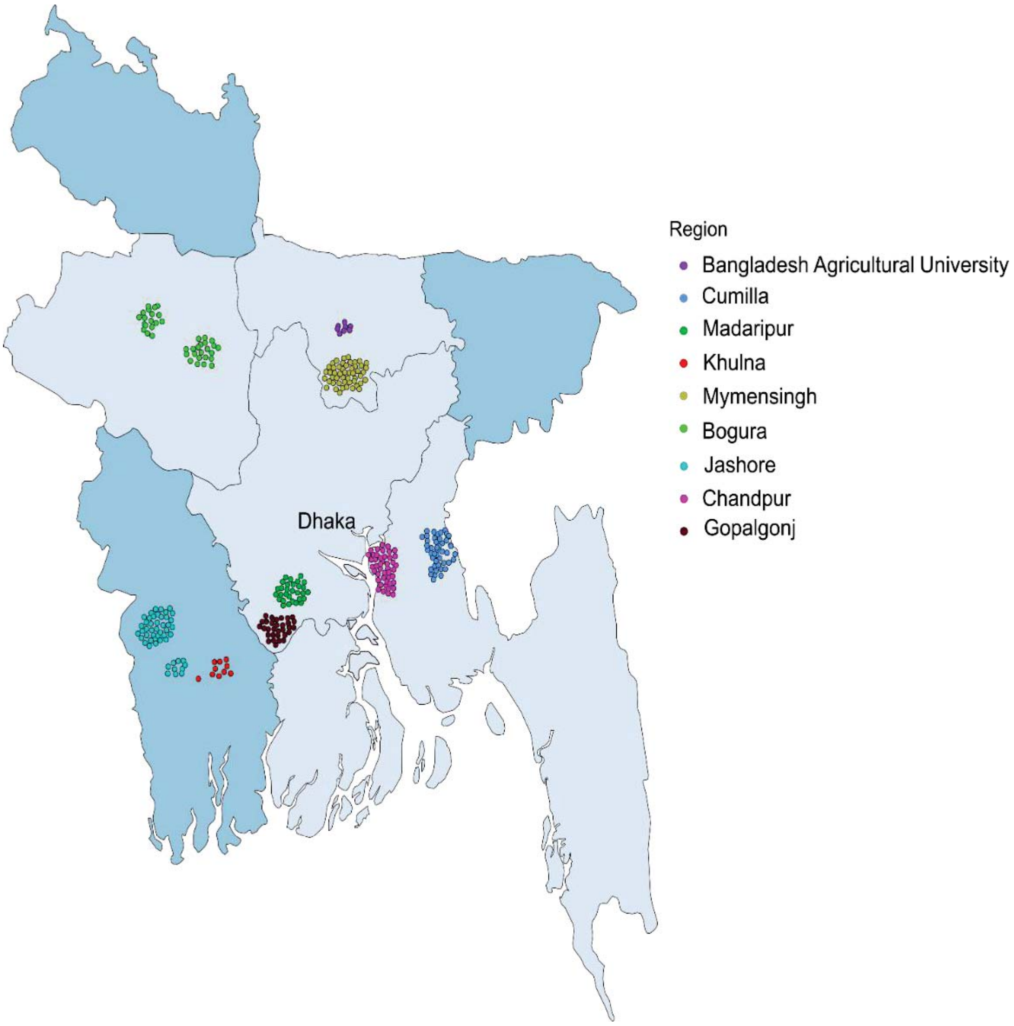

Figure 1. Map of Bangladesh showing all sampling locations of this study. The sampling ponds are colored according to the region in which they are located

2.2 Bacterial Strains, Plasmids, and Media

2.2.1 Tetracycline Biosensor Strain

The construction of the tetracycline biosensor strain *E. coli* K12 (pTetLux1) is described by Korpela et al. (1998). In brief, the luciferase operon luxCDABE of *P. luminescens* bacteria from pCGLS-11 was embedded as an EcoRI piece leveled out of the tetracycline-inducible tetA promoter/operator in pASK75. The subsequent plasmid build, pTetLux1, was changed by electroporation into *E. coli* K12 strain M72 to get a bioluminescent antibiotic-responsive biosensor strain. The bacteria were refined at 37 °C with air circulation (200 rpm) in Luria-Bertani stock (LB; 1% (w/v), tryptone, 0.5% (w/v) yeast, 0.5% (w/v) NaCl, pH 7.0) enhanced with 100 µg mL-1 ampicillin (LBAmp).

2.2.2 Arsenic Biosensor Strain

The construction of an arsenic biosensor, *E. coli* DH5R (pJAMA-arsR), is described by Stocker et al. (2003). Briefly, arsenic detection by the bacterial biosensor is based on bioluminescence created by the cells due to the presence of arsenic. Under the expression regulation of the ArsR repressor enzyme, bioreporter cells bear a plasmid with genes for bacterial luciferase (luxAB). Cell passage of arsenite causes the arrival of transcriptional constraint and the resulting amalgamation of luciferase by the cells. Arsenate is impulsively decreased by the cells to arsenite and can indirectly induce derepression and luciferase synthesis.

2.3 Preparation of Standard Solution

2.3.1 Tetracycline Standard Solution

On the analysis day, different concentrations of tetracycline standard solutions were prepared from tetracycline stock solution (10mg/ml in 70% ethanol). The concentration of standard solutions were: 150, 100, 75, 50, 25, 12.5, 6.25, 3, 2, 1.5 and 0 µg/l.

2.3.2 Arsenic Standard Solution

Standard solutions were freshly prepared on the day of analysis. For arsenate: Disodium Hydrogen Arsenate ($Na_2HAsO_4 \times 7H_2O$) in the 0- 3000 µg/l concentration range. For arsenite: Sodium arsenite ($NaAsO_2$) in the 0-300 µg/l concentration range.

2.4 Plate Assay

2.4.1 Tetracycline Plate Assay

A tetracycline plate assay was performed using cells cultured in LB media. Cells were cultured in 25ml LB media with 100µg/ml ampicillin in 100ml glass flask directly inoculated from an LB agar plate with ampicillin (100µg/ml) and incubated at 20˚C for 14-16 hours to obtain an OD_{600} around 1.5. The cultured cell was diluted in LB media without ampicillin to get OD_{600}=0.02. Cultured cells were divided onto white 96-well flat-bottom microtiter plates (NUNC^{TM}, ThermoFisher Scientific Inc., Massachusetts, USA) as 100 µL aliquots. Beforehand, the wells had been dispensed with 100 µL of samples and standard solutions. The plates were covered by a lid and incubated for 3hrs at 37˚C and 200rpm in darkness. Bioluminescence was read from the plates by a multi-detection microplate reader, the luminometer (FLUOStarOptima, BMG Labtech, Ortenberg, Germany).

2.4.1 Arsenic Plate Assay

Arsenic plate assay was performed by reviving the cell on LB-agar plates with 50 µg/L ampicillin at 37 °C overnight. One colony was transferred to 25 ml LB + 50 µg/L ampicillin the next day and grown horizontally at 37 °C at 200 rpm. The overnight culture was harvested at 5000 g for 10 minutes and suspended in LB to obtain an absolute OD600 of 0.02. 100 µL of standard or sample solution was mixed with 100 µL cell suspension in white 96-well microtiter plates and incubated at 28°C for 2 hours. Luminescence was measured with a plate reader where decanal (35 µL decanal + 10 mL 50 % ethanol) was used as an external substrate for the cells.

2.5 Calculation

2.5.1 Tetracycline Concentration

From the measurements of the standard solution rows, standard curves were derived, fitted by third-order polynomial regression.

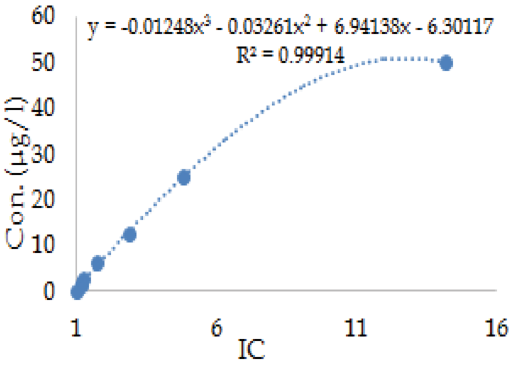

Figure 2. Standard curve for the biosensor assay with *E. coli* K12 (pTetLux1) for Tetracycline, respectively, showing the dependency of the batch for the analysis (IC = induction Coefficient; Con = Tetracycline concentration in µg/L)

The calibration curves were based on an induction Coefficient (IC) which relates the measured bioluminescence in the sample to the bioluminescence in the blanks to correct background noise and account for drift. It was calculated as follows:

$$\text{Induction coefficient (IC)} = \frac{\text{Luminescence in sample solution (LM)}}{\text{Background luminescence in blank (LW)}}$$

2.5.2 Arsenic Concentration

From the measurements of the standard solution rows for both As(V) and As(III), calibration curves were derived and fitted by third-order polynomial regression (examples for two different batches, respectively, are shown in Figure 3). As discussed earlier, pJAMA arsR primarily responds to As(III), and only after enzymatic reduction of As(V) to As(III) also to As(V), which is why As(III) induces the biosensor much stronger.

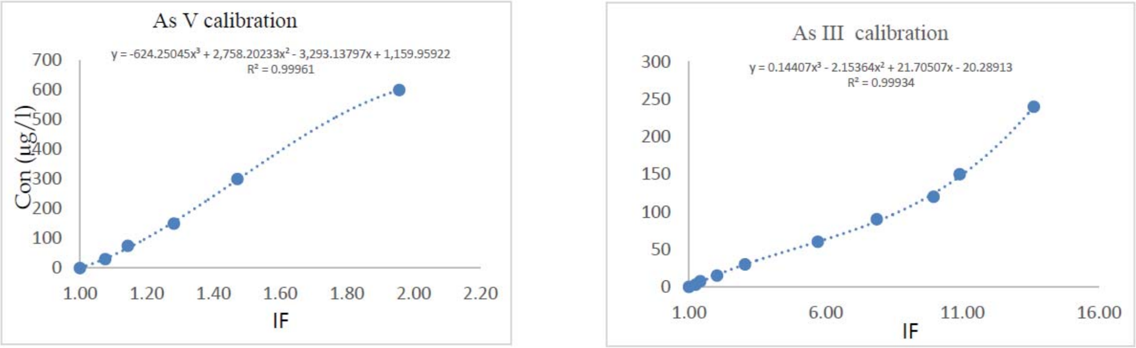

Figure 3. Two example calibration curves for the biosensor assay with *E.coli* pJAMA arsR for As(V) and As(III), respectively, showing the dependency of the batch for the analysis (IF = induction factor; Con = As concentration in µg/L)

The calibration curves were based on an induction factor (IF) that relates the measured bioluminescence in the sample to the bioluminescence in the blanks to correct background noise and account for drift. It was calculated as follows:

$$\mathrm{IF} = \frac{\text{bioluminescence in the sample}}{\text{mean bioluminesence in blanks before and after the sample}}$$

2.6 Statistical Analysis

Statistical analysis was done using Microsoft Excel Software 2010 and SPSS 23 (Statistical Package for Social Science). Collected data were coded and entered into a database system and analyzed.

3. Results

3.1 Bioavailable Tetracycline Concentration in Different Ponds

Bioavailable tetracycline concentrations of 325 ponds were analyzed in laboratory conditions using a whole-cell bacterial biosensor named *E.coli* K12 pTetlux1. A total of 62 samples were in the range of the tetracycline detection limit others were below the detection limit (Table S1). Biosensors can usually detect the bioavailability of any sample if the Induction coefficient is 50% higher than the neutral IC (IC 1). For this reason, the Induction coefficient of 1.5 and more than 1.5 is considered to measure the bioavailability of tetracyclines. The tetracycline concentrations were higher in some Jashore, Cumilla, and Mymensingh ponds and very low in some Chandpur, Madaripur, and Satkhira ponds. The highest concentration 31.27µg/l was found in a pond of Jashore and the lowest concentration 2.57µg/l was measured from Trishal, Mymensingh. Most samples in the Khulna region showed tetracycline concentration at the detection limit. All samples of Chandpur and Madaripur showed TC Concentration below the detection limit.

A comparative study of bioavailable tetracycline in different regions of Bangladesh was done and the results are shown in table 3.1. Samples were categorized into 9 sections. These were below detection, >0 to ≤3, >3.0 to ≤4.0, >4.0 to ≤6.0, >6.0 to ≤8.0, >8.0 to ≤10.0, >10.0 to ≤12.0, >12.0 to ≤15.0, >15.0 to ≤20.0 and >20 µg/l. Among these, the highest number of samples (258) were below the detection limit. Among the samples at the TC detection limit, the >4.0 to ≤6.0 section showed the highest number of samples and the number was 24. All the samples of Chandpur and Madaripur were below the detection limit. Only two samples with more than 20 µg/l concentrations were detected, from Bogura and Jashore. A comparative study of measured bioavailable tetracycline in different regions of Bangladesh is shown in Figure 4.

Table 1. Comparative study of bioavailable tetracycline in different regions of Bangladesh

Region	**No. of sample**	**Below detection**	**>0-≤3**	**>3.0-≤4.0**	**>4.0-≤6.0**	**>6.0-≤8.0**	**>8.0-≤10.0**	**>10.0-≤12.0**	**>12.0-≤15.0**	**>15.0-≤20.0**	**>20**
Bogura	50	43	0	0	1	1	3	1	0	0	1
Cumilla	50	39	0	1	2	1	3	1	1	2	0
Jashore	40	33	0	0	0	3	1	0	1	1	1
Khulna	10	1	0	0	3	2	2	0	0	2	0
Mymensingh	53	26	1	2	17	7	0	0	0	0	0
Chandpur	51	50	0	0	0	0	0	0	0	0	0
Gopalganj	31	27	0	2	1	0	1	0	0	0	0
Madaripur	30	30	0	0	0	0	0	0	0	0	0
Satkhira	10	9	0	0	0	1	0	0	0	0	0
Total	325	258	1	5	24	15	10	2	2	5	2

Percentages of TC detected samples within the total experimented sample within every region were calculated (Figure 3.6). Tetracyclines were detected in 19.57 % of all analyzed samples and varied from below the detection limit to a maximum of 31.27 µg/l. Khulna showed the maximum percentage of detected samples (90%), followed by Mymensingh (52%), Cumilla (27.5%), Jashore (14%), Bogura (14%) and Sathkhira (10%). The lowest value was found in the samples of Chandpur and Madaripur (0%).

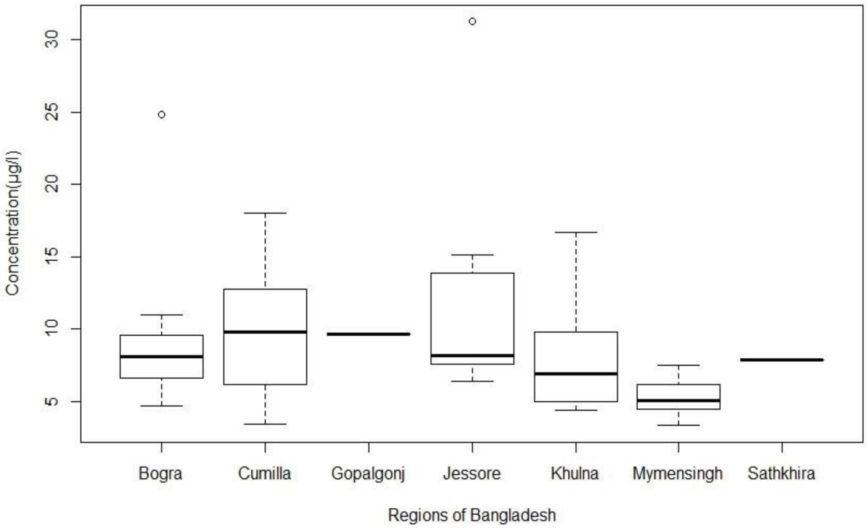

Figure 4. Measured bioavailable concentration of tetracycline (only detected values) in ponds water samples. The median, the 25th and 75th percentiles, the lowest datum within 1.5 times the interquartile range of the lower quartile, and the highest datum within 1.5 times the interquartile range of the upper quartile are shown in each box. Dots reflect outliers

3.2 Bioavailable Arsenic (As) Concentration of Ponds in the Study Area

Only 12 samples among 212 showed as presence (Table S2) as concentrations of the pond's water sample varied with the geographical location of the ponds. Some ponds showed a statable amount of as and some were null. In this study, the pick level of Arsenic was found in Madaripur, which was 9.45 µg/l. On the other hand, among the detected samples lowest figure was 2.35 µg/l, found in Cumilla. Concentrations were zero or below the detection limit in all ponds in Jashore, Chandpur, and Mymensingh regions.

Availability of as in water samples among the collected samples from selected regions was calculated in percentage value. Bioavailable As were detected in only 5.7% of all analyzed samples. Detectable as samples were higher in number among the collected samples at Madaripur and higher in percentage at Sathkhira (30%) followed by Madaripur (20%), Cumilla (5%), and Gopalgonj (3.2%). On the contrary, all the samples from Jashore, Chandpur, and Mymensingh were found below the detection limit and the percentage of arsenic was Zero (0%). Availability of as based on percentage value among samples from different regions of Bangladesh is shown in Figure 5.

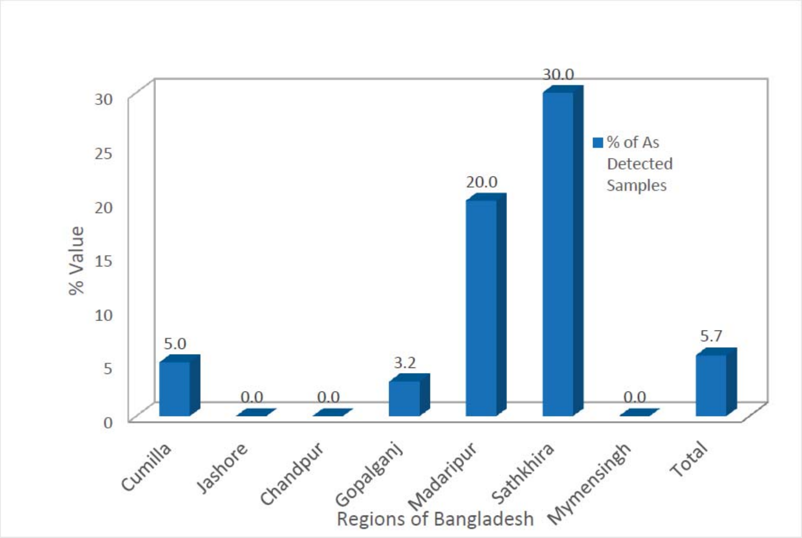

Figure 5. Percentages of samples at bioavailable arsenic detection limit

3.3 Bioavailable Arsenic (As) Concentration of Tube Wells in the Study Area

Individual water samples were collected from the tube wells during the study period to analyze the as concentration of tube well (underground) water from the same regions (Table S3). A total of 45 samples were culled from all these regions where five from each region. Among the supplied samples, twelve were found to be below the detection level, and their concentration was assumed to be zero. The highest value of as concentration was found in Madaripur which was 37.96 µg/l. Near all water samples of Gopalgonj, Jashore, Chandpur and Madaripur were found to be affected with arsenic but in variable concentrations.

3.4 Comparative Study on Available Percentages between Tube Well and Pond Water Samples

A comparative study was performed on the percentages of available As between tube wells and pond water. All of the tube well's sample of Gopalgonj was above the detection limit and the availability was considered 100%. But the percentage of availability of as in pond water samples was only 3.2%. The percentages detected in pond water were 5 and 0 in Cumilla and Chandpur, respectively, but had higher levels in tube well (70%). A relatively higher percentage of detected As was found both in pond and tube well water in Madaripur (20% and 80%) and Sathkhira (30% and 60%). Overall, the percentage of detectable bioavailable as in pond and tube well water were 5.7 and 71.1, respectively. A comparative study on available as percentages between tube wells and pond water samples has been given in Figure 6.

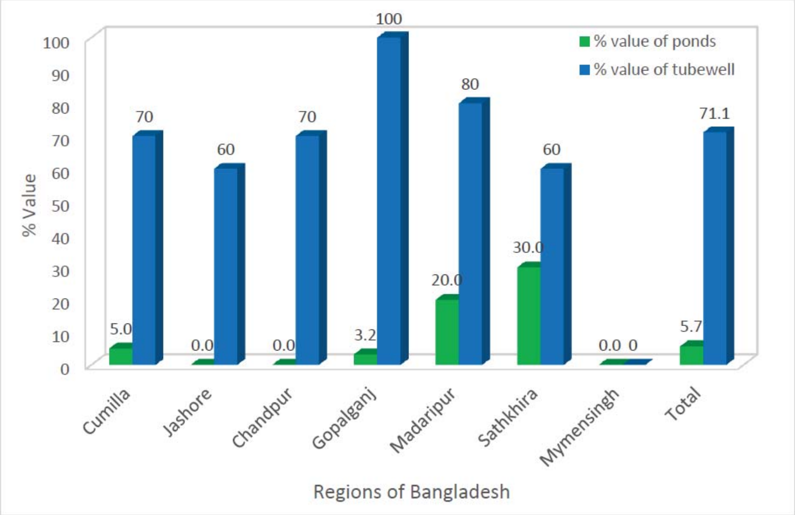

Figure 6. Percentage of As between tube well and pond water samples

4. Discussion

4.1 Tetracycline Concentration

Anti-microbial treatment has been applied in aquaculture for more than 60 years. Among the most used drugs in veterinary medicine, antibiotics are dominant (Sanders, 2005). The main motive behind the management of contagious diseases in hatcheries is to avoid production losses; stop microbes from accessing new facilities; stop the transmission of disease; and inhibit the intensification of pathogens already widespread in the water body (Phillips et al., 2004; Winton, 2001; Lupin, 2009). Utilization of antibiotics and other synesthetic compounds have contributed to the higher production and development of the aquaculture sector but has also been criticized due to probable harmful impacts on human being and ecology (Holmström et al., 2003; Heuer et al., 2009; Sapkota et al., 2008; Rico et al., 2013). Deposits of conceivably harmful substances of antibiotics can amass in the treated animal, bringing about a potential danger for buyers and to market and export of cultured products. (Heuer et al., 2009; Sapkota et al., 2008). The broad utilization of antimicrobials in aquafarming can prompt the opportunity of antibiotic-resistant bacteria both inside and outside the aquaculture systems (Le et al., 2005; Sørum, 1999; Inglis, 2000).

In this study, the range of tetracycline value in detection level was 3.3 to 31.27µg/l, which is more or less similar to Murat and Emine (2016), who detected the highest TC concentration was 50.0±2.5 µgL^{-1} at 1st week, and the lowest was 8.2±0.41 µgL^{-1} at 7th week. The average value of tetracycline was 1.82±3.99 µgl^{-1}. Karthikeyan & Meyer (2006) stated the Tetracycline concentration in the influent was 48±3.21µgL^{-1} and in the effluent, the TC concentration was 3.6±0.31µgL^{-1} which is more than the present study.

Results showed that the tetracycline varied up to a maximum of 31.27µg/L and a minimum of 3.3µg/l. Lalumera et al. (2003) found 246.3 and 578.8 µg/kg d.w of oxytetracycline and flumequine in surface water. Lalumera et al. (2003) also reported that flumequine was found in the highest toxicity in EC50 bioluminescence assay within a range of 12–15 mg/l, whereas the EC50 values for oxytetracycline ranged from 121–139 mg/l. That is more than the value of the present study.

Tetracyclines are significantly steadier in the ecosystem than other antimicrobial agents, permitting TCs to continue for prolonged periods, disperse more, and amass at high concentrations and sully water sources and soils (Ingerslev et al., 2001). Tetracyclines illustrate very low biodegradability in the state of administered tests and are seen as constant in fertilizer and soil, with high sorption potential (Kümmerer et al., 2000; Sassman and Lee, 2005).

4.2 Arsenic Contamination of Pond's Water

Arsenic concentrations are commonly higher in groundwater than in surface water. Food grown in contaminated water is detrimental and attributed threat of arsenicosis. Of collected water samples, 5.7% was detectable by *E.coli* K12 pTetlux1 where concentrations of as were found highest in a pond in Madaripur (Table S2). The highest concentration was found at 9.45 µg/l among the detectable samples and it was the only sample that scored closer to 10 µg/l while the standard arsenic limit in the case of Bangladesh is 50 µg/L (UNICEF, 2008). Arsenic concentrations at or above 50 µg/L are associated with potential human health risks. Ingestion of arsenic via food or water may also seriously affect the human cardiovascular system. Because acute and chronic exposure may lead to heart failure (Fennel et al., 1981; Goldsmith et al., 1986).

Among the total twelve (12) arsenic-detectable samples, nine (9) samples were found above 5 µg/L (Table S2). Within all the samples just 4.25% is over 5 µg/L which is as yet in resistance level both for As-influenced water body and As concentration in water body because any scientists enrolled no calamity in this convergence of As, more explicitly, any aquaculture products. Moreover, aquatic organisms raise above approximately 18 µg/L of As concentration has adverse effects. From a report, adverse effects of arsenicals on aquatic organisms have been found at concentrations of 19 to 48 ug/l in water, 120 mg/kg in diets, and 1.3 to 5 mg/kg fresh weight in tissues (Eisler, 1988). Arsenic is mainly accumulated in the livers of fish. The liver tissue of fish has shown a significant decrease in all enzymatic activity (Humtsoe *et al.,* 2007). Fathead minnow (*Pimephales promelas*) and flagfish (*Jordanella floridae*) to arsenite (4.3 mg/L, and 4.12 mg/L, for 29 and 31 days, respectively) showed a significant reduction in their growth (Lima et al., 1984). All of the calamities above from different sources materialized at high as concentrations, where arsenic concentration in the pond's water found through this study was relatively low and can be stated as a danger-free circumference.

4.3 Arsenic Contamination of Tube Well Water

The World Health Organization (WHO) created Guidelines for Drinking Water Quality (GDWQ) to protect general well-being from drinking water contaminants. The 1993 release of WHO GDWQ built up the arsenic drinking water rule of 10 µg/L (10 ppb). Currently, as far as possible in Bangladesh is set to 50 µg/L (UNICEF, 2008). In this study, most of the tube well water samples from Madaripur and Jashore were higher than 10 µg/L with the highest value of 37.96 (µg/L) in Madaripur which are below the standard limit for Bangladesh but a matter of great concern in case of international standard. Since the mean everyday admission of arsenic from drinking water will mostly be under 10 µg/L.

Though the concentrations of arsenic in groundwater (tube well water) were high in all studied regions, the concentrations of arsenic in pond water were low in every region (Figure 6). This might be the dilution of surface water/runoff water with underground water in the pond. Farmers often use underground water in the pond when the water level goes down, especially in the dry season.

The As concentration in the experimental ponds was neither very high nor within the danger limit. Dittmar et al. (2010), Khan et al. (2009, 2010) reported that as contaminated groundwater used for irrigation in Bangladesh and West Bengal (India) and also indicated that As concentrations in surface waters of these areas would be high. Nowadays, shallow tube well's water is not only used for irrigation but also for fish culture. It would be a reliable and possible source of as contamination of the selected water bodies. Again, other sources such as using fertilizers, drugs, pesticides, and herbicides possessed with as during fish culture might be another source of as contamination.

5. Conclusion

Only 62 of the 325 samples were within the detection limit. Tetracycline varied up to a maximum of 31.27µg/L and a minimum of 3.3µg/l. In this study, we report that there is a dangerous potential that results from the TC used in aquaculture in Bangladesh. Extensive use of antibiotics results in growing antibiotic resistance to harmful bacterial populations and the spread of antibiotic resistance in aquatic and terrestrial environments. The concentrations of as in shallow groundwater were usually low in the case of Bangladesh standards. Most are below the WHO provisional guideline value for drinking water of 50 µg/L. Most of the previous studies related to aquatic as focused mostly on As distribution, speciation, and bioaccumulation in groundwater and soil in Bangladesh, while the present study mainly focused on the bioavailability of As in freshwater ponds of highly As-affected areas. However, the as concentration in the detected pond's water samples was low. No researcher reported any catastrophe in such a concentration of as, specifically, aquaculture products. So, it can be stated that pangasius and tilapia raised in the studied regions are safe for consumption.

Considering the fast development and significance of aquaculture in various parts of Bangladesh and the widespread, intensive, and frequently uncontrolled utilization of antibiotics for fish culture, further endeavors are expected to stop the development and spread of antibacterial resistance in aquaculture. Again, for better assurance, the study on the bioavailability of As in aquatic biota more specifically in pangasius and tilapia of these selected farms would be performed in the future which will increase the acceptability of our products in the international market with appropriate value and thus enhance our national income.

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Authors Contributions

Dr. MEA, Dr. MAR, Dr. SRI, AA, and Prof. MLA were responsible for the planning and design of the experimental work; Dr. MEA with assistance from Dr. SRI and AA conducted fieldwork and laboratory analysis in Bangladesh; all authors contributed to the interpretation of data; MEA and SRI drafted the MS with input from Dr. MAR, and Prof. MLA.

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Data sharing statement

No additional data are available.

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Appendix

Table S1. Bioavailable tetracycline concentration of different regions

SL. No.	Region	IC	Con. (µg/l)	SL. No.	Region	IC	Con. (µg/l)
1		1.51	8.07	32		2.59	9.52
2		1.52	8.25	33		1.70	4.42
3		1.51	8.08	34		1.80	4.99
4	Bogura	1.64	4.71	35		2.19	7.23
5		1.68	4.97	36		1.54	3.53
6		1.63	24.85	37		1.51	3.33
7		2.63	11.10	38		1.71	4.50
8		2.13	11.38	39		1.88	5.46
9		1.52	7.65	40		1.83	5.18
10		1.55	8.06	41		1.70	4.43
11		2.19	17.52	42		2.02	6.23
12		1.67	9.85	43		1.91	6.29
13	Cumilla	1.73	4.46	44		1.53	4.20
14		1.55	3.45	45		1.64	4.90
15		1.77	4.68	46		1.71	5.26
16		1.66	9.78	47		1.53	4.19
17		2.22	18.05	48	Mymensingh	1.58	4.56
18		1.96	14.23	49		1.62	4.79
19		1.50	7.30	50		1.54	4.27
20		1.54	7.85	51		2.19	7.49
21		3.19	15.13	52		2.14	7.31
22	Jashore	2.12	8.18	53		1.59	4.62
23		2.80	12.60	54		1.69	5.19
24		5.96	31.27	55		1.89	6.21
25		1.86	6.43	56		2.05	6.92
26		2.04	6.39	57		1.60	4.66
27		3.83	16.60	58		2.02	5.97
28		2.14	6.93	59		1.95	5.60
29	Khulna	3.84	16.67	60		1.76	4.65
30		2.65	9.83	61	Gopalgonj	2.06	9.63
31		1.75	4.69	62	Sathkhira	1.51	7.90

IC=Induction Coefficient. IC≥1.5 is only considered to measure bioavailable tetracycline

Table S2. Bioavailable Arsenic concentration of ponds at studied regions

SL. No.	Area	IF	As Concentration (µg/l)
1	Cumilla	1.54	2.35
2		1.66	8.37
3	Gopalgonj	2.78	4.59
4	Madaripur	1.50	5.37
5		1.89	9.45
6		1.69	7.37
7		1.72	7.45
8		1.66	6.79
9		1.53	5.26
10	Sathkhira	1.66	6.26
11		1.69	6.53
12		1.66	6.76

Table S3. Bioavailable arsenic concentration of tube well water in different regions

SL. No.	Area	IF	As Concentration (µg/l)
1		5.59	33.10
2		3.68	21.02
3	**Gopalgonj**	3.33	18.71
4		3.64	20.72
5		2.05	9.46
6		4.88	28.64
7	**Madaripur**	6.34	37.96
8		3.20	17.80
9		2.25	10.99
10		5.59	27.91
11		5.51	27.51
12	**Jashore**	4.23	20.62
13		3.48	16.04
14		2.20	7.78
15		3.77	17.86
16		1.67	4.31
17		1.83	5.35
18		1.83	5.32
19	**Chandpur**	1.96	6.15
20		1.77	4.96
21		2.06	6.86
22		3.45	15.81
23		1.78	4.56
24	**Sathkhira**	3.92	17.05
25		3.43	18.90
26		2.23	7.79
27		2.31	11.10
28		3.03	16.71
29	**Cumilla**	3.43	18.80
30		1.59	4.77
31		3.01	16.71
32		3.81	18.86

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Impact of Biochar Applications on Tropical Soils under Different Land-use Regimes

Khasifah Muhamad[1, 2], Uchenna Ogbonnaya[1, 3], John Quinton[1] & Kirk Semple[1]

[1] Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, United Kingdom

[2] Malaysian Agricultural Research and Development Institute (MARDI) Cameron Highlands, Persiaran Dayang Endah, 39000 Tanah Rata, Cameron Highlands Pahang, Malaysia

[3] Department of Biology, Hong Kong Baptist University, Hong Kong

Correspondence: Kirk Semple, Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, United Kingdom. Tel: 605-491-1255. E-mail: khasifah@mardi.gov.my

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Abstract

The application of biochar to agricultural soils can either be beneficial or detrimental, as well as no clear effect to soils and crops. Therefore, the aim of our study was to investigate the effects of biochar addition on soil chemical and biological properties and nutrient leaching in three tropical soils with different types of land-use (forest, non-intensive and intensive farming). The soils were amended with and without 2% coconut shell (CS) and rice husk (RH) biochars by weight and incubated for up to 360 days. To assess the impact of biochar on soil leaching, 27 unplanted soil columns from the same types of land-use were also amended with and without 2% CS and RH biochars by weight. Five leaching experiments were conducted by passing through 100 ml of deionised water via each of the glass columns containing soil. The biochar addition significantly increased ($P<0.05$) the soil pH and total carbon, but had a marginal effect on CEC and had a limited effect on microbial activity. Biochar treatments reduced ammonium leaching in the forest soil, but had no clear effect on the other two soils. Our data showed that biochar application at a lower rate can ameliorate soil acidic conditions, enhance carbon sequestration and adsorb ammonium ion. However, the success depends on soil and biochar properties and land-use. The biochar samples studied have a limited capacity to reduce nitrate and phosphate leaching due to high biochar phosphate content.

Keywords: nutrients, leaching, carbon-14, mineralization, ammonium, phosphate, nitrate

1. Introduction

Soils of the tropics are dominated by Oxisols and Ultisols (Ishak and Jusop 2010), which are highly-weathered soils with low pH and a mineralogy dominated by quartz, kaolinite clays and higher oxides of iron and aluminum (Zhao et al. 2014). Tropical soils often have a low cation exchange capacity (CEC) and, in some cases, higher anion exchange capacity (AEC), (Yamato et al., 2006; Masulili et al. 2010). A higher AEC may result in the loss of ammonium ions through leaching and runoff. Hence, nitrogen fertilizer applications have to be much higher. The efficiency of the fertilizer utilization is lower, due to the leaching process (Ludwig et al. 2001). Furthermore, long-term intensive farming of arable land has decreased the carbon content of the soils of the tropics (Lal 2009), adversely affecting their fertility. According to Nottingham et al. (2020), soils in the tropics have a high tendency to lose more carbon as CO_2 following warming climates.

Increasing the content of soil carbon is important to improve the stability of soil structure, enhance water-holding capacity and facilitate water movement in the soil. It also helps to increase carbon sequestration and reduce soil loss (Victoria et al. 2012). Ultisols and Oxisols are known to have a low percentage of organic carbon (1% to 2%). The low level of organic carbon can be insufficient for good crop performance (Ishak and Jusop 2010). In addition, low level soil organic carbon limits soil aggregation and carbon sequestration which undermines sustainable soil health (Singh et al. 2016). Consequently, organic amendments can be applied to restore appropriate soil organic carbon levels in order to promote sustainable soil quality and crop productivity. Manure and compost are sources of organic carbon easily available to farmers. However, these amendments may not have optimal performance influence in soil recalcitrant carbon pools (Yanardağ et al. 2015). Biochar is an organic amendment that has been shown to improve soil quality by enhancing the recalcitrant carbon pool and resisting carbon degradation by microbes (Agegnehu et al., 2017; Mensah and Frimpong 2018). Biochar can be produced from various organic resources, including unwanted agricultural by-products, animal dung and wood. These materials are usually burned in a secure chamber, creating a condition with restricted or zero oxygen (Lehmann and Joseph 2009). The application of biochar to soil has been practiced in the past. The fertile soils found in the Amazon, called Terra Preta or dark earth, were generated by aboriginal societies through the use of biochars (Glaser and Woods 2004). This type of soils (dark earths) have also been found in Africa (Fraser *et al.*, 2014). Furthermore, research in biochar studies discovered that biochar has many advantages as a soil conditioner. For instance, biochar can increase pH and eventually be able to increase the CEC of the soil (Masulili et al. 2010; Sukartono et al. 2011).

Amending soil with biochar increases crop productivity and soil quality in subtropical regions where soil pH is normally very low and soil texture is coarse (Farhangi-Abriz et al., 2021). Lin *et al.* (2015) found that, adding biochar to soil at the rate of 16t ha^{-1} improved the development of wheat plants by 27.7%. Also, another study on the application of high rates of biochar (50 t ha -1) with nitrogen fertilizer to clay loam (low organic matter – 0.84%) soils was conducted by Jalal et al. (2020). The study was carried out over two years and involved maize and legume production. Results showed that wood biochar enhanced the yield of maize, biomass production and nitrogen use efficiency. However, some papers in the scientific literature have questioned the efficacy of biochar. Jay et al. (2015) showed that, amending soil with biochar improved crop yield and decreased nutrient leaching in studies conducted in temperate areas. These results are, however, not always positive (Van Zwieten et al. 2010). Other long-term biochar studies revealed that nitrate, ammonium, dissolved organic C and nitrogen did not affect N mineralization. Also biochar application caused little and temporary changes to the agricultural ecosystem (Jones et al. 2012; Quilliam et al. 2012). Crop performance for three growing cycles also showed a marginal effect after biochar addition to the soil (Jones et al. 2012). The drawback of biochar application is the presence of phytotoxic substances. These substances, such as phenolic compounds, formic acids or acetic acids and polycyclic aromatic hydrocarbons (PAHs) have been discovered from newly produced biochar (Quilliam et al. 2013b). If present in substantial amounts, these substances may affect plant performance (Busch et al. 2012), as well as become toxic to soils, plants and microbiomes (Quilliam et al. 2013b). In addition, Bruun et al. (2008) and Zhang et al. (2014) claimed that, there was no effect on the microbial biomass and activity, when biochar was added to soil, but Dempster et al. (2010) discovered that amending soil with biochar resulted in a reduction in microbial biomass. Indeed, differences in the feedstocks of biochar and in the characteristics of the soil influence the eventual result of biochar application.

Most biochar studies in the past focused on soils in temperate regions (Jones et al. 2012; Quilliam et al. 2013a). Some research work, however, examined the effects of biochar on tropical soils (Alling et al. 2014) or the long-term outcomes of biochar application (Jones et al. 2012; Quilliam et al. 2012). Therefore, the purpose of this study was to explore an aging effect of soil and biochar mixtures on soil properties in tropical region. Our hypotheses were that amending tropical soils with biochar would decrease nutrient leaching and enhance the biological and chemical characteristics of the soils.

2. Materials and Methods

2.1 Chemicals and Soils

^{14}C glucose was purchased from Sigma Aldrich Co. Ltd. UK. Goldstar multipurpose liquid scintillation cocktail was procured from Meridian, UK. Sample oxidizer cocktails (Carbotrap and Carbocount) were obtained from Meridian UK, and combustaid was obtained from Perkin Elmer, USA. Ammonium acetate, sodium acetate, chloroform ($CHCl_3$), potassium sulphate and sodium hydroxide were supplied by Fisher Scientific, UK.

Three tropical soils (Spodosols) were used in this study. A secondary forest soil (sandy clay loam), a non-intensively-farmed soil (sandy clay) and an intensively-farmed soil (sandy clay) were chosen based on differences in types of soil degradation (Table 1 and Supplementary Figure 1). An accumulation of Al and Fe in the subsoils is usually found in Spodosols which are acidic (pH < 5.5). In the secondary forest soil used in this study which is a sandy clay loam, logging activity has happened for several years. Meanwhile, soil that has been cleared for agricultural purposes only once is the non-intensively-farmed soil. The intensively-farmed soil which was the soil that has been planted with different crops under a rain shelter for a few years was also used in this study. All of the soils were sampled from the Cameron Highlands District, Pahang in central Peninsular Malaysia (Supplementary Figure 1). At an altitude of 1070 – 1830 m above sea level, the mountainous area has slopes between 10 and 35 ^{o} (Abdullah et al., 2001). Soil was obtained from 5 random samples with an auger to a depth of 10 – 15 cm within an area of 27.5 m^2. The soil samples were then composited and kept field-moist in a cold room at approximately 9 ^{O}C before being shipped to the United Kingdom for chemical and biological soil analyses. The soil samples from Cameron Highlands were then sieved through a 5 mm mesh to remove plant residues and stones prior to the experiment.

2.2 Biochars

Coconut shell (CS) and rice husk (RH) biochars, were used in this study. The RH biochar was obtained from Tanjung Karang, Selangor Malaysia. It was produced by a rotary husk furnace which resulted in a higher biochar yield at 900^{O}C to 1000^{O}C within a short period of time. On the other hand, the method which produced CS biochar is called slow pyrolysis, where the CS was heated in a drum. This burning process was conducted approximately 6 to 8 hours and the temperature adjacent to the drum can reach up to 400^{O}C. RH and CS biochar samples were crushed and sieved using a 2 mm mesh in the laboratory. Then, the soil samples were mixed with 2% of the RH and CS biochar samples by weight. Soil not mixed with biochar act as a control treatment. All samples were then incubated at the-five time point (0, 60, 120, 240 and 360 days) with 45% of moisture content and at a constant temperature of approximately 21^{O}C. This created an environment that closely resembled the conditions (temperature and moisture content) from which the soils were collected. The soil samples were then kept in screw-capped glass jars. Following methods by Kandeler (2007), the soils were dried in the fume hood and sieved using a 2 mm mesh to obtain suitable soil aggregates for the soil chemical and biological analyses at each time point.

2.3 Nutrient Leaching Study

Soil samples were placed into 27 glass soil columns. Each column has a diameter of 5 cm and is 20 cm long. Each column of soil was adjusted to 1.2 g cm^{-3} bulk density. At the bottom of the funnel used, a glass wool layer was inserted to prevent soil particulate blockage. On the soil surface, another layer of glass wool was inserted to protect the surface structure during the leaching process. Five leaching events (0, 60, 120, 240 and 360 days) were conducted by leaching 100 ml of deionized water through each of the soil columns. Erlenmeyer flasks were used to collect the leachate and then stored at 4 ^{0}C for two to three days before analysis. The leachates were then determined for ammonia, nitrate and phosphate contents using a Bran + Luebbe Autoanalyzer 3.

2.4 Soil Biological and Chemical Analyses

For biological experiments, the methodology used was substrate-induced respiration (SIR) as described by Hamer and Marschner, (2002) and; Kandeler, (2007). On days 0, 60 and 120 incubation time, samples containing 20 g wet weight of soil were mixed with 3mM of glucose solution with a radioactivity of 733 Bq. Meanwhile, on days 240 and 360 of incubation time, the soil samples had a radioactivity of 1086 Bq (Doick and Semple 2003). 1 ml NaOH (1 M) solution was added into a 7 ml vial attached to the respiratory bottle's lid to allow it to be suspended and therefore trap $^{14}CO_2$ generated by the $^{14}CO_2$ mineralization process. The samples were mixed and shaken with a shaker at 100 rpm. Then, the vials were replaced every 1, 2, 3, 4, 6, 8, 10 and 12 hours; and another 24, 48, 72, 96 and 120 hours. During the sampling, the vial containing 1 M of NaOH solution was detached from the respiratory bottle and the surface of the vial was cleaned using acetone to discard any residues of $^{14}CO_2$. Then, 5 ml of liquid scintillant cocktail was added into the vial. The mixture was incubated overnight in the cabinet. ^{14}C activity in the vial was then analyzed using a liquid scintillation analyzer (Canberra Packard Tri-Carb 2250A).

For microbial biomass determination, the soil slurry was sampled at the final day sampling of the SIR experiment. The method used to measure microbial biomass is fumigation and non-fumigation methods. Where 20 ml of 0.5 M K_2SO_4 was added to the non-fumigation sample. The samples were mixed and shaken with a shaker for 30 minutes at 100 rpm. Then, 5 ml of filtered supernatant was placed into a 20 ml vial. Before counting using liquid scintillation, 15 ml of liquid scintillant cocktail was also added into the vial and the samples were kept in a cabinet overnight. Subsequently, the other sample was fumigated in a desiccator, circled with a wet tissue. 75 ml ethanol-free chloroform ($CHCl_3$) was inserted at the middle of the desiccator. The desiccator was emptied until the $CHCl_3$ had boiled vigorously for 120 seconds. The residual $CHCl_3$ gas was discarded after 24 hours by repeated five- or six-fold evacuation. Furthermore, the samples were extracted and counted using a liquid scintillation analyzer like aforementioned. Finally, again the remaining soil samples from SIR, non-fumigation and fumigation experiments were used to measure the ^{14}C-glucose activity remaining in the soil. This was assessed through combustion on a sample oxidizer (Packard, Model 307) for 3 minutes.

pH was measured using a pH meter model PHM 220 which was calibrated using buffers at pH 4.0 and 7.0. The cation exchange capacity (CEC) was measured using 1 M ammonium acetate. This reagent (ammonium acetate) adsorbed cations (Na) which were retained by the soil (Hazelton and Murphy 2007). Using flame photometry, the concentration of displaced Na from the soils was obtained. Meanwhile, total carbon and nitrogen were determined using an elemental analyzer (Elementar Vario EL) via a dry combustion method. Where soil samples were dried in the constant room temperature at $21^{O}C$ for about two to three days. The soil samples were then ground using a pestle and mortar. The ground samples of approximately 30mg were weighed into tin cups, which were subsequently loaded into an auto-sampler, which dropped the sample into a combustion column maintained at $950^{O}C$. The sample and cup were flash combusted in a temporarily enriched atmosphere of oxygen. The combustion products were carried by a carrier gas, which is helium, past an oxidation catalyst of copper oxide kept at $950^{O}C$ inside the combustion column.

The combustion products such as CO_2, CO, N, NO and water passed through a reduction reactor in which hot metallic copper with the temperature at $550^{O}C$ that removed excess oxygen and reduced N oxides to N_2. These gases, including with CO_2 and water, were next went through sicapent to remove water then through a chromatographic column to a thermal conductivity detector. The detector generated an electrical signal proportional to the concentration of N or C present. This signal was graphed on a built in recorder and ported to a computer, which integrated the area under each curve and converted it to concentrations after each sample was run. Finally, the results were given in percentages.

2.5 Statistical Analysis

Statistical significance was determined using one-way ANOVA. There were 9 treatments and three replicates, with sum of 27 samples for each time point. Multiple mean comparison was conducted by applying the Holm-Sidek test at $P < 0.05$. We also used a non-parametric statistical test, the Kruskal-Wallis test, for values that were not normally distributed. To determine significant differences between the treatments for non-distributed values, Tukey test was applied. All statistical tests were run using SigmaStat v. 3.5 (Systat Software Inc.).

3. Results and Discussion

3.1 pH and CEC of the Soil

Biochar addition to soil significantly affected the pH of the soil. Amending soils with CS and RH biochar samples increased ($P<0.05$) their pH significantly (Supplementary Figure 2). Even though the pH of the soil increased, the application of biochar to the soils dropped the soil pH over time ($P<0.05$) due to loss of basic anions from the soils during microbial decomposition activities. As presented in Table 1, both biochars had a high pH. The pH of CS is 8.33 and that of RH is 8.46. According to Novak et al. (2009) and Masulili et al. (2010), adding a biochar with high pH is sufficient to raise the value of the soil pH and improve the condition of an acidic soil.

Table 1. Physical and chemical characteristics of soils and biochars

Soils	Secondary forest soil	Intensively farmed soil	Non-intensively farmed soil	CS biochar	RH biochar
Latitude /°	4.4710	4.4673	4.4668	-	-
Longitude /°	101.3907	101.3857	101.3871	-	-
pH	4.62	5.03	5.52	8.33	8.46
CEC/meq 100 g^{-1}	9.7	9.4	5.8	31.17	43.28
Carbon %	3.42	1.64	1.08	72.95	38.64
Nitrogen %	0.18	0.22	0.07	0.53	0.53
C/N Ratio	19.05	7.38	14.99	139.71	72.59
Inorganic P/mg g^{-1}	0.06	1.85	0.2	0.39	1.75
Clay %	28.63	35.06	33.89	-	-
Silt %	11.01	18.09	18.08	-	-
Sand %	60.36	46.86	48.03	-	-
Texture	Sandy Clay Loam	Sandy Clay	Sandy Clay	-	-

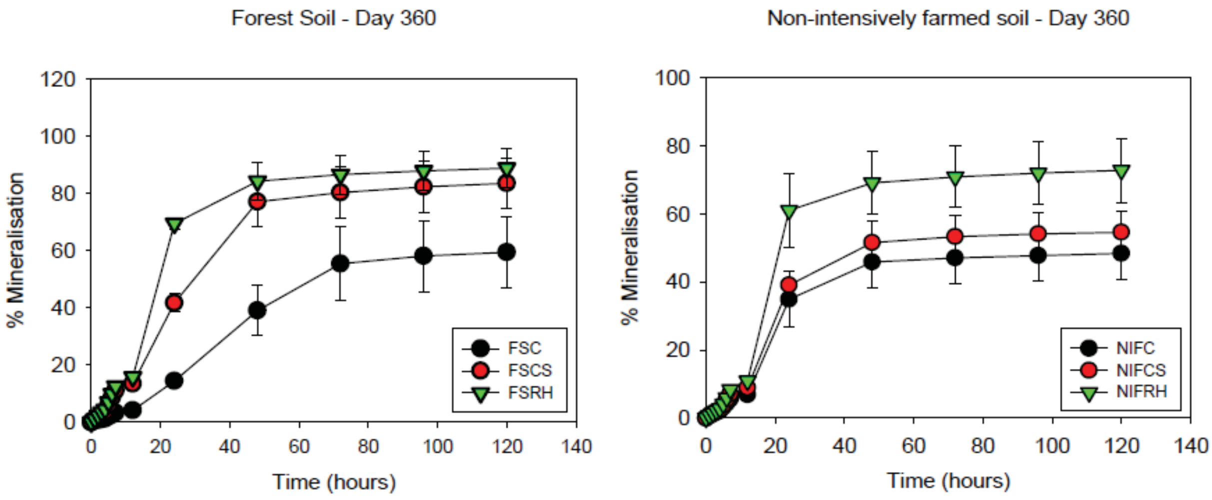
Application of biochar in this present study had a marginal effect on the CEC of the soil. For example, RH biochar had a small effect on the CEC in the secondary forest soil and in the non-intensively-farmed soil. Meanwhile, in the intensively-farmed soil, there was no effect on CEC after biochar application. In addition, the CS biochar did not affect the CEC in any of the soils studied (Supplementary Table 1). Amending soil with both biochars also did not significantly increase the CEC ($P>0.05$). However, some other research results showed that biochar addition to soil elevated the value of CEC (Masulili et al. 2010). In another study, Novak et al. (2009) found that the application of 0.5, 1.0 and 2.0% pecan-shell biochar had only a marginal effect on the CEC of soils. The authors believed that the temperature of biochar pyrolysis influenced the biochar's ability to increase soil CEC. There are often low negative surface charges on high temperature biochar, due to dehydration and de-oxidation of the H- and O-containing functional groups and can have little or no effect on the CEC of soils (Tomczyk et al. 2020). Owing to the high production temperature (RH biochar) and long holding time (CS biochar), our biochar exhibited low CEC values in comparison to literature with limited capacity to exert CEC influence to low CEC soils.

3.2 Carbon, Nitrogen and Phosphate in Soils

Biochar addition to soils increases the carbon content. The highest increase was observed in the CS biochar-amended forest soil (8.2%) (Supplementary Table 2). Nevertheless, the results exhibited a gradual reduction in carbon content over time, owed to the decomposition of the labile carbon pool within the biochar-soil matrix. CS biochar had very high carbon content (72%) that ensured a doubling carbon content effect in all soils over the incubation period when contrasted to un-amended soils. The RH biochar also increased significantly ($P<0.05$) the soil carbon content of all soils, but to a lesser extent than CS biochar due to the lower carbon content. Nevertheless, there was a significant decline in carbon content following 360 days of incubation period in forest (5.98-4.22%), non-intensively (3.13-2.44%) and intensively-farmed (2.67-2.28%) soils amended with RH biochar. In contrast, carbon content in CS biochar-amended soils decreased in forest (8.15-6.35%), remained stable in non-intensively (3.71-3.68%) and increased in intensively-farmed (2.50-3.47%) soils (Supplementary Table 2). This clearly shows that biochar can support carbon sequestration in soils, but the success of application largely depends on soil characteristics, biochar properties and land-use.

3.3 Mineralization of ^{14}C-glucose to $^{14}CO_2$ and Incorporation of ^{14}C-glucose into Microbial Biomass

The extent of ^{14}C-glucose mineralization in the three soils was not continually constant. Generally, the extent of mineralization of ^{14}C-glucose peaked ($P<0.05$) at the last of the incubation period in all the treatments (Figures 1a, b and c; and Tables 2-4). Furthermore, adding both biochar to the soils did not show any major change during the incubation period. It was observed that, after 120 days, the extent of change in ^{14}C-glucose in the forest soil amended with RH biochar (62.22 ± 6.40) was significantly higher ($P<0.05$) than that in the CS-biochar-amended forest soils (45.01 ± 6.05) (Supplementary Figure 3 and Table 2). The maximum rates of ^{14}C-glucose mineralization after 360-day incubation were observed to be higher in the forest soils amended with RH biochar, (4.47% h^{-1} ± 0.23), in comparison with the rates of the forest soil amended with CS biochar (2.35% h^{-1} ± 0.20), as well as the rate with no biochar (1.03% h^{-1} ± 0.30) (Table 2). Overall, the uptake of ^{14}C-glucose into the microbial biomass exhibited no constant trend in all the soils and treatments (Tables 2-4).



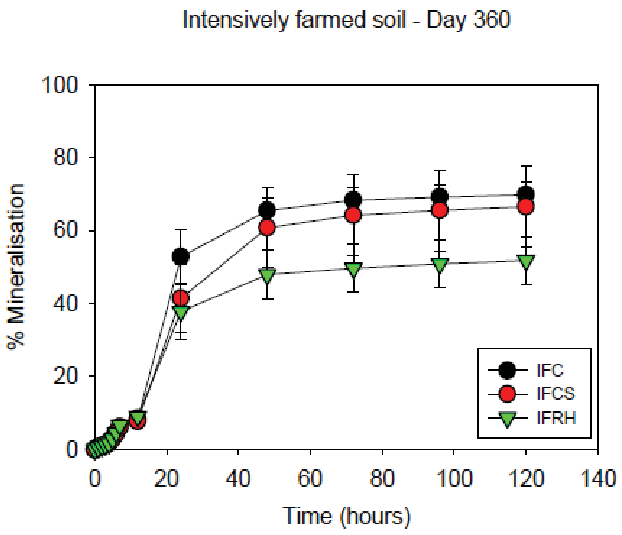

Intensively farmed soil - Day 360

Figure 1. Mineralization of 14C-glucose on day 360 of the a) forest b) non-intensively farmed and c) intensively-farmed soils amended with CS and RH biochar and without biochar. Error bars are SEM (n=3)

Table 2. Maximum rate, ^{14}C extent mineralization, ^{14}C biomass uptake and ^{14}C activity residue for forest (FS), soil treated with CS and RH biochar and without biochar, over a year. Error bars are SEM (n=3). *nd* = not determined

Treatment	Day	Maximum rate /% h^{-1}	^{14}C extents mineralization /%	^{14}C biomass uptake fixed k_{EC} /%	^{14}C activity residue in soil /%
FSC	0	1.79 ± 0.11	29.02 ± 2.69	14.19 ± 1.03	56.78 ± 3.66
	60	2.15 ± 0.19	49.41 ± 5.49	24.77 ± 3.61	25.81 ± 7.41
	120	2.03 ± 0.25	37.10 ± 2.11	*nd*	*nd*
	240	1.02 ± 0.08	48.55 ± 1.73	27.59 ± 6.22	23.86 ± 7.83
	360	1.03 ± 0.30	59.37 ± 12.23*	21.73 ± 2.31	18.90 ± 10.14
FSCS	0	2.06 ± 0.19	29.40 ± 1.44	14.53 ± 2.32	56.07 ± 2.04
	60	2.23 ± 0.13	44.71 ± 3.84	24.33 ± 6.45	30.95 ± 6.09
	120	2.33 ± 0.48	45.01 ± 6.05	29.44 ± 3.80	25.54 ± 4.27
	240	1.54 ± 0.19	44.91 ± 1.74	26.49 ± 3.45	28.59 ± 3.62
	360	2.35 ± 0.20	83.50 ± 8.92*	15.08 ± 2.61	1.41 ± 6.57
FSRH	0	2.99 ± 0.16*	35.68 ± 2.22	12.96 ± 4.11	51.35 ± 2.87
	60	1.65 ± 0.17*	58.60 ± 4.89	22.81 ± 3.79	18.58 ± 1.10
	120	2.12 ± 0.32*	62.22 ± 6.40*	14.31 ± 2.33	23.47 ± 8.62
	240	1.79 ± 0.08*	52.41 ± 6.16	28.81 ± 5.13	18.78 ± 1.56
	360	4.47 ± 0.23*	88.79 ± 6.86*	12.00 ± 1.83	0.00 ± 0.00

nd = not determined

Values in asterisk indicate significance at $P<0.05$

Table 3. Maximum rate, ^{14}C extent mineralization, ^{14}C biomass uptake and ^{14}C activity residue for non-intensively farmed (NIF), soil treated with CS and RH biochar and without biochar, over a year. Error bars are SEM (n=3)

Treatment	Day	Maximum rate /% h^{-1}	^{14}C extents mineralization /%	^{14}C biomass uptake (%) fixed k_{EC} /%	^{14}C activity residue in soil /%
NIFC	0	3.34 ± 0.52	50.88 ± 2.64	5.11 ± 0.57	44.00 ± 2.09
	60	1.51 ± 0.54	29.57 ± 10.24	11.49 ± 5.09	58.94 ± 15.07
	120	2.15 ± 0.31	45.70 ± 4.07	15.43 ± 2.94	38.87 ± 5.06
	240	1.96 ± 0.10	39.85 ± 1.47	15.63 ± 0.96	44.52 ± 1.83
	360	2.34 ± 0.70	48.37 ± 7.56*	18.76 ± 2.13	32.87 ± 6.18
NIFCS	0	3.49 ± 0.50	50.28 ± 4.83	8.67 ± 0.76	41.05 ± 4.09
	60	2.00 ± 0.79	34.65 ± 13.32	6.21 ± 1.82	59.14 ± 11.65
	120	1.89 ± 0.16	40.66 ± 1.92	16.87 ± 1.01	21.07 ± 1.08
	240	2.47 ± 0.37	43.90 ± 4.47	14.52 ± 2.80	41.59 ± 4.06
	360	2.51 ± 0.33	54.57 ± 6.17*	12.24 ± 1.94	33.19 ± 5.33
NIFRH	0	4.21 ± 0.58	47.35 ± 3.22	5.36 ± 0.94	47.29 ± 2.29
	60	1.46 ± 0.29	30.19 ± 3.80	3.06 ± 0.95	66.75 ± 4.74
	120	2.13 ± 0.20	44.73 ± 3.46	9.17 ± 3.61	46.10 ± 6.84
	240	2.71 ± 0.29	48.82 ± 3.20	13.87 ± 1.10	37.30 ± 2.65
	360	4.17 ± 0.91	72.77 ± 9.37	7.88 ± 1.29	19.35 ± 8.12

Values in asterisk indicate significance at P<0.05

Table 4. Maximum rate, ^{14}C extent mineralization, ^{14}C biomass uptake and ^{14}C activity residue for intensively-farmed soil (IF), soil treated with CS and RH biochar and without biochar, over a year. Error bars are SEM (n=3)

Treatment	Day	Maximum rate /% h^{-1}	^{14}C extents mineralization /%	^{14}C biomass uptake (%) fixed k_{EC} /%	^{14}C activity residue in soil /%
IFC	0	2.83 ± 0.33	44.1 ± 1.36	16.29 ± 3.67	39.61 ± 3.24
	60	1.65 ± 0.17	42.7 ± 2.94	17.82 ± 4.07	39.48 ± 5.70
	120	2.12 ± 0.32	43.91 ± 4.76	14.60 ± 1.14	41.49 ± 5.51
	240	1.79 ± 0.08	36.81 ± 1.48	15.44 ± 2.31	47.75 ± 3.60
	360	3.70 ± 0.61	69.80 ± 3.51*	14.41 ± 1.67	15.78 ± 1.88
IFCS	0	3.27 ± 0.36	45.79 ± 2.51	14.47 ± 2.99	39.73 ± 2.92
	60	1.83 ± 0.07	42.00 ± 1.70	12.75 ± 3.64	45.24 ± 4.89
	120	1.79 ± 0.25	40.47 ± 3.16	17.13 ± 2.24	42.39 ± 2.61
	240	2.05 ± 0.22	41.49 ± 2.97	15.62 ± 5.80	42.89 ± 8.44
	360	2.81 ± 0.77	56.58 ± 4.95*	9.67 ± 1.82	23.75 ± 12.60
IFRH	0	2.98 ± 0.72	51.90 ± 3.78	9.76 ± 3.47	40.24 ± 2.15
	60	1.58 ± 0.29	41.23 ± 2.75	18.00 ± 3.58	40.77 ± 1.21
	120	1.57 ± 0.19	38.42 ± 3.93	19.48 ± 3.57	42.10 ± 1.41
	240	1.54 ± 0.07	31.92 ± 1.90	15.26 ± 1.15	52.82 ± 2.76
	360	2.40 ± 0.58	51.77 ± 6.45*	13.51 ± 1.06	34.72 ± 5.41

Values in asterisk indicate significance at P<0.05

Adding either biochar had no effect on the ^{14}C mineralization and ^{14}C-glucose incorporation into the microbial biomass, except after 360 days of incubation in forest soil, where there was enhanced ^{14}C-glucose mineralization (Figure 1a and Table 2). Here, after 360 days of incubation, CS and RH biochar-amended soils had an average of 83% and 88% mineralization, respectively compared to forest control soil (59%). Owing to high levels of ^{14}C-glucose availability and mineralization in these amendments, the remnant ^{14}C-glucose fractions were taken up into the biomass and did not remain as residual carbon, when compared to other soils and control (Tables 2-4). Mineralization of ^{14}C-glucose accelerated due to the high carbon content as a result of RH biochar addition to the soil in comparison with the soil with no biochar. Unlike the forest soil, the intensively-farmed soil and non-intensively farmed soil displayed the reverse trend of biomass uptake and mineralization. For example, the mineralization of ^{14}C-glucose in the intensively-farmed soil was greater than that in the forest soil (44.1% and

29.02%, respectively) at the earlier time of incubation (Figures 2a and c; and Tables 2 and 4). However, the opposite pattern occurred towards the end of the incubation period. Mineralization of ^{14}C-glucose in the forest soil, amended with RH biochar (88.79%), (Table 2) was higher than in the intensively-farmed soil (51.77%) amended with the same biochar (Figure 1a and; Tables 2 and 4). Due to the high sand content in the forest soil, the opportunity for the biochar-soil colloid bridge interaction was limited. With this limitation, 14C-glucose availability was reduced. Uptake by the microbial population in the forest soil similarly declined, in contrast to the intensively-farmed soil (12% and 13.51%, respectively) (Tables 2 and 4). Mai et al. (2020) showed that biochars produced under oxygen exposure had high contents of soluble salts, which ensured bridging between soil colloids through increased ionic strength and multivalent cations. When such interaction occurs, a significant amount of glucose can then be adsorbed onto and within the biochar-soil matrix (Giovanna et al. 2017). Hence, biochar and soil interactive properties are of prime importance to influence labile carbon availability and microbial activity.

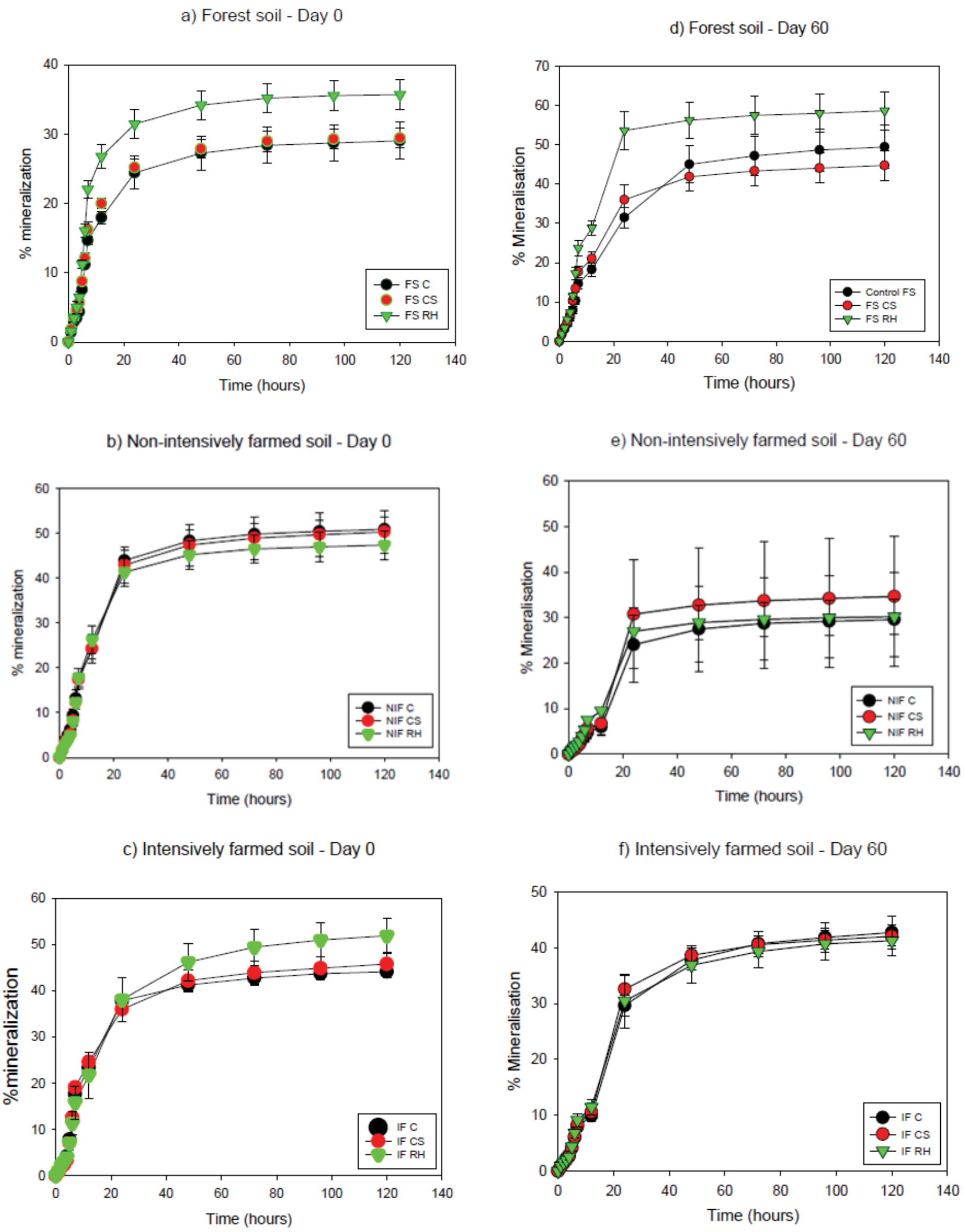


Figure 2. Mineralization of ^{14}C-glucose on days 0 and 60 of the; a), d) forest; b), e) non- intensively farmed; and c), f) intensively-farmed soils amended with CS and RH biochar and without biochar. Error bars are SEM (n=3)

3.4 Effect of Biochar on Ammonium Ion Losses via Leaching

There were decreases in ammonium ion leachate in all soils over incubation period (Figures 3a, b and c). However, this relationship varied between soils. For instance, as leaching commenced, biochar amendment ensured decreased ammonium ion leachate in the forest and non-intensively-farmed soil from 0.03 mg/L in control to 0.00067 (CS) and 0.003 (RH) mg/L ($P<0.05$) (Figure 3b). Meanwhile, in the intensively-farmed soil, there was insignificant effect on ammonium leaching following biochar amendment (Figure 3c). Results have also shown that in the forest soil control treatment, ammonium leaching was higher than in the biochar treatment. The biochar held ammonium ions in the forest soil over the course of the study ($P<0.05$) owing to the presence of negative charges on the biochar surface (Novak et al. 2009), which independently enables ionic interaction with positively-charged cations like ammonium (Wong et al. 2019).

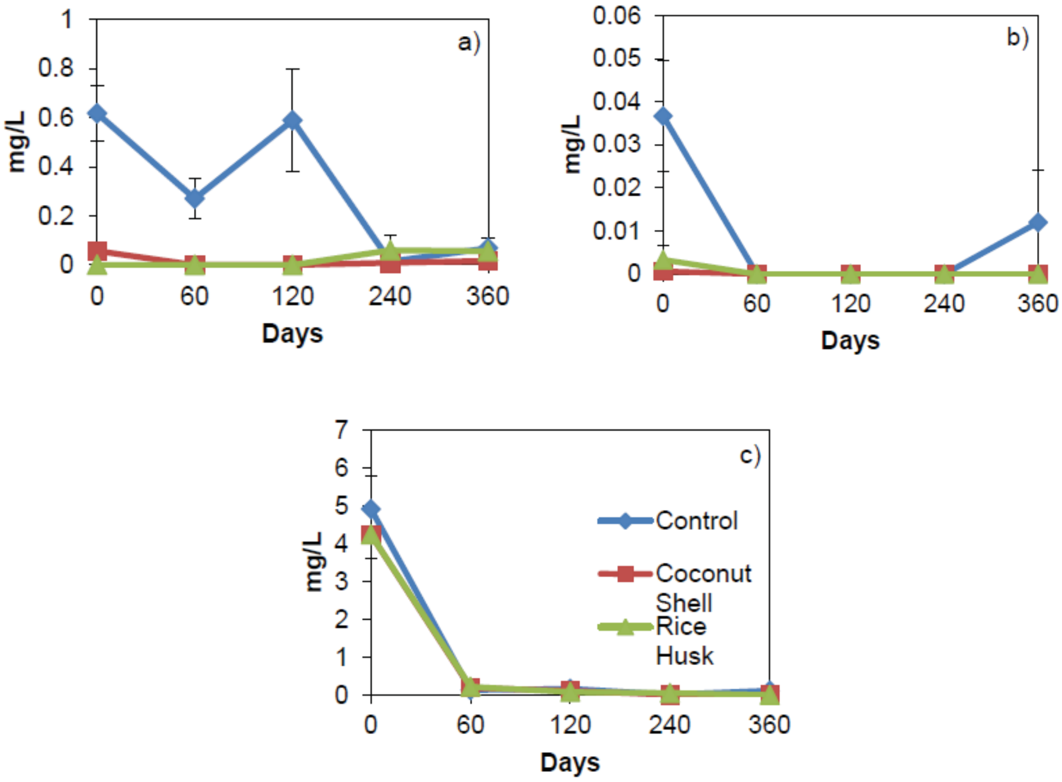


Figure 3. Concentration of ammonium over a year in the leachate of the a) forest, b) non- intensively farmed, and c) intensively farmed soils treated, with CS and RH biochar and without biochar. Error bars are SEM (n=3)

3.5 Effect of Biochar on Nitrate Ion Losses via Leaching

Nitrate leaching patterns were different amongst all soils studied. Compared to ammonium ions, the amount of nitrate ions in the forest soil leachate was higher over the course of the experiment ($P<0.05$). Meanwhile in the non-intensive and intensively-farmed soils, the concentration of nitrate ions decreased over time ($P<0.05$) (Figures 4a, b and c). Amending the soils with biochar did not produce significant differences in nitrate concentrations ($P>0.05$) in leachate (Figures 4a, b and c). In the forest soil, nitrate leachate concentration increased consistently to approximately 20 mg/L irrespective of biochar type or without biochar. Interestingly, biochar addition initially retarded nitrate leaching before 60 days (short-term) when compared to the control soil (Figure 4a), but as contact time increased, the limit for biochar to encourage nitrate retention was exceeded and leaching occurred as in the control. The forest soil exhibited lower pH and higher CEC compared to the other soils, but these properties were insufficient to limit nitrate leaching. The influence of the well-drained sandy feature of forest soils obviously accelerated leaching of nitrates (Shrestha et al., 2010; Fraters et al. 2015). In addition to the sandy soil texture, the C/N ratio (19) of the forest soil was much higher than those of other soils. This condition is highly suitable for degradation of organic nitrogen through nitrification. Apparently, the types of biochar used in this study were incapable to limit leaching in the soils for a longer time. Similarly, Ghorbani et al. (2019) reported that soils having higher clay contents amended with biochar exhibited much lower nitrate leaching compared to sandy soils. More recently, Lv et al. (2021) showed that rice straw biochar could not retard nitrate losses through the leaching process. Nevertheless, since biochars contained higher nitrogen contents than the soils studied, the data observed does not rule out nitrate release directly from biochar following oxidation. Yet, nitrate leachates decreased over time in the non-intensive and intensively farming soils. It is possible that this decrease is due to the leaching of nitrates derived from previous fertilization of the soil which was not replenished.

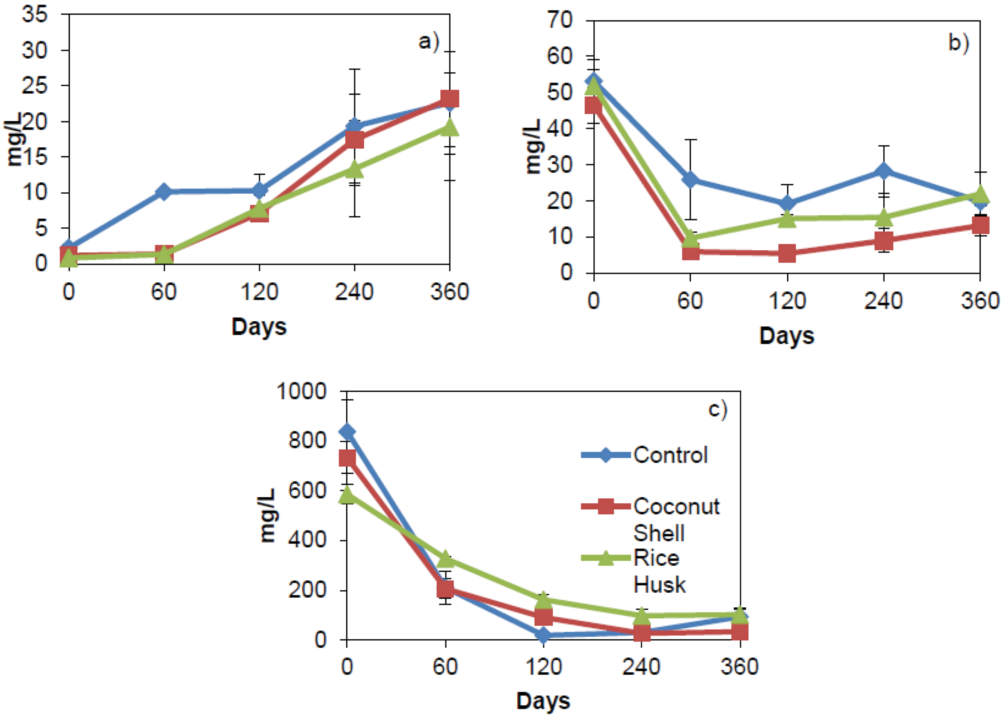


Figure 4. Concentration of nitrate over a year in the leachate of a) forest, b) non- intensively farmed, and c) intensively farmed soils, treated with CS and RH biochar and without biochar. Error bars are SEM (n=3)

3.6 Effect of Biochar on Phosphate Ion Losses via Leaching

The concentration of phosphate ions leached displayed different trends in all of the soils studied. For example, the amount of phosphate ions leached from the forest soil was low when compared to the intensively-farmed soil leachate. The phosphate concentration in the forest soil leachate was not constant over time and possibly close to the limits of detection, but in the non-intensively farmed and in the intensively-farmed soils the phosphate concentrations in the leachate declined over the course of the study. Likewise, the phosphate concentration in the leachate of both soils showed a little increase at the end of the leaching experiment (Figures 5a, b and c). The decline in phosphate leaching in these soils was probably due to the leaching of previously applied fertilizer P. Amending the forest soil with biochar insignificantly decreased ($P>0.05$) phosphate leaching, whilst amending the non-intensively farmed soil with the RH biochar had greater phosphate concentration in the leachate ($P<0.05$) at the beginning of leaching exercise due to higher P content in the RH biochar (Figure 5b).

The reduction in phosphate leaching in the forest soil was not just due to biochar, but other soil properties could influence it, such as the levels of iron and aluminum contents influence phosphate sorption in lower pH (<5) soils (Barrow 2017). In addition, biochars can only adsorb a minimal amount of phosphate in soils (Singh et al. 2010) due to a low anion exchange capacity. Further, Yao et al. (2012), observed that five out of thirteen different biochars amended in sandy soils adsorbed phosphate, whilst there was phosphate leachate release in the remaining biochars. Furthermore, results revealed that biochar produced hydrothermally leached the greatest amounts of nitrate and phosphate ions. Also more than 2% phosphate was leached from three types of bamboo biochar. In the present study, phosphate leaching was high from the soils amended with RH biochar. This was due to the fact that the biochar itself has a high phosphate content (1.75mg g^{-1}) (Table 1). Additionally, the phosphate content of the intensively-farmed soil was relatively high due to the addition of large quantities of fertilizer to the soil.

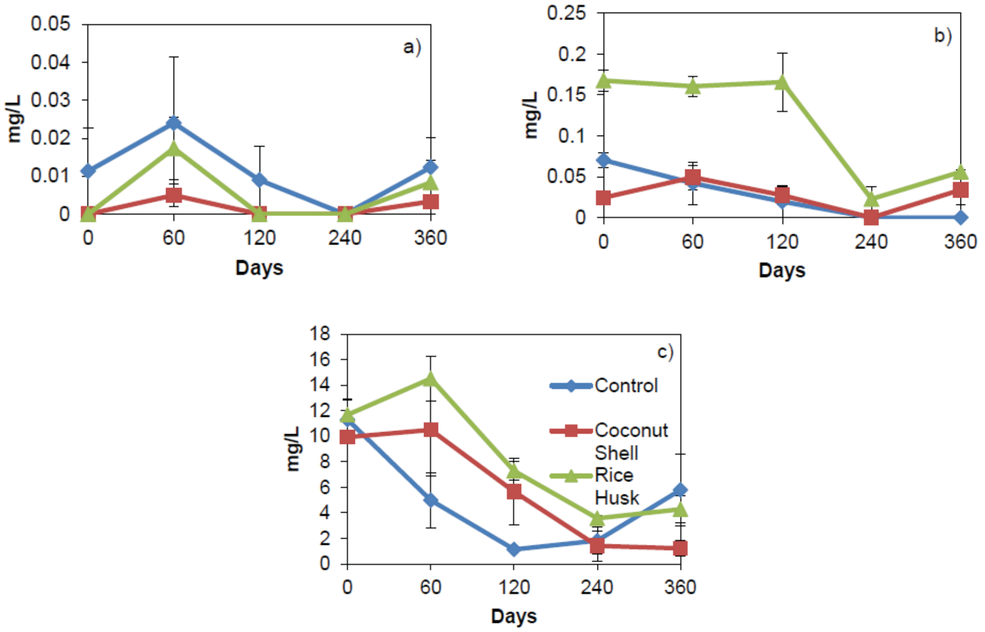


Figure 5. Concentration of phosphate over a year in the leachate of a) forest, b) non- intensively farmed, and c) intensively-farmed soils, treated with CS and RH biochar and without biochar. Error bars are SEM (n=3)

4. Conclusions

In conclusion, adding biochars (CS and RH) to tropical soil exhibited a minimal outcome in this study. The biochar addition increased the pH and carbon, and reduced ammonium leaching of forest soil. Application of biochars also had marginal effects on the CEC and microbial activity. However, biochar had no effects on the other soil characteristics, such as nitrogen and phosphate contents in the soil, as well as microbial biomass. Nevertheless, successful deployment of biochar in soils, strongly depends on the properties of the biochar and soil. Although the biochar additions had mostly a neutral effect on the soils, the positive effect on soil pH is worthy of explorations at a bigger scale, for instance in a field test, to evaluate whether the effects persist in natural conditions. Lime is costly in tropical countries and biochar may provide a useful alternative for pH management. In addition, further studies are required to evaluate the influence of such biochar on the fate of heavy metals in soil. Also, investigations on optimizing the pyrolysis conditions for enhanced agronomic properties can be explored.

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Authors contributions

Author Khasifah Muhamad contributed to the material preparation, data collection and analysis. The first draft of the manuscript was written by Khasifah Muhamad. The manuscript was commented by Prof. John Quinton and Prof. Kirk Semple. The revised draft of the manuscript was written by Khasifah Muhamad. Author Dr Uchenna Ogbonnaya written and revised the final draft of manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

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The Publication Ethics Committee of the Canadian Center of Science and Education.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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Farmers' Perception of Indigenous Seasonal Forecast Indicators in North Central Burkina Faso

Pamalba Narcise Kaboré[1], Aboubacar-Oumar Zon[2], Dasmané Bambara[1], Souleymane Koussoubé[1] & Amadé Ouédraogo[2]

[1] Institute of Environment and Agricultural Research, Environmental, Agricultural Research and Training Center of Kamboinsé, Burkina Faso

[2] Life and Earth Sciences Training and Research Unit, Plant Biology and Ecology Laboratory, Joseph KI-ZERBO University, Burkina Faso

Correspondence: Pamalba Narcise Kaboré, 01 P. Box 476 Ouagadougou 01, Burkina Faso. E-mail: kaborenarcise@yahoo.fr

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Abstract

West African Sahel is one of the most exposed areas to the adverse effects of climate variability in the world. All agricultural production systems are affected. However, farmers use indigenous knowledge that enable them to make short, medium, and long-term seasonal predictions in order to adapt their agricultural calendar to these climatic risks. In the North Central region of Burkina Faso, this knowledge is not well documented. Therefore, this study aimed to identify the indigenous indicators of seasonal forecasts and analyze factors affecting their reliability. Surveys were carried out in focus group discussions with 204 farmers in 10 localities across the region. Results showed that farmers use meteorological (cold, heat, wind, clouds, rainfall distribution), biological (food plants phenology, migratory bird behaviour, occurrence of insects), astronomical (sun, moon, stars), religious or magical indicators to predict the coming rainy season. The intensity and duration of the cold period, heat intensity and the formation of dark clouds (April-May) are signs of an early start of the rainy season (or a wet season). Likewise, the abundant leafing, flowering and fruiting of *Vitellaria paradoxa*, *Lannea microcarpa*, *Lannea acida*, *Adansonia digitata* and *Tamarindus indica* (April-May) predict a wet rainy season, while abundant fruiting of *Sclerocarya birrea* indicates a drought. The arrival period (May-June) of migratory birds heralds a start of the season. Nowadays, climate change, the degradation of plant resources and increasing human pressure are affecting the reliability of these indigenous seasonal forecast indicators in the North Central region of Burkina Faso.

Keywords: adaptation, indigenous knowledge, seasonal forecasts, semi-arid environment

1. Introduction

In recent decades, global warming has become a fact of life for the whole Africa. This warming is due to anthropogenic climate change in particular, with serious repercussions for climate sensitive sectors (IPCC, 2014), including agriculture. Indeed, the agricultural sector in the West African Sahel is the most vulnerable to the negative effects of climate change (Roudier et al., 2011; Traoré et al., 2011). This vulnerability is linked to low agricultural production and the limited capacity of rural populations to adapt to climate change (Bryan et al., 2013).

West African agriculture is facing climatic risks that have become more recurrent these last decades (Sultan et al., 2020). All production systems are exposed to rainfall extremes, the most recurrent of which in the Sahelian zone are "false starts of rainy seasons", long dry spells, torrential rains and early season cessation, all of which increase the risk of food insecurity (Salack et al., 2020) and growing poverty. Indeed, rainy seasons during the dry years of the 1970-2013 period were characterized by low rainfall, late onset and early cessation, and a high frequency of dry spells (> 7 days) (Ibrahim et al., 2022). Cumulative rainfall, intra-seasonal rainfall distribution and start and cessation dates influence rainfed crops yields and determine the agricultural calendar (Marteau et al., 2011).

Declined and irregular rainfall considerably alters cropping seasons, forcing farmers to restructure their agricultural calendar, based on local knowledge (Agbodan et al., 2020). Indeed, African farmers use several local seasonal climate forecast indicators to adapt to climate variability and change (Jiri et al., 2015). In East Africa (Ethiopia, Tanzania, Uganda), farmers and herders combine meteorological, biological and astronomical indicators to make important agricultural and livestock decisions (Radeny et al., 2019). The main indicators are environmental (clouds, wind), biological (animals, plants), magical and religious (Chang et al., 2010).

In West Africa, farmers also use indigenous knowledge of seasonal forecasts (Ingram et al., 2002, Roncoli et al., 2008; Zongo et al., 2015; Ouédraogo et al., 2018; Nyadzi et al., 2021). They contribute to reducing the impact of climate on agricultural production (Nyong et al., 2007). The use of these forecasts helps farmers to guide their decision in the choice of crop plots, varieties, rotation, sowing dates and precautions for good agricultural production (Roudier et al., 2014). Hence, the main categories of indigenous seasonal climate forecast indicators are environmental, biological, magical and religious, and are transmitted from one generation to the following through oral tradition (Zongo et al., 2022). In Benin, indigenous seasonal climate forecasts are based on the observation of abiotic (moon, sun, stars, sky) and biotic (plants phenology, bird and insect behaviour) indicators with the observations largely undertaken by local elders and professional traditional forecasters (Amegnaglo et al., 2022). For people living in the savannah zones of northern Ivory Coast, the rainy season starts with the dry season leaf renewal of trees species such as *Adansonia digitata* and *Ceiba pentandra* (Brou and Chaléard, 2007).

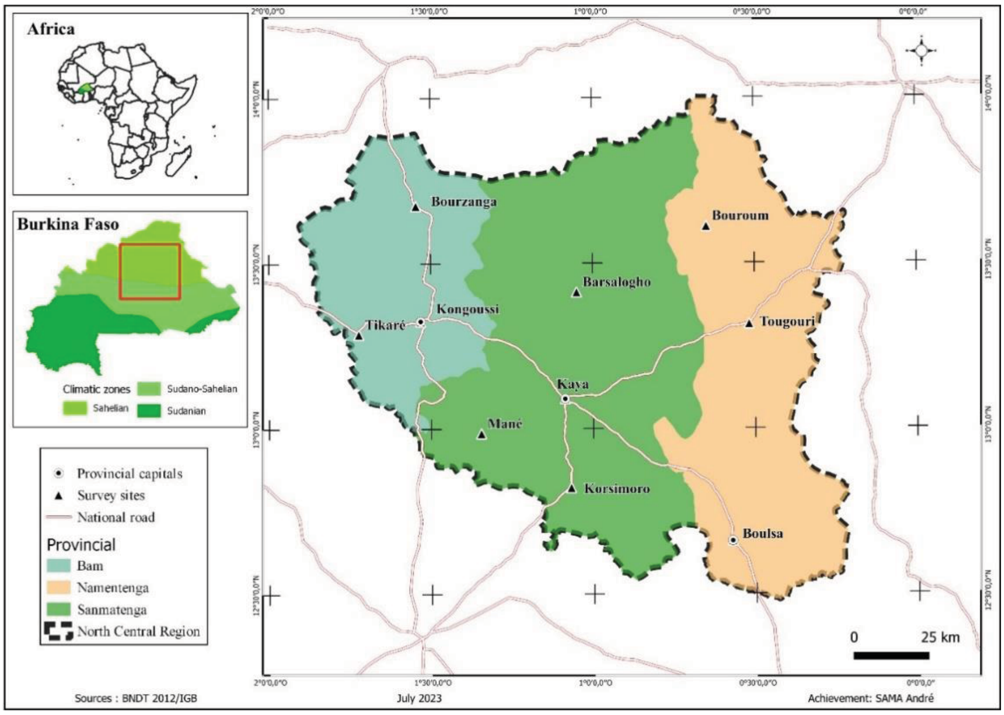
In Burkina Faso, seasonal forecasts are based on biophysical, religious or magical signs (Yaka et al., 2012). According to these authors, they include environmental observations (behaviour of some birds and insects, phenology of some plant species, wind direction, moon and star cycles), traditional divination and interpretation of Christian or Islamic scriptures. For example, the Fulani of the northern region (Yatenga province) of the country use a variety of indicators to predict the quality of the coming season. These include observations of the wind, sun, stars and constellations, the phenology of some species (*Sclerocarya birrea*, *Lannea acida*, *Lannea microcarpa*), and some herbaceous plants (such as *Blepharis leariifolia* and *Blepharis maderaspatensis*) (Bergeret, 2002).

In North Central of Burkina Faso, farmers rely on their indigenous knowledge to predict rainy seasons, in the absence of weather forecasts. Indeed, few farmers have little access to scientific climate information, provided by national radio (Zongo et al., 2015). Indigenous knowledge of seasonal climate forecasts is not well known or documented. This knowledge often varies according to locality, tradition and culture. Improving of indigenous knowledge could help farmers strengthen their adaptation strategies in the face of climatic risks. This requires, above all, some knowledge of these skills. Therefore, this study aimed to apprehend the perception of indigenous seasonal forecast indicators by farmers in the North Central Burkina Faso. Specifically, it sought to: (i) identify the indigenous indicators on which farmers rely to know beforehand the nature of the rainy season, and (ii) analyze the factors that reduce the reliability of these indicators. The study was based on the following assumptions: (i) Farmers in North Central region combine several categories of indigenous seasonal forecast indicators to predict rainy seasons; (ii) There are factors affecting the reliability of indigenous seasonal forecast indicators in this area.

2. Materials and Methods

2.1 Study Area

The North Central region of Burkina Faso covers three administrative provinces: Bam, Namentenga and Sanmatenga. Climatically, this region lies between the Sahelian and Sudano-Sahelian zones of Burkina Faso (Figure 1). Sahelian zone is characterized by average annual rainfall of 300 and 600 mm, and the Sudano-Sahelian zone, with an average rainfall of 600 and 900 mm. The climate is Sahelo-Sudanian, present two distinct seasons: a long dry season from November to May, and a short rainy season from June to October. Rainfall is lower in the north than in the south of the region (Zombré, 2006). The average annual temperature is 29 °C for the Sahelian zone, and 28 °C for the Sudano-Sahelian zone. Average annual potential of evapotranspiration (PTE) ranges from 3200 to 3500 mm in the Sahelian zone, and between 2600 and 2900 mm in the Sudano-Sahelian zone.



Sources : BNDT 2012/IGB July 2023 Achievement: SAMA André

Figure 1. Location of Survey sites in the North Central region of Burkina Faso

According to the National Meteorological Agency (NMA) of Burkina Faso, the rainy season starts on average on June 4 in the south and June 19 in the north of this region (1981-2010 period). In 80 % of cases, the rains stop after October 6 in the south and after September 18 in the north. The length of the season varies on average from 110 to 120 days in the south and 75 to 85 days in the north. Harmattan and monsoon are the two main types of wind blowing in the region.

The overall natural vegetation is dominated by steppes and shrub to tree savannahs (Fontès and Guinko, 1995), with gallery forests bordering water bodies and wetlands. The northern part of the region is the shrub and tree steppe zone. The main tree and shrub savannah species encountered in Dem and Korsimoro localities (Sanmatenga province) are: *Vitellaria paradoxa*, *Parkia biglobosa*, *Tamarindus indica*, *Bombax costatum*, *Khaya senegalensis*, *Faidherbia albida*, *Diospyros mespiliformis*, *Sclerocarya birrea*, *Lannea microcarpa*, *Balanites aegytiaca* and *Piliostigma reticulatum* (Belem et al., 2008). According to the Ministry of Agriculture, agriculture is the main economic activity of households. Indeed, over 80 % of the region's inhabitants depend on this activity, which accounts for 41 % of their main source of household income (MAHRH, 2008).

2.2 Theoretical Framework

The purpose of this study is to identify the indigenous climate seasonal forecasting indicators used by farmers to predict the quality of rainy seasons, and analyze the factors reducing the reliability of these indicators. The studies showed that Africa farmers use several categories of indigenous knowledge for seasonal forecasts. These are meteorological, biological, astronomical (Radeney et al., 2019), biophysical, religious or magical (Yaka et al., 2012; Zongo et al., 2022). The identification of indigenous indicators of seasonal forecasts was based on surveys carried out in farming areas. Analysis of the factors reducing the effectiveness of these indicators was based on the limitations to their use, that could lead to their disappearance. Several studies showed that there are factors challenging and reducing the reliability of indigenous knowledge of seasonal climate forecasts. Therefore, these factors increase their vulnerability to disappearance (Mafongoya et al., 2021). Climate variability and change are among these factors (Ingram et al., 2002; Roncoli et al., 2008). Environmental degradation, ecosystem disturbance and changing climate have seen important traditional predictor indicators disappear or lost completely from the environment (Murgor, 2022). Analysis of these factors was therefore based on the relevant scientific literature.

2.3 Data Collection and Analysis

Surveys were carried out in 10 departments in the region (Figure 1). The selection of sites took into account criteria such as rainfall variability and climatic aridity (Kaboré et al., 2017). Indeed, the Barsalogho, Bouroum, Bourzanga and Tougouri sites are located in the semi-arid zone of the country. This zone is characterized by mean annual rainfall between 350 and 600 mm (Sarr et al., 2015). The other sites (Boulsa, Kaya, Kongoussi, Korsimoro, Mané, Tikaré) are located in the humid zone of this region. Interviewees were selected at random from a list of people fulfilling well-defined criteria such as: be experienced farmers, at least 45 years old and have lived long time ago in the study area. Older people are assumed to hold local knowledge. Indeed, sound knowledge are held by experienced farmers (usually the elderly) (Ogallo et al., 2000). Knowledge is transmitted from generations to other ones through oral tradition. Information have been collected through focus group discussions (Roncoli et al., 2008; Jiri et al., 2015) and key informant interviews, due to budget constraints. Two hundred and four (204) farmers, made up of men (153) and women (51), were surveyed using 25 focus groups with 8 people each. A questionnaire has been used, focused on indigenous indicators for predicting the nature of the rainy season (wet or dry), the start of the season (early or late) and the cessation of the season (early or late). An indicator is defined as a biological, abiotic, biophysical or meteorological parameter whose occurrence, presence, abundance or evolution at a given time of year makes it possible to predict the nature of the rainy season. The interview also focused on the cropping practices adopted by farmers to mitigate the climatic risks. These practices include crop sowing dates, rotation, varieties used, and off-season irrigation. The data have been collected between April and June in the years 2015 and 2016. Indeed, it is during this period that some indicators can be observed. Data analysis consisted in identifying the main indigenous seasonal climate forecast indicators in the various localities of the study area. These different indicators have been categorized. In the discussion section, survey results have been compared with those obtained by other authors in our area, and in other parts of Africa, to see how similar they are.

3. Results

Farmers have identified several indicators for predicting the nature and distribution of the rainy season. They are meteorological, biological, astronomical, religious or magical in nature.

3.1 Meteorological Indicators

Farmers in the North Central region use several meteorological indicators to predict the quality of the rainy season. Indigenous indicators for predicting the nature of rainy seasons, onset and cessation periods of the season are presented in Tables 1, 2 and 3. The intensity and duration of cold period (over three months) indicate an early start of the coming rainy season, a late cessation or a wet rainy season. On the other hand, the short duration of the cold period (two months) is indicative of a deficient rainy season, marked by a late start and an early cessation of the rains. Similarly, an interruption of the cold period by heat waves is a sign of a deficient season, with dry spells.

Furthermore, heat intensity during the warm period (March, April, May) is a sign of an early start of the rainy season. The formation of dark cloud in April-May towards the south and the frequent movement of winds from west to east predict a wet rainy season. In addition, farmers predict deficient seasons based on the frequency and intensity of winds blowing from east to west (May-June) at the start of the rainy season. The other indicators are "the first good rain that fall at night or early morning", "the heavy rain that fall in the second decade of June, and the "first rain with hail". They advertise an early start and a wet rainy season. However, the intense and irregular rains that sometimes occur in May, the late start to the season (around mid-July) which causes late crop sowing, the uneven distribution of rain over the rainy season and the frequency of rains falling during the day are perceived by farmers as indicators of an early cessation or a dry season. In the localities of Kongoussi and Tikaré, few farmers also predict the coming rainy seasons related to alternating dry and wet years, observed since many decades.

3.2 Biological Indicators

3.2.1 Plants Indicators

Farmers rely on the phenological phases (leaf renewal, flowering, fruiting) of some plant species to predict the nature of the rainy season and rainfall distribution. They identified seven (07) plant species that enable them to predict the quality of the season in their zone. The high leaf renewal, flowering and fruiting of *Vitellaria paradoxa*, *Lannea microcarpa*, *Lannea acida*, *Tamarindus indica* and *Adansonia digitata* before the onset of rainy season are indicators of an early start or a wet season in their locality. According to some farmers, rainy season will start early if *Adansonia digitata* foliage allows two or three harvests. However, late (or low) fruiting of *Vitellaria paradoxa*, *Lannea microcarpa*, accompanied by fruit dropping before full maturity, heralds a late start of the rainy season. In particular, the abundant fruiting of *Sclerocarya birrea* reflects a deficient rainy season, with long dry spells. Farmers also have observed that many fruit trees (For example *Mangifera indica*) produce at the same time during wet seasons, whereas in dry years, fruiting occurs at different times. This study shows that farmers in the North Central region rely mainly on the phenology of some food plants species to predict the quality of the rainy season.

3.2.2 Animal Indicators

Farmers also rely on the behaviour of some animals to predict the course of the rainy season. These include migratory birds, myriapods (millipedes) and insects such as black ants (Magnant) (*Dorylus sp.*), red ants (*Oecophylla sp.*) and termites (*Macrotermes sp.*). For instance, the passage in April-May of some migratory bird species (commonly known as “*Sigr-Wali*” or “*Teng-Luila*” in the national *Mooré* language) from the south to the north, or their presence, is seen as a harbinger of an early start of the season or a wet season. If the "*Teng-Luila*" build their nests with and east-facing opening, this is seen by farmers as a sign of a sudden end to the rains. On the other hand, if the opening is facing west, it means a late end of the season (or a good season). The movement of "*Kilonkoré*" birds from south to north announces the start of the rainy season. The strong presence of "*Leigdenga*" birds heralds an early start of the season. The presence of "*Luilgoamdga*" birds heralds a good rainy season.

Similarly, the rapid movement of red ants (*Oecophylla sp.*) from waterholes to slopes with their eggs and food reserves (cereals) announces the approach of a heavy rain. Moreover, the construction of termite mounds near waterholes is a sign of a deficient rainy season. The presence or abundance of black ants at the height of the season is a sign of a cessation of the rains. The abundance of red millipedes in fields and fallows during the season indicates a late cessation of the rains, while those of black millipedes (iules) heralds an early end of the season.

3.3 Astronomic Indicators

Astronomic indicators are based on farmers' observations of the movements of celestial bodies (sun, moon, stars) during May, June and August. The appearance of the sun and the constellation of stars allow some people to make predictions about the early or late start of the rainy season, duration, and its early or late cessation. For example, the appearance in early May of a large star "*Sagbonssa*" (in the national *Mooré* language), and its positioning in the middle of the sky in June, indicates that the rainy season will be surplus to requirement. Similarly, the constellation of certain stars ("*Gobé*" in the national *Mooré* language) heralds a late start of the rainy season. Furthermore, the moon's southern position in August is perceived by farmers as a late end of rains (a long rainy season). On the other hand, the moon's easterly position in August indicates an early end of the rainy season.

3.4 Religious or Magical Indicators

Annual festivals or customary rites, and dreams (or musings) of certain resource people are religious (traditional) or magical indicators. These rites are practiced in Korsimoro and Tikaré. Chicken sacrifices during festivals enable farmers to predict the quality of the coming season. The position in which the rooster is slaughtered is an indicator of the coming season. At Korsimoro, if the rooster slaughtered during the "*Kiougou*" feast struggles and falls on its back, this indicates a wet season. But, if it falls on its right or left side, this is interpreted as a late start of the season. This analysis shows that farmers rely on a variety of indigenous indicators to predict rainy seasons.

3.5 Farmers' Adaptation Practices Response to Climate Risks

The indigenous knowledge helps farmers to guide their decision-making when choosing plots and crop varieties, crop rotation and sowing dates. Short-cycle crops varieties (sorghum, millet, maize, cowpea, sesame, etc.) are used when a late onset of the rainy season is forecast. Seeds of improved varieties are also used to intensify crop production. Adaptation practices such as peanut-cowpea, cowpea-sesame rotation, and changing the sowing data, have been adopted by farmers. Some farmers refer to lunar cycles of the year to determine when to sow maize because of its sensibility to climate risks. Similarly, declining rainfall, late onset and early cessation of rains are climatic risks that can affect crop yields. To mitigate these risks, farmers whose plots are located in lowlands or in developed perimeters use off-season irrigation. The main crops are vegetables and cereals (rainfed rice, maize).

Table 1. Perception of indigenous indicators for predicting the nature of the rainy season (wet or dry)

Nature of the rainy season		
Indicators	Wet season	Dry season
Biological indicators	-Abundant foliage, flowering and fruiting of *Vitellaria paradoxa*, *Lannea microcarpa*, *Lannea acida*, *Tamarindus indica* and *Adansonia digitata* before the start of the rainy season -Many fruit trees produce at the same time -Migratory birds move from south to north in April-May -Red ants move from the shallows to the slopes with their eggs	-Low foliage, flowering and fruiting of *Vitellaria paradoxa*, *Lannea microarpa*, *Lannea acida*, *Tamarindus indica* and *Adansonia digitata* -Abundant fruiting of *Sclerocarya birrea* -Tree fruiting occurs at different times -Termite mounds near water sources
Astronomical indicators	-Observations of the position of the sun, moon, and star constellations in May, June and August	-Observations of the position of the sun, moon, and star constellations in May, June and August
Meteorological indicators	-Cold intensity and duration (over three months) -Heat intensity in March, April and May -Formation of dark clouds in April-May towards the south -Winds shift from west to east in May-June -First rains accompanied by hail -Wet years follow dry years, and vice versa -If heavy rain falls in the second decade of June -If the first rain falls at night or early in the morning	-Less intense, short-lived cold (two months) -Cold period interrupted by heat waves (frequent dry spells during rainy season) -Frequency and intensity of east to west winds -Frequency of daytime rainfall -Intense and irregular rains that sometimes occur in May -Uneven distribution of rains over the season -Late start of the rainy season (toward July) -Late sowing period (around mid-July)

Table 2. Perception of indigenous indicators for predicting the start (early or late) of the rainy season

Indicators	**Early start to the rainy season**	**Late start to the rainy season**
Biological indicators	-Abundant fruiting of *Vitellaria paradoxa, Lannea microcarpa, Lannea acida* before the onset of the season. -Fruiting of *Mangifera indica* at the same time -Birds migration from south to north (April-May) -The strong presence of some migratory birds	-Late fruiting of *Lannea microcarpa*, *Lannea acida*, *Vitellaria paradoxa*, *Sclerocarya birrea* -Fruiting of *Mangifera indica* occurs at different times (pockets of drought during the rainy season)
Meteorological indicators	-Heavy cloud formation in April to the south -Winds shift from west to east in May-June -Heat intensity in March, April and May -Intensity and duration of cold period	-Less intense, short-lived cold (two months) -Winds shift from east to west in May-June -Cold persists into March -Winds shift from east to west in May-June

Table 3. Perception of indigenous indicators for predicting the end (early or late) of the rainy season

Indicators	**Early end of the rainy season**	**Late end of the rainy season**
Biological indicators	-Low fruiting of *Vitellaria paradoxa, Lannea microcarpa* -Migratory birds ("*Teng-Luili"*) build their nests with east-facing openings -Presence of termite and ant mounds near water sources -Black millipedes (iules) in fields and fallow land	-Abundant fruiting of *Vitellaria paradoxa, Lannea microcarpa* -Migratory birds ("*Teng-Luili*") build their nest with the opening facing west -Passage of migratory birds from south to north in April-May -Presence of red millipedes in fields and fallows
Meteorological indicators	-Short cold period (two months) -Heavy rains at the start of the season (May) -Uneven rainfall distribution throughout the rainy season -Rains are accompanied by strong winds -Sowing period begins in mid-July	-Duration of cold period (three months) -Heat intensity in March, April and May -Rainy season begins around mid-June -Low rainfall that fall at the start of the season and their distribution during the season -Weak winds during the rainy season

4. Discussion

4.1 Farmers' Perception of Indigenous Seasonal Forecast Indicators

Farmers in the North Central region of Burkina Faso use the combination of several categories seasonal forecast indicators to adapt to the adverse effects of climate variability and change. The intensity and duration of cold weather and the heat intensity are meteorological indicators that predict a wet season or an early start of the rainy season in the region. Experienced farmers make assumptions about the coming season by observing natural phenomena such as the period, intensity and duration of cold or hot temperatures (Ogallo et al., 2000). According to farmers in the North Central, cold and warm temperatures are usually associated with a wet rainy season. Smallholder farmers in Bikita District (Zimbabwe) have observed that extreme winter temperatures (between May and August) are usually associated with a good farming season (Mafongoya et al., 2021). Several reports agree that an intense cold season lasting three to four months heralds good rains for the coming season (Bergeret, 2002).

Winds blowing from west to east (May-June) herald a wet rainy season or an early start of the season. At the Fulani of northern Burkina Faso, winds blowing from west to east herald a very good season for people and animals, while winds blowing from east to west are harbingers of major natural disasters (lack of rain, poor harvests, long herd movements). Similarly, Winds from the southwest herald the sowing season (Bergeret, 2002). The shift of winds from west to east could reflects the penetration of the West African monsoon, which can be early or late depending on the year. The start of the rainy season is linked to the early or late penetration of the West African monsoon, which moves from southwest to northwest (Dékoula et al., 2018). According to Sultan and Janicot (2003), the mean date for the preonset occurrence of the West African monsoon is14 May during the period 1968-1990. The mean date for the onset occurrence of the monsoon is 24 June during the same period.

This study shows that farmers are able to predict a wet or dry season, as well as an early or late cessation of rains, based intra-seasonal rainfall variability observed in May and June. The pattern of intra-seasonal rainfall variability at the start of the season could be a predictor for the coming rainy season. Indeed, Lodoun et al. (2013) showed that the pattern of intra-seasonal rainfall distribution in May and June is predictive of the start date of the cropping season (false start or real) and the nature of the season (wet or dry). Few farmers in the North Central refer to the alternating wet and dry years to predict the coming season. According to them, deficient seasons follow wet seasons, and vice versa. Kaboré et al. (2017) observed alternating dry and wet years between 1961 and 2015 in this area.

Farmers also predict the coming season in relation to the phenology of food plants. Consequently, the abundant leaf renewal, flowering and fruiting of *Vitellaria paradoxa*, *Lannea microcarpa*, *Lannea acida*, *Tamarindus indica* and *Adansonia digitata* before the onset of the rainy season heralds an early start season (or a wet season). In Burkina Faso, fruiting of *Lannea microcarpa* heralds the start of crop sowing for farmers (Dialla, 2005). The flowering of *Millettia thonningii*, *Vitellaria paradoxa* and *Delonix regia* species, and the bursting of *Ceiba pentandra* fruit are temporal markers of the start of the rainy season (sowing period) in the Guinean zone of Togo (Agbodan et al., 2020). Among small-scale farmers in the Chiredzi (Zimbabwe), abundant flowering and fruiting of *Mangifera indica* (observed primarily at the start of the season) is seen as an indicator of a wet rainy season (Zvobgo et al., 2023). Similarly, heavy flowering of *Adansonia digitata* indicates a good rainy season (Mafongoya et al., 2021). However, abundant fruiting of *Sclerocarya birrea* predicts imminent drought (Bergeret, 2002; Jiri et al., 2015). Phenological changes in plants are inextricably linked to climatic variations and can therefore serve as key events for local populations (Cleland et al., 2007; Rosenzweig et al., 2008). The variation in leafing, flowering and fruiting periods depends on factors both intrinsic and extrinsic to the plant (Nguemo et al., 2004; Mallard, 2016). Climate is an extrinsic factor, which plays a dominant role in the onset of phenological phases.

The behaviour of migratory birds (arrival period, presence, orientation of nest access) in April-May is used by farmers to predict the start of the season. Indeed, in the Lake Chad region, the westward orientation of *Poliemaetus bellicosus* nest openings heralds a wet rainy season and good flooding, while eastward orientation presages drought (Nimrod, 2020). The appearance of red ants announces that substantial rainfall is coming (Jiri et al., 2016).

Customary festivals and the dreams or musings of certain resource people are religious or magical indicators to which farmers refer in order to know in advance how the season will unfold. According to Dialla (2005), the "*Tengsoaba"* (traditional land manager in *Mossi* villages) performs sacrifices to intercede between the living and the ancestral spirits who influence the rains. Predictions are made based on the behaviour of sacrificed animals (usually a chicken). These include the time they take to fall, the direction in which they fall, the position of the body at the moment of fall and the place where the blood is spilled. "*Tengsoaba"* and other traditional specialists may receive rain predictions from ancestors or gods in dreams or stories. Our results are similar to those of Yaka et al. (2012) who showed that in Burkina Faso, indigenous seasonal forecasts are based on environmental, religious or magical signs.

Indigenous seasonal forecast information help farmers in making the right decisions when in choosing plots and crop varieties, rotation, and sowing dates. Farmers in Bonam locality (Namentenga) generally wait for 10 to 12 days of dry weather in June before sowing maize. This period generally occurs between mid-June and early July, and coincides with the visible phase of the 8th lunar cycle of the year (Roncoli et al., 2001). Climatic risks such as late onset and early cessation of rains, long dry spells can affect agricultural yields and income. Irrigation appears to be an adaptation option in the face of this uncertainty. Kaboré et al. (2019), using a binary *Logit* model, showed that lower rainfall and late onset of the rains influence the probability of adopting irrigation at 5% threshold in the North Central region. In Benin, the use of indigenous seasonal climate forecasts increased a maize producer's net income by at least 3%, implying that indigenous seasonal climate forecasts are valuable goods (Amegnaglo et al., 2022). Indigenous seasonal forecasts also help farmers to predict climatic events, such as seasonal droughts (Bergeret, 2002; Jiri et al., 2015). Indeed, Mujere et al. (2023) maintain that indigenous knowledge system is capable of predicting seasonal droughts in way that the local communities depend on when making farmers decisions and devising appropriate adaptions measures to climate change. Subsistence farmers in developing countries still rely on indigenous knowledge systems to adapt to climate variability. In the Delta State of Nigeria, indigenous knowledge preferred to scientific systems of weather forecasting (Ebhuoma and Stimatele, 2019).

4.2 Factors Affecting the Reliability of Indigenous Seasonal Forecast Indicators

Not all of these indicators appear to be sufficiently reliable to provide accurate information to potential users. Indeed, some biological indicators are based on the phenology of food plant species. On the other hand, this study reveals a low diversity of food plants enabling farmers to make seasonal predictions. However, these species have become rare and are experiencing a decline in fruit production. Indeed, Bambara et al. (2013) report a decline in fruit production from wild and domestic woody plants in the Sahelian (Tougou) and Sudano-Sahelian (Donsin) zones of Burkina Faso, attributable to the adverse effects of climate change and increasing human pressures. For example, *Vitellaria paradoxa*, *Lannea microcarpa*, *Tamarindus indica* and *Ximenia americana* have become rare in the Sudano-Sahelian zone of Burkina Faso (Boulsa Department) (Kaboré, 2020). The scarcity and decline in fruit production are likely to affect the reliability of biological indicators. Indeed, in East Africa, the extinction of some plants and animals, desertification in pastoral areas, and the degradation of vegetation resulting from rapid urbanization and high population growth affect the biological indicators (Radeney et al., 2019).

Planet Earth has been experiencing a warming in average temperatures since 1950 (IPCC, 2013). A drop in nutrients and water availability in migration areas can affect the reproductive cycle of some vulnerable migratory birds. Likewise, global warming also may favor the proliferation of infectious diseases, affecting the population of vulnerable migratory birds. These ecological factors could threaten the survival of many migratory birds species. According to Moller et al. (2008), ongoing climate change will increasingly threaten vulnerable migratory birds species, increasing their risks of extinction. The disappearance of these birds could affect the reliability of some biological indicators based on the observation of migratory birds behaviour. For example, in northern Ghana, some animal and birds behaviour such as the movement of migratory birds, which was used to predict the likelihood of weather patterns of seasons, has been adversely affected by the changing climatic conditions (Jabik, 2022).

Farmers in the North Central region of Burkina Faso have observed that the classic cold season of yesteryear (December to February) has become warmer in recent decades (Kaboré et al., 2019). With this warming trend, farmers will not be able to make reliable predictions based on the intensity and duration of the cold period. Meteorological indicators related to rainfall are varying, and could experience a strong variability with climate change. Indeed, in West Africa, the length of rainy season is varying, with the number of rainy days changing from one year to the other (Sultan and Janicot, 2003; Traore et al., 2013). The adverse effects of climate change could affect rainfall indicators and make them less reliable. In Burkina Faso, indigenous climate forecasts are becoming less reliable due to climate change over the past two decades (Ingram et al., 2002; Roncoli et al., 2008). Likewise, distortions in the transmission of indicators from one generation to the next also call into question the reliability of these forecasts (Roncoli et al., 2008). The results of this study are in line with the hypotheses previously put forward, namely "The existence of indigenous seasonal forecast indicators and factors affecting their reliability".

5. Conclusion

In the North Central region of Burkina Faso, climatic risks affect agricultural production systems. Farmers use indigenous knowledge to mitigate these risks. They combine several categories of indigenous indicators to make forecasts or hypotheses on the nature of the rainy season, the onset and the cessation of the season in the short, medium and long term. These indicators are meteorological, biological, astronomical, religious or magical in nature. This knowledge is transmitted on from one generation to the other through oral tradition. Indigenous seasonal climate forecasts information guide farmers in their choice of crop plots, varieties, rotation, and sowing dates. An indicator is said to be reliable and beneficial when it can provide the farmer with actual seasonal climatic information, enabling him to implement his adaptation strategy. Global warming, degradation of plant resources and increasing anthropogenic pressure are threatening the reliability of indigenous seasonal forecast indicators. Species such as *Vitellaria paradoxa*, *Lannea microcarpa*, *Lannea acida*, *Tamarindus indica* and *Adansonia digitata* should be preserved and promoted for their important role in predicting rainy seasons. In perspective, a comparative study between indigenous knowledge and scientific climate information is therefore needed to determine the degree of concordance. The combination of indigenous knowledge of seasonal forecasts and scientific climate information would strengthen Sahelian farmers ' ability to adapt to climate variability and change.

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Authors contributions

Dr. KPN is responsible for study design, data collection and drafting the manuscript. Doctors ZAO, BD, KS and CPJA revised the manuscript. Prof. OA also revised the manuscript. All authors read and approved the final manuscript.

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Utilization of Black Soldier Fly (*Hermetia illucens*) Larvae as a Potential Substitute for Fish Meal in the Production of Nile Tilapia (*Oreochromis niloticus* L.)

Jonathan Munguti[1], Francis Wekesa[1], Isaac Osuga[2], Mercy Kariuki[2], Rodrigue Yossa[3], Daniel Mungai[5], Domitila Kyule[1], Jacob Abwao[1], Mary Opiyo[1], Kevin Obiero[6], Nicholas Outa[7], Erick Ogello[7], Jacob Iteba[8], James G. Kirimi[9], Anne Maundu[10], David Liti[11] & Chrysantus M. Tanga[4]

[1] Kenya Marine and Fisheries Research Institute (KMFRI), National Aquaculture Research Development and Training Center (NARDTC), P. O. Box 451-10230, Sagana, Kenya

[2] Department of Animal Science, Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000 - 00200, Nairobi, Kenya

[3] WorldFish, Jalan Batu Maung, Batu Maung, Bayan Lepas 11960, Malaysia

[4] International Centre of Insect Physiology and Ecology, P. O. Box 30772-00100 Nairobi, Kenya (ICIPE)

[5] Kenya Fisheries Service, National Aquaculture Centre, P.O Box 26 Sagana, Kenya

[6] Kenya Marine and Fisheries Research Institute (KMFRI), Sangoro Aquaculture Research Center, P.O Box 136 Pap Onditi, Kenya

[7] Department of Animal and Fisheries Sciences, Maseno University, P.O. 3275-40100 Maseno, Kenya

[8] Directorate of Fisheries, County Government of Busia, P.O Box 142, Busia, Kenya

[9] Department of Animal Sciences, Chuka University, Department of Animal Sciences, Chuka University, PO Box 109, Chuka, Kenya

[10] Department of Zoological Sciences, Kenyatta University, P. O. Box 43844 Nairobi, Kenya

[11] Department of Biological Sciences, University of Eldoret, PO Box 1125 Eldoret, Kenya

Correspondence: Jonathan M. Munguti, National Aquaculture Research Development and Training Center (NARDTC), Kenya Marine and Fisheries Research Institute (KMFRI), P.O. Box 451, Sagana, Kenya. E-mail: jmunguti2000@gmail.com

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Abstract

Utilization of quality aqua-feed relies heavily on fish meal sources of protein because of its nutritional balance. However, due to its limited supply, high cost, and decline of wild fish populations, aquaculture production has shifted focus to cheaper and more readily available alternatives to guarantee sustainable aquaculture productivity. Black soldier fly (*Hermetia illucens*) larvae are a promising replacement for fish meal in fish diets due to their relatively high crude protein, lipid and mineral contents, and the bioactive potential with anti-microbial, and other probiotic properties. This study determined the effect of partially replacing fish meal with black soldier fly meal (BSFLM) on the growth performance of Nile tilapia (*Oreochromis niloticus)*. Four isonitrogenous (30% crude protein) diets in which fish meal protein was gradually substituted with BSFLM were prepared as follows: No BSFLM (control)-T0; 25% (BSFLM25)-T25, 50% (BSFLM50)-T50 and 75% (BSFLM75)-T75. The feeds were fed to the Nile tilapia fingerlings (mean weight 25 ±5 g) which were randomly stocked in 12 cages at a stocking density of 30 fish per cage. The experimental fish were manually fed at 3% of the body weight for 28 days, and 4% of the body weight for 154 days twice a day. The study found that 25% and 50% replacement of fish meal protein with BSFLM resulted in the best growth performance of Nile tilapia, as measured by final mean body weight gain (BWG), specific growth rate (SGR), feed conversion ratio (FCR) and condition factor (K). This suggests that BSFLM is a promising alternative to fish meal in aqua-feeds in the production of Nile tilapia.

Keywords: black soldier fly larvae, nutrition, tilapia, sustainability, aquaculture

1. Introduction

The global fish demand has increasingly surpassed the supply (production) due to ballooning population growth, especially in developing countries (FAO, 2022). The capture fisheries are no longer sustainable due to a decline in the amount of fish being caught and a surge in demand for fish products globally. There have been efforts to promote aquaculture as a viable alternative to wild fish stocks (Friend & Funge-Smith, 2012) and also in order to meet the demand for aquatic foods (Nyonje et al., 2018). Aquaculture has grown significantly in the past 50 years and is now comparable to catch fisheries in terms of world food output (Ogello et al., 2014). Developing countries, dominate aquaculture production, with roughly 90% of total aquaculture production coming from these countries (FAO, 2013a). However, despite the availability of rich and diverse natural resources, aquaculture production in most African developing countries is insufficient (FAO, 2010).

Aquaculture relies heavily on providing the necessary nutrients for fish production, which depends on the level of intensification. Properly balanced diets are essential for fish health and increased fish production (Bandara, 2018). However, one of the main obstacles to boosting aquaculture production is the lack of quality and affordable aqua-feeds. The cost of fish feeds accounts for about 60% of production costs and is a hindrance to fish production, especially among smallholder fish farmers (Munguti et al., 2021). Commercial fish feeds are costly and not accessible to most rural African fish farmers, who mostly live below a dollar a day (Charo-Karisa et al., 2013). Therefore, fish meal (FM) can no longer be relied upon as the primary protein source in aquaculture because of its unstable supply and increasing prices (Muin et al., 2017).

Insect-based protein has gained increasing research attention recently, with studies demonstrating their potential as a protein source in aqua-feeds (Barroso et al., 2014; Henry et al., 2015). Insects are a promising source of proteins for farmed animals, and since many fish species feed on insects in their natural habitat, their use as a dietary ingredient in aquaculture is promising. However, their contribution to household fish production remains insignificant (Govorushko, 2019). Currently, only about 20% of the approximately one million known species of insects have been investigated as potential replacements for fish meal in feed (Sanchez-Muros et al., 2014). However, recently there has been a relief in the utilization of insect-derived and insect-derived products in proteins for farmed fish (Tan et al., 2018), due to the lifting of the ban by the European Commission. This has allowed the utilization of seven authorized species of insects. These species include black soldier fly (BSF), *Hermetia illucens*; housefly, *Musca domestica*; yellow mealworm, *Tenebrio molitor*; lesser meal worm, *Alphitobius diaperinus*; three species of crickets, (*Acheta domesticus*;, *Gryllodessigillatus*; and *Gryllus assimilis*) with distinguished required safe rearing conditions for these insects (Gasco et al., 2020; Madau et al., 2020).

Recent research has shown an increase in interest in the utilization of insect-derived meals as a source of protein in fish feed formulation and production. Studies suggest that insect-based meals can be a sustainable replacement for conventional fish or plant protein meals used in aqua-feeds (Gasco et al., 2016; Henry et al., 2015), this is because insects have the ability to upgrade low-quality organic material, require less resources and have comparatively lower carbon footprint hence lower greenhouse gas emissions (Van Huis, 2013). The shift to insect-based aqua-feed offers bio-circular economy opportunities, enhancing environmental sanitation by recycling bio-waste (Ermolaev et al., 2019; Mertenat et al., 2019). Insect-based meals have a high nutritional content and are environmentally friendly, with low water and carbon footprints and land requirements (Tschirner & Kloas, 2017; Makkar, 2017). The black soldier fly larvae, in particular, contains high-quality amino acids and lipids with fatty acids when grown in substrates of good quality (Rumpold & Schluter 2013; Gasco et al., 2018). The BSF larvae are cheap, easy to rear using domestic organic waste and can provide high-value protein with a better amino acid content that can enhance fish growth (Tran et al., 2015). This study, therefore, investigated the effects of partially substituting fishmeal with partially defatted BSF larvae as protein sources on the growth performance of Nile tilapia (*O. niloticus*).

2. Materials and Methods

2.1 Study Area

This study was carried out at the Kenya Marine and Fisheries Research Institute (KMFRI), Sagana Center (Figure 1) located in Central Kenya (0^0 19´S and 37^0 12´E).

Figure 1. The National Aquaculture Research Development and Training Center, Sagana (Experimental site)

2.2 Ethical Approval

This study was granted approval by the Institutional Animal Care and Use Committee (IACUC) of Kenya Agricultural and Livestock Research Organization (KALRO)-Veterinary Science Research Institute (VSRI); Muguga North, in compliance with all applicable regulations and guidelines, under the reference code KALRO-VSRI/IACUC028/16032022.

2.3 Diet Preparation

Four different diets were prepared for the experiment, all containing approximately 30% crude protein. The control feed was made using fish meal (FM), *Rastrineobola argentea*. Table 1 displays the ingredients and chemical composition of the experimental diets. The experimental feeds were formulated to meet the nutritional and growth requirements for *O. niloticus*. Since the nutritional composition of black soldier fly larvae meal (BSFLM) differed significantly from that of FM, substitution levels were calculated using an Excel spreadsheet to ensure that the other ingredients in the diet were adequate. The ingredients were ground and then mixed thoroughly to make a homogeneous blend. The formulations were made into pellets by adding warm water to the mixture at a rate of 5% and mixed thoroughly to achieve consistency. The mixture was then pelletized using a 2 mm meat mincing equipment. The resultant pellets were properly dried under a shade and stored in airtight dark bags during the period of the experiment.

Table 1. Ingredients and nutritional content of experimental diets fed to tilapia grower/finishing diets

Ingredient	**T0**	**T25**	**T50**	**T75**
Wheat pollard	7.00	7.00	7.00	7.00
Rice polishing	20.00	19.25	19.00	18.75
Maize germ	22.00	22.00	21.50	21.00
Fish meal	7.00	5.25	3.50	1.75
BSFLM	-	2.50	5.00	7.50
Soybean meal	35.00	35.00	35.00	35.00
Sunflower cake	5.00	5.00	5.00	5.00
Lysine	1.00	1.00	1.00	1.00
Methionine	1.00	1.00	1.00	1.00
Fish premix	2.00	2.00	2.00	2.00
Total	**100.00**	**100.00**	**100.00**	**100.00**
Nutrient Level				
CP (%)	30.60	30.52	30.42	30.32
Energy (MJ/kg)	3,037.21	3,049.11	3,049.95	3,050.80

*T0- Diet 1- control (without black soldier fly larvae meal), T25-Diet 2 (25% BSFLM substitution), T50-Diet 3 (50% BSFLM substitution) and T75-Diet 4 (75% BSFLM substitution).

2.4 Experimental Design

The study utilized twelve cages with dimensions of 2m × 2.5m × 1m, which were set up in a large earthen pond measuring 40m × 20m, with 3m maintained between each cage. Prior to filling the pond with water up to a depth of 1m, agricultural lime was applied at a rate of 100 g/m^2 and was allowed to dry for a period of two weeks. Mixed sex fingerlings of *O. niloticus* numbering three hundred and sixty were procured from KMFRI Sagana Research Centre hatchery and randomly assigned to the cages at a stocking density of 30 fingerlings per experimental cage. The fingerlings were fed on commercial feed for one month to adapt to the experimental environment before the feeding trial started, during which their initial weight was recorded.

The experiment involved feeding four types of isonitrogenous diets to the fingerlings, with varying proportions of defatted BSFLM. These diets were labeled as 0% (BSFLM0)-T0, 25% (BSFLM25)-T25, 50% (BSFLM50)-T50 and 75% (BSFLM75)-T75. Each diet was tested in triplicate, and the fingerlings were fed manually twice a day (at 10:00 hrs. and 16:00 hrs.) at 3% of their body weight over the first 28 days and 4% of their body weight for the following 154 days. The feeding trial lasted for 26 weeks.

2.5 Feeding Trials and Data Collection

Throughout the 26-week experimental period, data was collected every 21 days (3 weeks) to monitor the growth rates of the fish in terms of their length and weight. The length (TL) was measured using a measuring board while their weight was determined using a weighing scale (model EHB-3000, China). The amount of feed given to the fish was adjusted every three weeks according to the changes in their mean body weight. Fish mortality was recorded and replacement was done during the first 30 days of introducing the fish to the test (experimental) diets. The growth performance of the fish; daily weight gain, survival rate, and feed conversion ratio were calculated. The feed conversion ratio (FCR) was calculated by dividing the daily feed intake in grams (g) by the change in fish weight (g). The water parameters particularly pH, conductivity, temperature (ºC), total dissolved solids and salinity, were monitored on a weekly basis and during fish sampling using a multi-parameter meter (model H19828, Hanna Instruments Ltd., Chicago, IL, USA).

2.6 Evaluation of Dietary Performance

To determine the growth and fish feed efficiency the following parameters were measured:

Weight gain (WG), percentage WG (%WG), specific growth rate (SGR) and condition factor (K) were calculated following the formulae by Sveier et al (2000) as follows:

1. WG = W_f-W_i, where W_f is final body weight and W_i is initial body weight
2. %WG = $[(W_f-W_i)/W_f] \times 100$
3. SGR = $[(\ln (W_f) - \ln (W_i)/ T] \times 100$, where T is experimental period (days)
4. K = $(TBW/TL^3) \times 100$, where TBW is total body weight (g) and T length (cm).

The Feed Conversion Ratio (FCR) and survival rate (SR) were calculated based on formulae derived by Qi et al (2012) as follows:

5. FCR = FI/WG, where FI is feed intake (g/day) and WG is weight gain (g/day)
6. SR = $(N_f/N_i) \times 100$, where N_f is the final number of fish and N_i is the initial number of fishes

2.7 Statistical Analysis

The collected data was processed by removing errors or inconsistencies and statistical analysis was conducted using MS Excel and R Studio software. A one-way ANOVA test was conducted to determine the differences among the diets. This was followed by a Tukey HSD post hoc test for pairwise comparisons. Differences were considered significant when p<0.05.

3. Results

3.1 Water Quality

The results of selected water quality parameters are summarized in Table 2. All values fell within the recommended range for Nile Tilapia culture.

Table 2. Mean variation (Mean±SD), the minimum and maximum values of physio-chemical water quality parameters during the experimental period in the earthen pond where the experimental cages were mounted

Parameter	Mean±SD	Minimum	Maximum
Temperature (^{o}C)	21.81±0.66	17.200	26.500
Dissolved Oxygen (DO) (mg/L)	8.76±0.15	7.050	9.870
pH	7.57±0.09	6.9200	8.2000
TDS (mg/L)	67.64±3.42	54.25	98.20
Salinity (ppt)	0.05±0.002	0.04000	0.06000
Conductivity (µS/cm)	83.17±2.36	60.09	92.15

3.2 Fish Growth Trends over the Experimental Period

Figure 2 shows the growth trends of mean weights for *O. niloticus* over the course of the experiment. There were similarities and overlaps between the treatments throughout the period of the experiment. At the end of the experiment, the growth curve for T25 (25% BSFLM inclusion) had the highest weight (77.08±2.45g), followed by T50 (50% BSFLM inclusion) with 76.95±2.52g, while T75 (75% BSFLM inclusion) had the lowest weight at 70.1±2.08g.

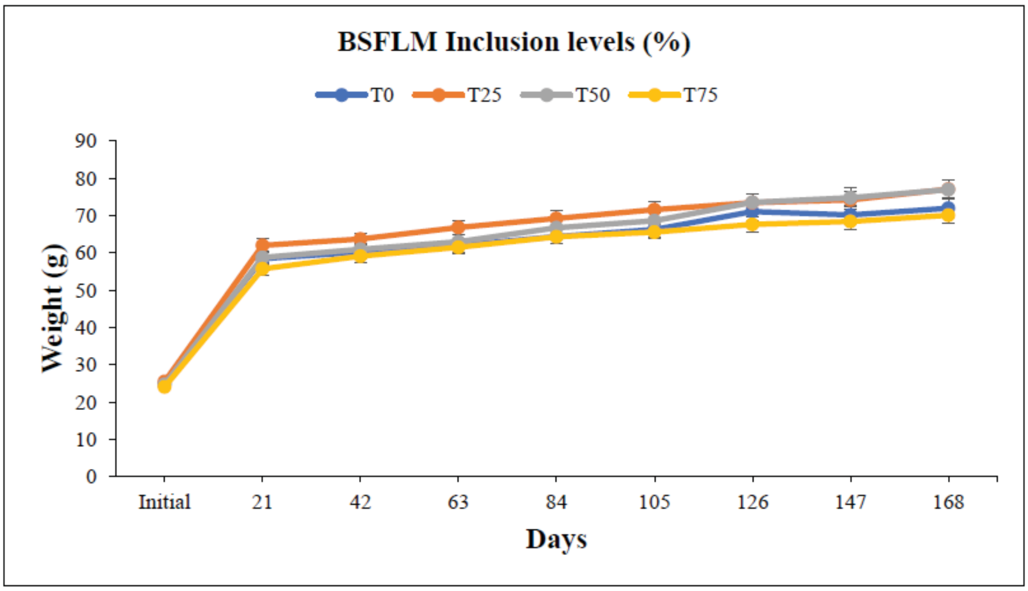

Figure 2. Growth rate (weight) of *O. niloticus* fed on varying levels of BSFLM inclusion during the culture period

3.3 Growth Parameters and Feed Utilization

The growth performance parameters presented in Table 3 showed no significant differences in growth performance among the treatments (diets) (P>0.05). However, experimental diets T50 and T25 recorded slightly higher weight gain (BWG) and specific growth rate (SGR) (BWG; 64.71±1.30; 63.88±1.28, SGR; 0.60±0.02; 0.59±0.02 respectively) than the other treatments, although the differences were not significant. The lowest values for BWG and SGR were recorded in the control diet T0 (62.69±1.36; 0.57±0.02 respectively). The survival rates during the experimental period of Nile tilapia fed on experimental diets T50, T25 and T75 were significantly higher (100%, 96.7% and 96.6% respectively) than those of the control diet T0 (85.6%). The feed conversion ratio was lowest for T0 and T50 (1.36±0.14; 1.46±0.16 respectively) but highest for T75 (1.67±0.17). Diet T25 exhibited the highest condition factor (1.73±0.02), while diet T50 recorded the lowest condition factor (1.67±0.01).

Table 3. Growth performance of *O. niloticus* fed on diets with varrying BSFLM proportions

	Dietary Treatment				**ANOVA test**	
Parameter	T0	T25	T50	T75	F-Value	P-value
Mean initial weight (g)	24.49±0.37^{ab}	25.48±0.32^{a}	24.72±0.39^{ab}	24.02±0.36^{b}	2.94	0.033
Mean final weight (g)	71.96±2.63^{a}	77.08±2.45^{a}	76.95±2.52^{a}	70.10±2.08^{a}	2.17	0.092
Mean weight gain (g)	47.46±2.62^{a}	51.60±2.45^{a}	52.22±2.58^{a}	46.08±2.13^{a}	1.56	0.199
BWG (%)	62.69±1.36^{a}	63.88±1.28^{a}	64.71±1.30^{a}	63.01±1.29^{a}	0.48	0.694
SGR (%)	0.57±0.02^{a}	0.59±0.02^{a}	0.60±0.02^{a}	0.57±0.02^{a}	0.66	0.578
Condition factor (K)	1.68±0.02^{ab}	1.73±0.02^{a}	1.67±0.01^{b}	1.70±0.01^{ab}	2.57	0.054
Survival rate (%)	85.6	96.7	100	96.6	-	-
Feed conversion ratio (FCR)	1.36±0.14^{a}	1.66±0.25^{a}	1.46±0.16^{a}	1.67±0.17^{a}	0.73	0.536

**Means on the same row with different superscript letters are significantly different at $p< 0.05$. SGR - Specific growth rate. T0- Diet 1- control; T25-Diet 2 (25% BSFLM), T50-Diet 3 (50% BSFLM) and T75-Diet 4 (75% BSFLM).

4. Discussion

Farmers in aquaculture have a major challenge of over-reliance on fish meal and fish oil in their feed formulations. This necessitates a need for a more sustainable, cost-effective, and environmentally friendly alternative protein source. Finding such alternatives is difficult because the substitutes need to contain the necessary components required to maintain fish health and welfare standards are adhered to. Insect-based feeds have become more popular because of their relatively low impact on the environment. Black Soldier Fly (BSF) larvae meal is particularly attractive as it meets the growth requirements of both terrestrial and aquatic animals, making it a viable alternative protein source in animal feeds. A study by Katya et al., (2017) reported that as much as 28.4% of fish meal replacement by BSF larvae meal without any adverse effect on growth performance in juvenile barramundi (*Lates calcarifer*). According to Nairuti et al., (2021), Nile tilapia achieved the best growth performance with an inclusion rate of 33% of BSF larvae meal in its diet.

Physico-chemical parameters in this study were at optimum levels for biochemical reactions that enhance growth, as recommended by Kirimi et al., (2022). The length coefficient was less than 3, indicating a negative allometric growth. This contrasts with Shati et al., (2022) findings that Nile tilapia fed BSFM-based diets exhibited isometric growth with a length coefficient of 3. Fish fed on BSFLM50% had the highest body weight increase at 64.71%, followed by BSFLM25% at 63.88%, BSFLM75% at 63.01% and BSFLM0% at 62.69%. Other studies on *O. niloticus* have reported varying results, such as a lower body weight gain of 30% as reported by Tippayadara et al., (2021), and higher body weight gains of 64% (Devic et al., 2018), 73% (Muin et al., 2017) and 89% (Ogello et al., 2022). These differences may be due to varying fish development stages and study periods, with previous trials lasting between 32 and 96 days compared to the current study with a duration of 182 days.

Fish that were fed with a diet consisting of 50% BSFLM (T50) had comparatively lower FCR among the test diets. The FCR values observed in this study were lower than those found in previous studies like Muin et al. (2017) and Tippayadara et al. (2021) which also used BSFLM as a feed ingredient for Nile tilapia. However, Limbu et al. (2022) reported even lower FCR values in a similar study. A lower FCR indicates better feed utilization. The comparatively low FCR observed in the fish fed with T50 may be attributed to the efficient utilization of defatted BSFLM. Insect meals that have been defatted have been shown to improve digestibility and nutrient utilization, although the chitin content is similar between defatted and non-defatted insect-based meals (Basto et al., 2020). The relatively high fat content in full-fat BSFLM may manifest in the diet increasing dietary energy density, leading to decreased feed intake by the fish. The high FCR values recorded in fish fed with T75 suggest that a high content of BSFLM negatively influenced feed utilization, possibly due to inhibition of chitin. Besides protein, BSFLM has been reported to have higher chitin content which has been observed to increase the fiber content of feeds. This could be due to low levels of fish meal in the diet, compromising the amino acid profile. Fish meal contains high-quality, digestible amino acids and fatty acids (Cho & Kim, 2011).

The utilization of BSF larvae meal has been linked to a decrease in FCR in other fish species like the Atlantic salmon post smolt (Lock et al., 2016) and Siberian sturgeon (Rawski et al., 2020). Studies have shown that de-fatting of insect meals can improve digestibility and nutrient utilization, thereby increasing feed efficiency (Basto et al., 2020). In Nile tilapia, the growth performance was improved when soybean meal was replaced with BSFLM at 100% (Shati et al. 2022). The experimental fish in this study had high survival rates, which could be attributed to the control of experimental conditions as well as the increased feed efficiency of the defatted BSFLM. Recent studies have also reported similar outcomes in Nile tilapia, including those conducted by Abdel-Tawwab et al., (2020), Wachira et al., (2021), Limbu et al., (2022), and Shati et al., (2022).

5. Conclusion

Identifying cost-effective fish feeds is a major problem impeding aquaculture production today. In recent years, the utilization of insect meal as an alternative source of protein in aqua-feed has gained popularity. Our research has shown that BSF larvae meal can replace fish meal by up to 50% without compromising growth quality. This is particularly important as fish meal is expensive and its market price is very competitive due to scarcity and overfishing in the African water bodies. By substituting fish meal with BSF larvae meal at 25%, the cost of producing well-balanced pelletized aqua-feed for Nile tilapia could be significantly reduced. However, it is important to conduct further research to optimize the aqua-feed and validate the quality of fish carcasses fed these diets to promote adoption among fish farmers and increase their profitability.

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Authors contributions

JM-Conceptualization, Funding acquisition, Investigation, Methodology, Project Administration, Writing-original draft; FW- Conceptualization, Methodology, Project administration, Validation, Writing-original draft; IO-Conceptualization, Investigation, Methodology, Project administration, Writing-review & editing; MK-Methodology, Project administration, Writing - review & editing; RY-Investigation, Methodology, Validation, Writing- review & editing, DM- Methodology, Project administration, Writing-review & editing; DK-Conceptualization, Funding acquisition, Methodology, Project administration, Writing-review & editing; JA-Investigation, Project administration, Writing-review & editing; MO-Conceptualization, Methodology, Project administration, Writing-review & editing; KO- Conceptualization, Methodology, Validation, Writing-review & editing; NO-Methodology, Project administration, Validation, Writing - review & editing; EO-Conceptualization, Methodology, Writing - review & editing; JI- Methodology, Project administration, Writing-original draft, Writing - review & editing; JGK- Methodology, Validation, Writing-review & editing; AM-Conceptualization, Methodology, Writing-review & editing; DL- Validation, Writing - review & editing; CMT- Methodology, Validation, Writing- review & editing.

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Competing interests

The authors declare that they have no conflicts of interest.

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Obtained.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Passive Solar Greenhouse-A Sustainable Option for Propagating Sweet Potato for Colder Climatic Regions

Sajjad Ali Rao[1] & Poonam Singh[1]

[1] Russ Edwards School of Agriculture and Environment, Assiniboine Community College, Brandon, Canada

Correspondence: Sajjad Ali Rao, Russ Edwards School of Agriculture and Environment, Assiniboine community College, Brandon MB, R7A 2Y9, Canada. Tel: 1-204-7259-8700x6024. E-mail: raos@assiniboine.net

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Abstract

Sweet potatoes (*Ipomoea batatas* L.) are nutritious and well adapted to a variety of growing systems around the world. This widely consumed root crop is propagated using cuttings, known as slips. Slips are predominantly cultivated in commercial settings, outdoors under field conditions, primarily in warmer regions, such as the southern states of the United States. Canada's slip production capacity is restricted due to its colder climate. Production of slips within a greenhouse system could prove to be a profitable enterprise for Canadian propagators and growers, especially with the availability of cost-effective greenhouse technology to support efficient slip production. A 2-year study was conducted at Assiniboine Community College, Brandon, Manitoba, Canada (49^{o}N, 99^{o}W). in 2019 and 2020, in a controlled commercial greenhouse (C1) with two passive solar greenhouse systems (PS1 and PS2) to determine the most efficient and economical way to produce slips commercially. The results from this study indicate passive solar greenhouse, PS1 and PS2 greenhouse technologies, produced comparable numbers of sweet potato slips (286.5, 273.3 per square meter respectively) compared to commercial standard greenhouse C1 (278.8). Days to sprouting of slips between C1, PS1 and PS2 greenhouses differed significantly ($P<0.05$). However, slip growth parameters, including number of nodes, stem diameter and total marketable slips produced in each greenhouse were not significantly different between C1, PS1 & PS2 greenhouses. In conclusion, local slip propagators can use PS1 and PS2 passive solar greenhouses to grow affordable, quality slips for sweet potato growers for timely field production in Canadian growing regions. Additionally, implementation of adapted passive solar greenhouse systems underscores the advancement of passive energy-based technology, which not only diminishes environmental repercussions but also offers year-round production alternatives.

Keywords: *Ipomoea batatas,* vegetative propagation, northern climate, greenhouse technologies

1. Introduction

Sweet potato (*Ipomoea batatas* L.) is a warm-season root crop grown mainly in tropical and subtropical regions (Iese et al., 2018). The crop requires a long frost-free period and relatively high soil and air temperatures to produce quality root yields (Teow et al., 2007). Sweet potatoes, a rich crop in anti-oxidants, fiber and vitamins, have increased in popularity among Canadian consumers in recent years. In Canada, due to climate challenges, sweet potato production is limited in crop growing regions as production is affected by lower temperatures and a shorter growing season, and limited access to propagation material. When comparing Canadian crop production areas, the province of Manitoba has a shorter, colder, climate having 75 to 125-135 frost-free days, which, are a major restrictive factor for commercial production of many field vegetables. However, some warm season crops with shorter maturity and amended agronomic practices can be grown as fresh produce in Manitoba. There is a significant and increasing interest in expanding commercial sweet potato production in Western Canada (Vanraes, 2016 & Walker, 2018). Sweet potato consumption in Canada has been steadily increasing and most consumer supply is imported from the United States (Agriculture and Agri-Food Canada, 2019). Canadian sweet potato production volume increased 30.5%, (12953 tonnes 2018 to 16883 tonnes in 2022). There has been a 22.7 % increase in imports over the last 5 years, from 66,240 tonnes (2017) to 81,274 tonnes (2021) (Statista, 2022). Canadian production has also increased and reached 2810 acres (2022) up from 1793 acres (2018) (Statistic Canada 2023 & OMAFRA 2023). According to Plant the Seeds: Opportunities to Grow Southern Ontario's Fruit and Vegetable Sector report, Ontario produces slightly more than 53,000 tonnes of sweet potatoes annually

(Greenbelt Foundation. 2021). As per the report, in October 2019, the average Canadian import price on US sweet potatoes was $0.46/pound, whereas Canadian sweet potatoes averaged at over $0.50/pound on the market.

There is significant potential to offset sweet potato slip imports and support industry expansion by local production. However, there are several factors and challenges that limit slip production expansion and competitiveness of sweet potatoes in Canada. Among these challenges, growers must be able to cultivate, store, and transport sweet potatoes into distribution channels in a financially viable manner, all while keeping prices closely aligned with those of imported sweet potatoes in the United States. One of the most immediate challenges for Canadian growers is to limit reliance on the US for slips (Young, M. 2020). However, this is contingent upon the local availability of slips for local growers. In the US, the sweet potato slip supply provided by commercial growers, are seeded into open fields in spring. This is not an option for Canadian slip propagators due to climatic conditions. As a result, there is very limited commercial sweet potato slip propagation in Canada. Canadian growers must import slips from the US to transplant into production fields in early June. Shipping losses are common and results in financial losses while impacting opportune seeding timetables. Increasing capacity for local slip propagation will provide Canadian sweet potato growers access to quality slips at the optimum cropping/planting time while eliminating transportation and administration costs, quarantine requirements and shipping losses.

Passive solar greenhouse has played a significant role in production of leafy and cool season vegetables in during winter months but also helped in extending the growing season in template area (Angmo et. al. 2019) and has now a common practice to raise vegetable nurseries in spring and grow leafy vegetables during winter months. Ahamed et. al (2018) studied the conceptual design of conventional greenhouses, using five different shapes of greenhouses including even-span, uneven-span, modified arch, vinery, and quonset shape for Canadian Prairies using a heating simulation model and concluded that uneven-span gable roof shape receives the highest solar radiation, whereas the quonset shape receives the lowest solar radiation. Similarly, Angmo et. al. (2019) evaluated different passive solar greenhouse structures such as Chinese style, trench, polytrench, polyench, polycarbonate, and polynet with a need to improvise economically viable and technologically feasible greenhouse design for crop production in winter season. Dolma et. at. (2023) studied two different sized passive solar greenhouses and found that a large size greenhouse performed better than small greenhouse size greenhouse as the larger greenhouse maintained 1.5±0.3 to 7.4±2.1 °C warmer during daytime, and 0.6±0.1 to 1.5±0.8 °C warmer at night and recommended large passive solar greenhouses for farmers in high altitude trans-Himalayan Ladakh regions for growing cauliflower and cabbage in winter season. Similarly, Ahamed et. al (2018) concluded that in high northern latitudes, east-west oriented greenhouse with more than 1 length-width ratio is more energy efficient and heating energy saving potential of the large span width in single-span greenhouses is relatively higher as compared to the multi span greenhouses. Angmo et. at (2020) study also suggested that cabbage can be successfully grown under improvised passive solar greenhouse during severe winter months in the trans-Himalayan Ladakh region. Research on the energy-intensive greenhouse production of sweet potato slips is limited, as indicated by a study conducted in Ontario (Valerio and Pearson, 2020). This study represents the inaugural investigation into the propagation of sweet potato slips within the PS1 and PS2 passive solar greenhouse technologies in the Canadian environment. The data obtained from this research holds substantial value for those contemplating the adoption of PS1 and PS2 passive solar greenhouse systems for slip propagation, serving as a valuable resource for potential slip propagators in colder climates. This study suggested the necessity for further research aimed at reducing input costs and enhancing slip yield to bolster profit margins, especially among greenhouse slip producers and commercial growers. The objective of this research is to a) evaluate the production of sweet potato slips within various passive solar greenhouse systems, each characterized by distinct technological inputs with an aim to generate and distribute locally propagated, high-quality planting material to Canadian growers timely and at a competitive price point b) adoption of passive solar greenhouse technology, with reduce environmental impact, providing year-round crop production option for Canadian growers.

2. Material and Methods

2.1 Experimental Site

A two-year study was conducted in three technology different greenhouses at Assiniboine Community College, Brandon, Manitoba, Canada (49^{o}N, 99^{o}W). in 2019 and 2020. The 10-yr average normal climate for Brandon is as follows: mean temperature varies from −22 °C to 25 °C; frost-free days is between 105 and 115 and growing season precipitation is 373 mm (source: Environmental Canada Weather Station, Brandon Meteorological Station (ID: CA005010490)).

2.2 Description of Greenhouse

This study evaluated sweet potato slips production performance in in three physically attached but separate greenhouse sections with different design technologies. Sweet potato cultivar “Covington” was used in a single-factor independent experiment. The treatments were (i) commercial greenhouse, with high technology inputs, named C1, a standard A-frame greenhouse features (triangular, cross-rafters with a peak) and advanced control of climate due to supplemental heating and lighting (mix of 400 W metal halide lamps and 400 W high-sodium pressure lamps in alternate rows); (ii) passive solar greenhouse, with medium technology inputs, named PS2, a half-dome structure with a passive solar system in addition to in-floor heating, consisting of standard passive solar greenhouse features but warmer due to better heat sinks; and (iii) passive solar greenhouse, with low technology inputs, named PS1, a half-done structure with a passive solar system, three-layer transparent polyethylene glazing material with basic features (Abbey and Rao. 2018). The passive solar greenhouses, PS1 and PS2, were designed to collect, store, and distribute solar energy in the form of heat in the winter and dissipate heat in the summer. The main components of both (PS1 and PS2) greenhouses included steel framing, a three-layer transparent polyethylene film, a north wall for conserving solar energy, and one hydronic unit heater (Model: RH165HO1SAB Zehnder Rittling, NY USA) connected through glycol loops to a propane fueled boiler (Camus DynaMax DMPG-0701-MSI, Mississauga, Canada), configured with Argus Titan Control system to maintain target temperature(s). The south side of both greenhouses features a sloping 45^o facing steel framing structure resting on a 1.2 m high concrete insulated vertical wall. The surface is glazed with Solawrap, a three-layer transparent polyethylene film, with air bubbles in the middle acting as energy-saving insulation (Growing Technologies, Solawrap Canada), which has a solar radiation transmissivity of 0.83. The east and west walls were covered with 6 mm Macrolux twin polycarbonate (0.80 solar radiation transmissivity) constructed with 15.2 cm studded insulated wall. The north side interior wall is insulated and covered with 24ga black painted steel material (Cascadia Metals Ltd). PS1 has an extended floor area equipped with rows of 8 black PVC barrels (95 gallons capacity) to conserve solar energy. However, this variable was not used in this study. In addition to PS1 heating features, PS2 received additional floor heating from the active solar heating panels, 5 sets of 30 SunMax Vacuum Heat Pipe solar evacuated tube collectors, installed on standing extruded aluminum frame (2.6mx2.0m) in front of the south facing greenhouse complex. These solar collectors absorb and transfer heat to the solar hot water tank (StorMaxxCTec-211-3HX) installed in PS2. The in-floor heating system draws energy from the solar hot water tank to heat PS2. The C1 on the other hand, was designed to meet industry standards with relatively high technological input and was glazed with double-layer semi-rigid polycarbonate. Unlike the PS1 and PS2, the environmental variables in the C1 were fully controlled. Experimental area on greenhouse bench measured, 2.6mx0.8mx0.8m (LxWxH), and were the same for all three greenhouses.

2.3 Greenhouse Temperature Setting and Data Acquisition

Both external and internal greenhouse environmental conditions were controlled and recorded using Argus Titan system version 718 (Argus Control Systems limited, Surrey, British Columbia, Canada). Titan WS2 weather station, installed at the top of greenhouse building, was configured with the Argus Titan Control System to record on-site weather data for outdoor temperature (°C), light energy (W/m^2), wind speed and direction. Inside greenhouse climate information were recorded by Titan I/O modules (Omni-Sensors SEN-OSM-1.3A), installed at the same distance in each greenhouse. Data recording included climate temperature (°C), climate humidity (% RH), and Photosynthetically Active Radiation (PAR μmol) and CO_2 (ppm). The temperature profile for all three greenhouses was set at 20 °C (day) and 18 °C (night) from March to May. Argus control system was configured to deliver the amount of heat required to match the current rate of the heat loss to maintain the target temperature. This configuration calculates Heating Required Temperature (HRT %). HRT considers current temperature conditions in relation to the target set point temperature and develops a proportioned result from 0% to 100%. At 0%, no heat is required for temperature management. Whereas at 100%, maximum heating resources are required to meet the current demand (Rao, et. al. 2018).

2.4 Plant Materials and Data collection

The sweet potato cultivars Covington (COV) was used to evaluate slip production in all three greenhouses. Generation 2 (G2) US grade # 2 root seed was bedded into four black plastic crates, measuring 60 × 38 × 22 cm (L×W×H) from March to early June in each greenhouse to produce G2 slips. Black landscape fabric, 1.5 oz non-woven, lined the bottom and sides of the black plastic crates to hold the Pro-mix BX^{TM} soilless potting medium (Premier Horticulture Inc., Quakertown PA) and roots. Moistened pro-mix layer of 10 cm was spread evenly in the black plastic crates. Seed roots of sweet potato cultivars were distributed evenly and placed manually on 01 March 2019 and 2020 at equal covering seed root density in each crate without overlapping or stacking, providing optimum sprouting potential. Seed roots were covered with 4 cm of moistened pro-mix layer in crates after planting. N17-P5-K19 soluble fertilizer was applied every two weeks at the rate of 1.16 g-1 per crate after sprouting started. Plants were watered as required.

Data included recorded slips production and growth characteristics, including days to sprouting for all four crates from each greenhouse. Harvesting of slips, that attained the length of 25 cm or greater, was completed three times, May 25th, June 1st and June 8th. Manual harvesting was completed by cutting vine stems 1 inch above the soil line. Slips were harvested in the morning and data collection was conducted on the same day. Harvests from each greenhouse were sorted and measured to determine the number of marketable slips produced per square meter. In addition to slip yield, slip quality parameters including number of nodes and stem diameter were measured on 10 individual, randomly selected slips from each replication at each greenhouse in 2019 and 2020 and averaged for analysis. Slip quality measurements (stem diameter and number of nodes) were performed on a randomly selected individual slip. Slip length was determined by measuring from the cut end to the apical meristem. The nodes of each sample were counted from the cut end to the apex, but did not include the growing point. Slip stem diameter was measured, using a caliper tool, within 1 cm of cut end and nodes were avoided. Data was averaged for comparison and analysis.

2.5 Experimental Design and Data Analyses

The treatments were greenhouse design technologies, C1, PS1 and PS2, and with 4 crates of each sweet potato cultivar randomly interspersed on the benches in each greenhouse. To avoid pseudoreplication as explained by Schank and Kohnle (2009), the experiment was replicated in time i.e. two replications in 2019 and 2020. Data were subjected to analyses of variance (ANOVA) using CoStat (ver. 6.45; CoHort Software CA U.S.A). Differences between treatment means were determined using Fisher's least significant difference (LSD) at 0.05.

3. Results and Discussion

Monthly minimum, maximum and average outside air temperatures and light conditions varied between years 2019 and 2020 from March to May. Minimum, maximum and average monthly outside air temperatures were higher in year 2019 and slightly warmer than 2020. Whereas, outside light energy trends were higher for the month of March, in 2020, and there was more light energy in April and May 2019 compare to 2019 (Table 1). Overall, there was an observed upward trend in both outside air temperatures and light conditions from March to May. During this period, the crop experienced an augmentation in heat accumulation and photosynthetically active radiation, which contributed to its growth in each consecutive month.

In this study, all three greenhouse technologies (C1, PS1 and PS2) created varied microclimates (Fig. 1) and had a different influence on HRT (Fig. 3) and days to sprouting of sweet potato slips (Fig. 4) in particular. Similarly, varied microclimate recorded by Ahmad et. al (2023) while studying on design and thermal performance of innovative greenhouse and reported that the solar greenhouse ensures proper microclimatic conditions all day long by reducing the temperature by 11.14 °C compared to conventional greenhouses. Maximum and minimum temperatures exceeded set points in all greenhouses in both study years from March to May, excluding PS1 greenhouse where minimum night temperatures remained below set setpoint in March (14°C) and April (16°C) in 2019 and was off set points for minimum and maximum temperatures in March (12°C and 16°C respectively) 2020 (Table 2 and Fig. 1). PS2 greenhouse maintained a higher mean temperature (22.9°C) in the month of March compared to C1 (22.1°C) and PS1 (20.0°C) greenhouse technologies (Fig. 1). The temperatures in all three greenhouses created varied climatic conditions and affected sweet potato sprouting differently in each greenhouse. The results were statistically significantly ($P<0.05$) different for days to sprouting in greenhouse technologies tested in this study (Table 5). The increase in greenhouse climate temperature in PS2 observed in this study, was possibly due to the concrete floor and in-floor heating solar heating system in PS2, differentiating from PS1 and C1 greenhouse technology as reported by Rao et al. (2018) in a passive solar greenhouse studied in the Canadian prairies (50°N). A similar study was conducted by Bazgaou et. al. (2021) on the performance of an Active Solar Heating System (ASHS) consisting of two solar water heaters equipped with flat solar collectors, two storage tanks and exchanger pipes, and assesses the performance of the Active Solar Heating System, climatic and agronomic parameters in two identical canarian greenhouses, one equipped with ASHS heater and the second without. Results from this study showed that the ASHS system improve the nocturnal climatic conditions under greenhouse, and the economic analysis indicated that the ASHS system is a cost effective in terms of investment and energy saving.

Table 1. Two years monthly average outside temperature (^{o}C) and light energy (Wm-^{2}) at experimental site

Month	2019			2020			2-Years Average		
	Outside Temperature (^{o}C)								
	Min[1]	Max[1]	Mean[1]	Min[1]	Max[1]	Mean[1]	Min[1]	Max[1]	Mean[1]
March	-16.0	9.0	0.0	-18.9	3.4	-5.9	-17.5	6.2	-3.0
April	-4.0	11.0	3.9	-7.9	6.0	0.2	-6.0	8.5	2.1
May	3.0	22.0	11.5	2.9	18.2	11.3	3.0	20.1	11.4
	Outside Light Energy (Wm-^{2})								
March	25.0	200.0	104.4	61.0	226.0	150.1	43.0	213.0	127.3
April	75.0	291.0	199.0	24.0	285.0	178.9	49.5	288.0	189.0
May	54.0	389.0	258.6	38.0	327.0	183.3	46.0	358.0	221.0

[1] average measured daily over 3 hours interval for each day of the month.

Table 2. Monthly average inside climate temperature variations (^{O}C) in C1, PS1 and PS2 greenhouses for two study years

Month	2019						2020					
	C1		PS1		PS2		C1		PS1		PS2	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
March	23.0	21.0	22.0	14.0	26.1	18.9	24.4	21.6	23.6	12.6	26.8	20.8
April	23.0	21.0	25.0	16.0	26.9	17.5	25.1	22.1	23.5	21.8	26.1	21.2
May	27.0	21.0	29.0	22.0	30.4	21.8	25.6	22.4	27.8	21.3	30.3	21.7

Table 3. Monthly average photosynthetically active radiation (µmoles m-^{2}s-^{1}) variation in C1, PS1 and PS2 greenhouses for two study years

Month	2019						2020					
	C1		PS1		PS2		C1		PS1		PS2	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
March	114.0	20.0	101.0	8.0	194.0	15.0	130.0	39.0	111.0	0.0	209.0	28.0
April	162.0	59.0	130.0	15.0	250.0	38.0	175.0	19.0	126.0	6.0	253.0	16.0
May	186.0	37.0	137.0	13.0	275.0	30.0	176.0	26.0	136.0	9.0	264.0	21.0

Table 4. Monthly heating temperature required (%) variations in C1, PS1 and PS2 greenhouses for two study years

Month	2019						2020					
	C1		PS1		PS2		C1		PS1		PS2	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
March	38.0	11.0	90.0	14.0	20.6	15.1	57.5	10.9	66.9	3.3	67.6	6.1
April	27.0	6.0	92.0	24.0	21.6	4.8	37.2	11.1	75.7	25.3	62.3	11.7
May	30.0	0.0	67.0	3.0	12.9	0.0	19.9	1.3	43.2	2.1	20.8	0.2

Starting from March 2019, there was a rise in photosynthetically active radiation (PAR) within all three greenhouses, corresponding to an increase in outside solar radiation levels. (Table 3). PS2 greenhouse recorded significantly ($P<0.05$) higher PAR over C1 and PS1 in each month and between months for the individual growing seasons (Fig. 2). The highest PAR intensity was measured in PS2 (275) in the month of May 2019, followed by C1 (186) and PS1 (137) respectively. A similar trend of higher PAR was recorded in PS2 greenhouse for the month of April and March for the year 2019 and 2020 compare to C1 and PS1 greenhouse technologies (Table 3). This higher PAR in PS2 greenhouse technology, as reported by Rao et. al 2018, resulted from the concrete floor reflection as compared to the interceptive gravel floor in the PS1 and in C1 greenhouses. This may also have contributed to higher maximum temperatures in PS2 as solar radiation had more influence in the greenhouse temperature compared to outdoor temperature (Beshada, 2006). Zhang et. al. (2021) reported the direct solar radiation flux and net radiation flux on building surface areas changed significantly while studying the influence of urban three-dimensional structure and building greenhouse effect on local radiation flux. The absorption of the diffused light by the gravel floor surface was also in agreement with the studies carried out by Papadakis et al., in 2000. Tao et. al (2016) evaluated the light distribution and its effect on plant growth in Chinese Solar Greenhouse (CSG), and showed that PAR intensity in the south and middle sections of CSG was permanently higher than the north section which resulted in distinct plant growth performance. Specifically, plants grown in the north section of CSG exhibited a shade avoidance response with stem elongation phenotype and leaf expansion. Furthermore, the north-plants showed lower leaf photosynthetic capacity which correlated with a lower total nitrogen and chlorophyll contents in comparison with the plants grown in the middle and south sections. Tao et. al (2016) concluded that due to heterogeneous light distribution plant growth is not uniform in CSG, which was caused by unbalanced greenhouse structures and inputs. The results of the present study agree with Rao et al. (2018) who reported higher photosynthetically active radiation in a concrete floored greenhouse compared to a gravel floored greenhouse and influenced the microclimate of the greenhouse.

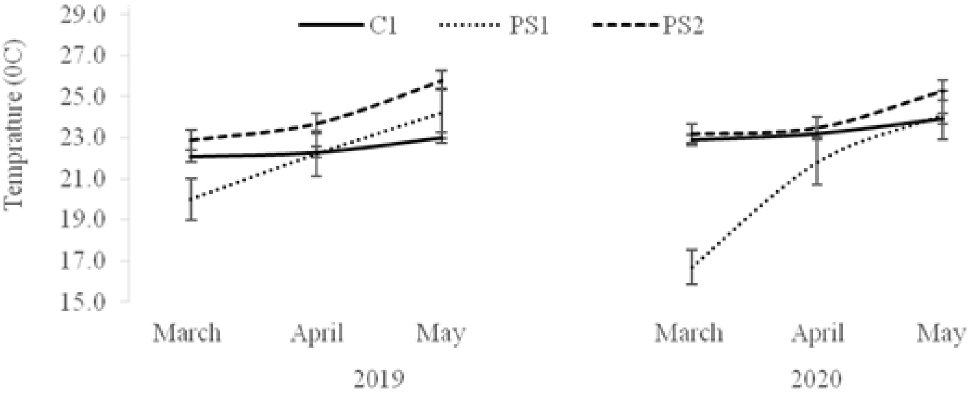

Figure 1. Greenhouse climate Temperature variations in C1, PS1 and PS2 greenhouses

Vertical bars ±SE (n=240, 248, 248, 224, 248, 240 for March, April and May respectively)

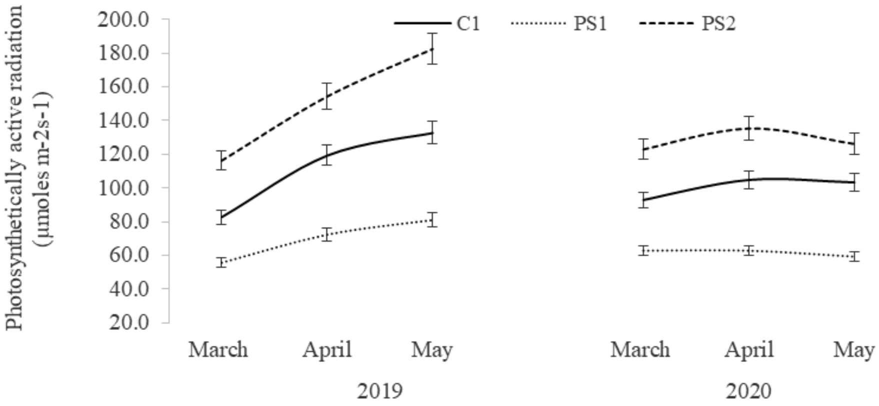

Figure 2. Photosynthetically active radiation variations in C1, PS1 and PS2 greenhouses

Vertical bars ±SE (n=240, 248, 248, 224, 248, 240 for March, April and May respectively)

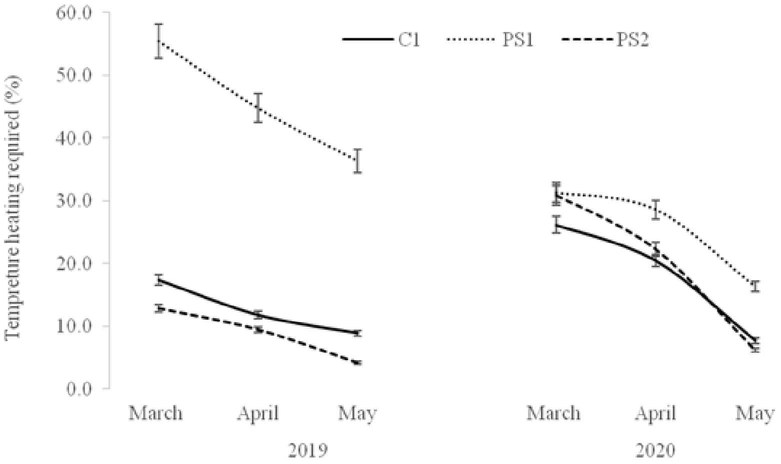

Figure 3. Temperature heating required (%) variations in C1, PS1 and PS2 greenhouses

Vertical bars ±SE (n=240, 248, 248, 224, 248, 240 for March, April and May respectively)

The required heating temperature for each C1, PS1 and PS2 greenhouse was measured daily over two years. Yearly averaged, maximum and minimum HRT was recorded and presented in Table 4 and Figure 3. PS1 required significantly higher heating (55.5%, 44.8% & 36.4% and 31.3%, 28.3% & 16.3%) in for March, April and May respectively for both years, in order to maintain inside temperature compared to PS2 and C1 greenhouses. Whereas a non-significant heating requirement was recorded between the PS1 and C1 greenhouses for the month of March 2020 (Fig. 3). This lower demand of required heating in PS2 resulted from high temperatures generated through the combined climate energy effect, outdoor temperature and light effect, average daily energy storage and release by the north wall and soil surface (Beshada et al., 2006) and in-floor heating system as reported by Rao et. al. (2018); consequently, maintaining a higher climate temperature in PS2 than C1 and PS1. Rao et al. (2018) additionally noted a considerably reduced influence of outdoor heating temperatures in April as compared to March. Moreover, they observed a non-significant disparity in the heating light effect between the months of March and April while investigating the implications of solar energy on greenhouse climate and crop production. Similarly, Gupta and Chandra (2002) conducted research to explore different energy conservation measures for the establishment of an energy-efficient greenhouse. Their findings revealed a 2.6% and 4.2% reduction in heating requirements for gothic arch-shaped greenhouses compared to gable and Quonset shapes, respectively. They also reported an additional substantial heating reduction of 23% and 30% through the implementation of double wall glazing and insulation on the north wall of the gothic greenhouse. Xu et. al. (2021) compared passive solar greenhouse heating with and without active solar water wall and reported 4.1 °C higher night time temperature than that in the control greenhouse and conclude that retrofitting the water wall into Chinese solar greenhouses can make warm-season crop production feasible throughout winter by eliminating supplemental heating and supported the present finding of this study.

Table 5. F ratios and effect of greenhouse technology on sweet potato slips production and growth characteristics evaluated during 2021 and 2019 (2 years Average)

	Days to sprout	1st harvest	2nd harvest	3rd harvest	Total Marketable Slips	Nodes (no. /cm.)	Stem Diameter (mm)
Greenhouse	Means						
C1	29^{c}	69.2^{ab}	90.0^{a}	128.6^{a}	287.8^{a}	9.8^{a}	3.38^{a}
PS1	35.1^{a}	63.25^{b}	88.7^{a}	121.7^{a}	273.7^{a}	10.5^{a}	3.34^{a}
PS2	30.5^{b}	75.0^{a}	90.0^{a}	121.5^{a}	286.5^{a}	9.7^{a}	3.18^{a}
LSD	1.18	8.2	8.9	10.77	15.82	0.86	0.45
Source of Variation	Significance						
Year	*	NS	NS	NS	NS	NS	NS
Greenhouse Technology	***	*	NS	NS	NS	NS	NS
Year x Greenhouse Technology	NS	NS	NS	NS	NS	NS	NS
CV	3.56	11.28	9.46	8.27	5.32	8.21	13.24

*, **, *** represents P=0.05, 0.01, 0.001 respectively and ns, not significant

$^{a-b}$=means within a column followed by the same letter are not significantly different at P<0.05 according to LSD.

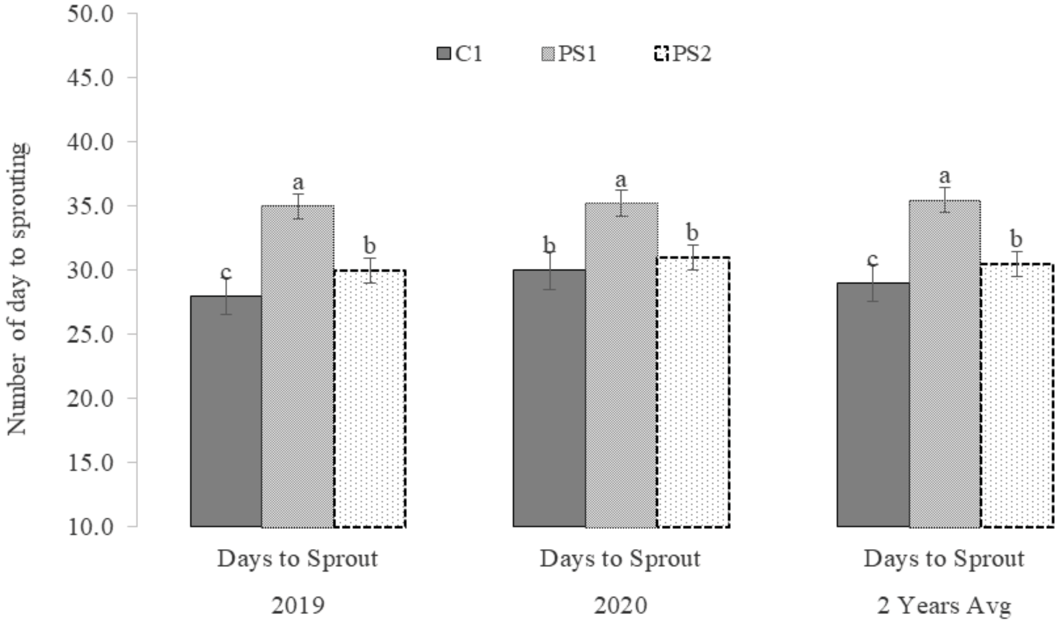

Figure 4. Sweet potato slip days to sprout in Commercial (C1), Passive Solar 1 (PS1) and Passive Solar 2 (PS2) greenhouses. Different letter on error bars indicate the dsignificant diffence (p=0.05)

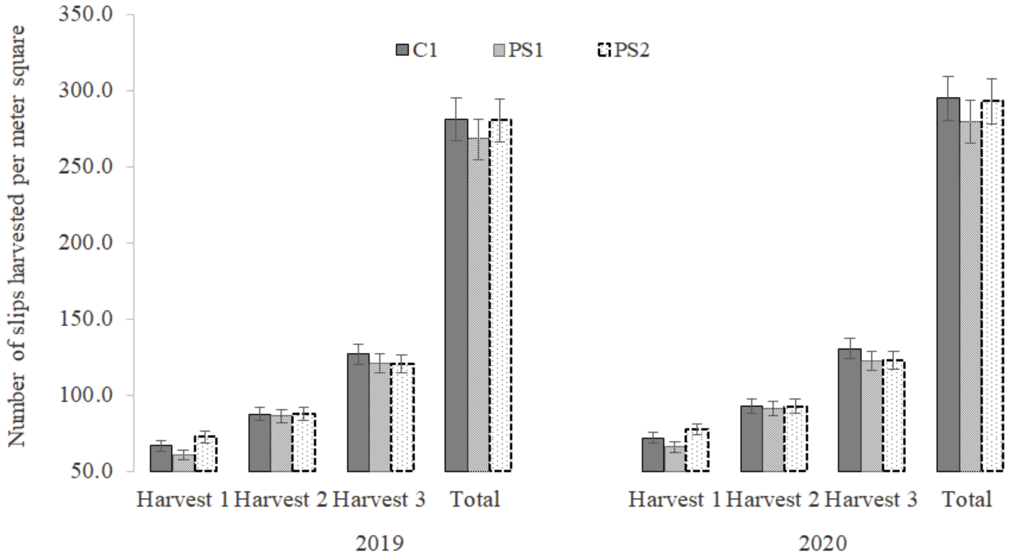

Figure 5. Marketable slips (m-^{1}) in Commercial (C1), Passive Solar 1 (PS1) and Passive Solar 2 (PS2) greenhouses. Different letter on error bars indicate the dsignificant diffence (p=0.05)

Sweet potato slips production and growth parameters in all three greenhouse technologies are presented in Table 5, and Figures 4 & 5. Analysis of variance revealed a significant (P<0.05) difference for days to sprouting between three, C1, PS1 & PS2, greenhouse technologies (Table 5). Sweet potato slips sprouted 5 to 6 days earlier in C1 greenhouse compared to PS1 greenhouse (Fig. 4). A higher minimum temperature of, 21°C and 21.6 °C, was maintained in C1 during the month of March 2019 and 2020 respectively, which favoured early slips sprouting in C1 compared to PS1 where minimum temperatures was 14°C and 12.6 °C during the month of March 2019 and 2020 respectively (Table 2). Significant difference (P<0.05) was recorded between C1 and PS2 greenhouse environments for the number of days to sprouting. A significant (P<0.05) difference was recorded for slips harvested on May 25th, 1st harvest, in PS1 greenhouse where lower number of slips were harvested comparing PS2 and C1 greenhouses, whereas, non-significant differences were found for the 2nd, 3rd harvests and in total number of slips harvested between the C1, PS1 and PS2 greenhouse technologies. Similarly, a non-significant difference was found for number of nodes and stem diameters of the slips harvested in each greenhouse. The two-way interaction between years and greenhouse technology was non-significant for all slip production and growth characteristics evaluated during this study (Table 5). The findings from the two-year study demonstrate that employing PS1 and PS2 greenhouse technologies provided a comparable advantage in slip production when initiating the process in early March to ensure that slips are prepared for transplanting by the beginning of June. This is evidenced by the presence of non-significant interaction of year versus greenhouse technology (Table 5).

Results from this study indicated all three, C1, PS1 and PS2 greenhouse technologies produced comparable (287.8, 273.3 and 286.5 respectively) numbers of sweet potato slips for field transplantation in early June. Gourdo et. at. (2019) studies on evaluating the effect of a solar heating system, using black plastic sleeves filled with water, on the greenhouse microclimate and tomato yield in canarian greenhouses and recorded 3.1 °C higher nighttime temperature inside the greenhouse compared to the control greenhouse and tomato production increased by 35% compared to the control greenhouse due to this microclimate improvement. Hoppenstedt et. at. (2019) compared two growing environments, high tunnel versus an open field for slip production and reported inconsistent slip yield from high tunnel when tested two years in a row. However, Hoppenstedt et. at. (2019) showed the result for mean comparisons for vine length and stem diameter of slips were not significantly different between high tunnel and open field systems in both tested years and thus support findings for the growth parameter evaluated in this study. Hoppenstedt et. at. (2019) also reported the mean high tunnel (120.3 slips/m2) and open field marketable slip (123.3 slips/m2) yield harvested in year 2017 were nearly the same and are like this current study's findings. Earlier investigations into sweet potato slip production, as documented by Valerio and Pearson (2020) in a conventional greenhouse setting, as well as studies carried out by Knewtson et al. (2010) in various growing systems, including high tunnels, align with the findings of this research. This research underscores that sustainable passive solar greenhouse technologies represent a viable choice for sweet potato slip production within the Canadian environmental context.

4. Conclusion

The results of this study suggest sweet potato slip production in PS1 and PS2 passive solar greenhouse technologies may be a viable alternative to produce sweet potato slips for Canadian growers. PS2 greenhouse design with an in-floor active solar heating system provided an optimum slip production environment as compared to PS1 greenhouse. PS2 with a lesser number of days to sprouting and higher total marketable slips give better option over PS1 greenhouse. PS2 greenhouse will also allow growers to reduce greenhouse heating expenses and maximize early and more slips production in PS2 greenhouse. Further research exploiting different planting dates and using different growing media is recommended to determine better methodology and material to optimise slip production in passive solar greenhouse conditions.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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Production Systems and Management Practices of Chicken Populations in Zambia

Sylvia Jana Harrison[1], Mayoba Barbara Moono[2] & Idowu Kolawole Odubote[1]

[1] Department of Animal Science, School of Agricultural Sciences, University of Zambia, Lusaka, Zambia

[2] Department of Livestock Development, Ministry of Fisheries and Livestock, Lusaka, Zambia

Corresponding author: Sylvia Jana Harrison, Department of Animal Science, School of Agricultural Sciences, University of Zambia, Lusaka, Zambia. Tel: 260-977-255-380. E-mail: sylvia.harrison@unza.zm
ORCID: 0000-0002-8893-3344

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Abstract

The study was carried out to describe the population, population dynamics, production systems and management practices of chicken types reared in Zambia, using the 2017/2018 livestock and aquaculture census data provided by the Zambia Statistics Agency and the Ministry of Fisheries and Livestock. Data on the chicken types - Indigenous, Broiler and Layer, was analyzed for both quantitative and qualitative parameters. The population estimates for the chickens were 15,313,780, 6,078,694 and 742,981 for indigenous, broiler and layer, respectively. Flock dynamics could not be ascertained conclusively due to inadequate information. Chicken ownership was significantly skewed towards the male gender for broilers (67%) and layers (79%) while almost equal for the indigenous chickens. Indigenous chickens were more prominent in provinces with high agricultural production (Southern, Central, and Eastern at 51%). Broilers and Layers were more prominent in provinces with commercial centres (Copperbelt and Lusaka at 68% and 75% respectively). The main purpose of rearing indigenous chickens was mainly sales for income (66.1%) and home consumption (32.3%). The main production systems were found to be traditional for indigenous chickens (87%) and intensive for broiler and layer chickens (70.3% and 44%, respectively). The main feeding practices were free-range feeding (80.6%) and free-range with supplementation (17.4%) for indigenous chickens). Diseases notably, Newcastle was found to be debilitating and a great hindrance to livestock production and productivity. The data collection instrument will require fine-tuning to obtain more technical details on production and productivity and better estimate the population dynamics.

Keywords: broiler, census, diseases, indigenous, layer, population dynamics

1. Introduction

The livestock sub-sector in Zambia is an important component of agriculture, contributing 42% of the agricultural sector's gross domestic product (GDP), which is equivalent to 3.2% of the national GDP, and 50% of employment in the rural areas (Bwalya and Kalinda, 2014). The sub-sector has great potential, as it can contribute to economic diversification, food security and nutrition, improved rural livelihood and sustainable income generation. The Government of the Republic of Zambia identified the livestock sub-sector as one of the key drivers of economic growth through enhancing livestock production and productivity, and prioritization of livestock research and development, as stated in the Eighth National Development Plan (8NDP) and the National Livestock Development Policy (MoFNP, 2022; MFL, 2020).

The livestock sub-sector in Zambia is largely cattle, goat, sheep, pig and poultry populations as the major livestock reared. Poultry constitutes domesticated avian species, including chickens, guinea fowls, ducks, geese, pigeons, and turkeys, that are kept for economic significance (Abadula et al., 2020; Adei and Asante, 2012). RALS (2019) affirmed that over 80% of smallholder households own at least one chicken. Chickens are thus the most common type of poultry and livestock owned by the majority of smallholder households in Zambia.

Chicken production, therefore, has the potential to play a significant role in the economy of Zambia because of its widespread distribution and the likely impact of interventions on livelihoods. Currently, the demand for animal protein sources does not match the supply and is expected to increase as a result of the increasing human population (MoFNP, 2022; Sianangama et al., 2022). Consumption of livestock products directly correlates to income and affordability, implying that a higher income will indicate an increase in livestock products in the diet. Compared to other livestock, chickens are small-sized, cheaper to acquire and widespread in distribution, accounting for their incorporation into the diet. It has been revealed that women are more involved in the management of smaller-sized livestock such as poultry, sheep and goats (Banda and Tanganyika, 2021). Chickens would therefore be an important developmental tool in poverty alleviation.

The Government of the Republic of Zambia, in its quest to determine the contributions of livestock to the GDP, conducted a Livestock and Aquaculture Census in 2017-2018. The Ministry of Fisheries and Livestock, in its preliminary report, provided summaries of poultry production and its distribution across provinces and establishments (MFL, 2019). However, the information on chicken production systems and management practices was limited. In light of the above, this study was conducted to perform a detailed analysis of the chicken census data - the population dynamics, the production systems and management practices with a view to intrusively analyze the census data and point out areas of improvement. The study will also help identify the challenges of the production system and management practices and suggest areas of intervention. This knowledge will be useful in policy formulation, possible investment injection and resource allocation for the development of the livestock sector.

2. Materials and Methods

The Government of the Republic of Zambia, through the Ministry of Fisheries and Livestock and the Zambia Statistics Agency (ZAMSTATS), conducted the 2017/2018 Livestock and Aquaculture Census for households and establishments. The sampling exercise adopted a stratified cluster sampling method based on households raising livestock in the earlier 2010 Population and Housing Census. The sampling frame included both rural and urban areas, and the sampling size was deemed large enough to generate definitive estimates. All households in selected clusters were enumerated. Additional and detailed information on the sampling design specifications can be obtained from the summary report by the Ministry of Fisheries and Livestock (2019) and Odubote (2020).

2.1 Data Collection

Already cleaned data was obtained from Zambia Statistics Agency (ZAMSTATS). For this study, the data collected were those on chicken production, focusing on population and demographics, flock dynamics, ownership, production systems, management practices and health. Data related to egg production was not included in our study.

2.2 Data Analysis

The methods used to analyze the data included both qualitative and quantitative approaches. The collected data were analyzed using simple descriptive statistics (means, frequencies and cross-tabulations) in STATA 18 software. Basic descriptive statistics and the results were presented visually using tables and bar charts. The flock dynamics were estimated based on entry and exit characteristics to provide more insights into quantitative and qualitative patterns in the flock populations.

3. Results

The number of households raising chickens is presented in table 1, while chicken populations by type and province at household level are summarized in table 2. Table 3 highlights the chicken population parameters and household gender demographics.

Table 1. Number of Households Raising Chickens by Province as at 2018

Province	Chicken Types					
	Indigenous		Broiler		Layer	
	HHs	HH%	HHs	HH%	HHs	HH%
Central	173,108	12.9	2,975	10.0	320	10.0
Copperbelt	107,554	8.0	10,013	33.7	372	11.7
Eastern	218,685	16.3	2,258	7.6	302	9.5
Luapula	109,922	8.2	1,233	4.2	156	4.9
Lusaka	74,894	5.6	6,061	20.4	699	21.9
Muchinga	110,997	8.3	1,178	4.0	658	20.7
Northern	144,874	10.8	1,132	3.8	136	4.3
North-western	79,191	5.9	1,445	4.9	130	4.1
Southern	217,963	16.2	3,175	10.7	369	11.6
Western	105,651	7.9	224	0.8	43	1.4
Zambia	1,342,839	100.0	29,694	100.0	3,185	100.0

Table 2. Number of Chickens by Type, Raised by Households as at January 2018

Province	Indigenous		Broiler		Layer		Provincial overall Total	Provincial overall %
	Number	%	Number	%	Number	%		
Central	2,618,909	17	409,017	7	56,670	8	3,084,596	14
Copperbelt	1,377,544	9	1,795,154	30	48,284	6	3,220,982	15
Eastern	2,011,608	13	322,272	5	9,237	1	2,343,117	11
Luapula	796,075	5	160,328	3	1,237	0	957,640	4
Lusaka	1,254,527	8	2,282,752	38	557,679	75	4,094,958	19
Muchinga	1,148,255	7	172,853	3	16,140	2	1,337,248	6
Northern	1,299,368	8	141,943	2	8,196	1	1,449,507	7
North-Western	755,366	5	354,069	6	10,433	1	1,119,868	5
Southern	3,150,184	21	409,691	7	17,538	2	3,577,413	16
Western	901,944	6	30,615	1	17,567	2	950,126	4
Zambia	15,313,780		6,078,694		742,981		22,135,455	

Table 3. Chicken Population Parameters and Household Gender Demographics

Characteristics	Description	N	Population	Percentage
Total Population			22,135,455	
	Indigenous		15,313,780	69%
	Broiler		6,078,694	28%
	Layer		742,981	3%
Number of HH	Indigenous	1,342,839		
	Broiler	29,694		
	Layer	3,185		
Flock Size (Mean)	Indigenous		11	
	Broiler		205	
	Layer		233	
Gender: Ownership F	Indigenous			45%
M				55%
F	Broiler			33%
M				67%
F	Layer			21%
M				79%

M = male; F = female

3.1 Chicken Population and Demographics

Results indicated that Southern, Central and Eastern provinces hold 51% of the total indigenous chicken population. For broilers, Lusaka and Copperbelt provinces accounted for 68%, while Lusaka province alone was responsible for 75% of the total layer production. Households that kept indigenous chickens in Eastern, Southern, Central and Northern provinces constituted 56.2% of the total households, while the lowest numbers of households were observed in Lusaka and North-western provinces. Broiler raising households were more in Copperbelt and Lusaka provinces, making up 54.1% of the production base, whereas Western province recorded the lowest (0.8%). Lusaka, Muchinga, and Southern provinces comprised 54.2% of the total households for layer production, while Western province accounted for only 1.4%.

Indigenous chicken flock size ranged from 7 - 17, with an average of 15 chickens observed for Lusaka, Central, Southern and Copperbelt provinces. Contrarily, Luapula, Eastern, Northern and Western provinces recorded a range of 7 - 9, with an average of 8 chickens. Broiler flock sizes ranged from 125 - 377, with an average of 311 chickens observed in Lusaka and North-western provinces. Conversely, Northern, Southern and Luapula provinces had an average of 128 chickens. For layers, flock sizes ranged from 8 - 797, with an average of 605 chickens noted in Lusaka and Western provinces, with a range of 413 - 797. In contrast, an average of 21 was observed in Luapula, Muchinga and Eastern provinces, with a range of 8 - 31 chickens per household.

3.2 Flock Dynamics

Table 4 below shows negative flock dynamics for the chicken types. The overall net flow for the chicken types given in table 5 was equally negative, except for differences in the population decrease obtained.

Table 4. Entry and Exit of Poultry Between October 2016 and January 2018 (Annualized)

Characteristics	Description	Chicken Types		
		Indigenous	Broilers	Layers
Entry	Hatched		23,038	1,025
	Purchased/ bartered	1,443,783	1,478,552	66,214
	Received as gifts		6,240	9
	Subtotal	1,443,783	1,508,830	67,248
Exit	Sold	17,280,000	12,000,800	435,392
	Slaughtered (offtake)		346,819	45,014
	Disease (mortality)			
	Theft	847,490	64,016	499
	Accident	81,607	14,547	1,223
	Bartered out/ exchanged		72,854	63
	Given out	1,754,601	106,086	4,569
	Others	388,961	79,455	2,249
	Subtotal	20,352,658	13,483,797	489,008
	Net flow	(18,908,874)	(11,975,967)	(421,760)

Table 5. Net flow Population Decrease Between 2016 and 2018

Year	Number of Indigenous Chickens	Number of Broilers	Number of Layers
2016	21,300,000	8,988,613	1,147,805
2017/2018	15,300,000	6,078,693	742,981
Change in population	(6,000,000)	(2,909,920)	(404,824)
Per annum	-5142857	-2494217	-346992
% Decrease	28.2	32.4	35.3

3.3 Ownership

It was observed that 93.7% of the households owned indigenous chickens, with an average of 44.8% female household members (Fig 1). The highest percentages of female household members owning indigenous chickens were observed in Western and Central provinces. For broiler production, the average percentage of 33.1% of female members owning broilers was observed from the 69.2% owned by the households, which was relatively low across the provinces. Of the layers owned by the household, female members accounted for 21%.

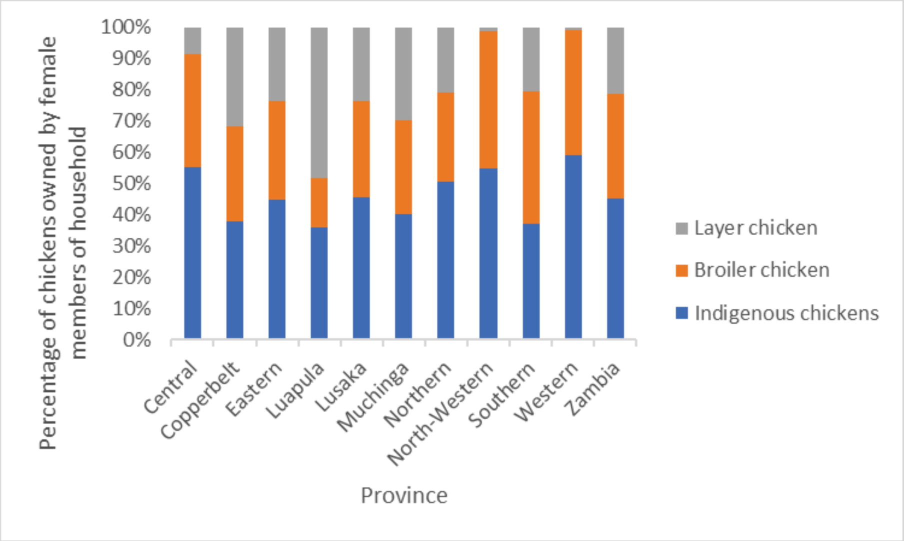

Figure 1. Percentage of Chickens Owned by Female Household Members

3.4 Purpose of Raising Indigenous Chickens

The main purpose of raising indigenous chickens in Zambia was income generation and home consumption as meat, as shown in table 6.

Table 6. Purpose of Raising Indigenous Chickens

Province	Meat (home consumption)	Selling/income	Eggs	Manure	Aesthetic value
	%	%	%	%	%
Central	34.9	58.4	6.7		
Copperbelt	39.3	60.6		0.1	
Eastern	53.3	46.7			
Luapula	100.0				
Lusaka	22.0	75.9			2.0
Muchinga	29.3	70.7			
Northern	22.7	77.3			
North-Western	14.1	85.9			
Southern	18.2	79.6			2.2
Western	36.0	64.0			
Zambia	32.2	66.1	1.0	0.0	0.7

3.5 Production Systems

The traditional system was the most practiced system for households that raised indigenous chickens, while the intensive was mostly used for broilers (table 7). Layers were raised using both traditional and intensive systems. A very low number of households raised indigenous chickens (1%) practiced intensive production system.

Table 7. Production Systems

Production Systems	Chicken Types		
	Indigenous	Broiler Chicken	Layer Chicken
	%	%	%
Traditional	87.0	7.7	33.3
Extensive	6.2	12.7	9.1
Semi-intensive	5.8	9.3	13.6
Intensive	1.0	70.3	44.0

3.6 Management Practices

The main feeding practices (table 8) included free range and free range with supplementation. Households that raised broilers mainly utilized feeding and feeding with supplementation. Layer raising households utilized all four feeding practices. Table 9 showed that above 80% of the households in Luapula, Northern, North Western, Muchinga and Western provinces raised indigenous chickens on free range. It was, however, noted that about 20% of the households in Southern, Copperbelt, Eastern and Lusaka provinces employed free range with supplementation. Broiler and layer keeping households mainly used zero grazing/pecking and supplementation (tables 10 and 11, respectively).

Table 8. Feeding Practices

Feeding system	Chicken Types					
	Indigenous		Broiler		Layer	
	HHs	%	HHs	%	HHs	%
Free range	1,081,849	80.6	1,460	4.9	741	23.3
Mainly feeding	10,609	0.8	9,170	30.9	483	15.2
Free range with supplementation	233,019	17.4	3,100	10.4	754	23.7
Feeding and supplementation	16,785	1.3	14,743	49.7	1,091	34.3
Other	579	0.0	1,220	4.1	115	3.6
Total	1,342,840	100.0	29,693	100.0	3,185	100.0

Table 9. Indigenous Chicken Feeding Practices

Province	Free range	Scavenging	Free range with supplement	Scavenging and supplement	Other
	%	%	%	%	%
Central	77.7	0.4	17.5	4.5	0.0
Copperbelt	75.3	1.3	21.6	1.6	0.2
Eastern	72.5	0.7	25.6	1.1	0.1
Luapula	93.6	0.03	5.8	0.6	0.0
Lusaka	70.4	2.1	24.7	2.7	0.2
Muchinga	86.6	1.1	12.1	0.2	0.0
Northern	94.3	1.1	4.3	0.3	0
North-Western	92.8	0.3	6.6	0.2	0.1
Southern	69.2	0.5	29.7	0.5	0.01
Western	89.9	1.3	8.6	0.3	0.01
Zambia	80.6	0.8	17.4	1.3	0.1

Table 10. Broiler Chicken Feeding Practices

Province	Free range	Scavenging	Free range with supplement	Scavenging and supplement	Other
	%	%	%	%	%
Central	10.4	30.8	8.5	42.5	7.9
Copperbelt	1.5	22.7	8.7	60.6	6.5
Eastern	3.4	41.7	12.2	42.4	0.3
Luapula	10.7	23.6	18.4	45.6	1.8
Lusaka	3.9	30.9	14.1	48.8	2.4
Muchinga	17.5	20.9	7.6	52.6	1.4
Northern	14.5	42.1	6.7	30.9	5.9
North-Western	6.9	41.1	14.4	33.9	3.7
Southern	2.0	47.6	6.6	43.1	0.7
Western	10.7	22.2	16.9	50.2	0.0
Zambia	4.9	30.9	10.4	49.7	4.1

Table 11. Layer Chicken Feeding Practices

Province	Free range	Scavenging	Free range with supplement	Scavenging and supplement	Other
	%	%	%	%	%
Central	7.7	5.7	44.5	42.1	
Copperbelt	5.6	11.0	9.0	50.4	24.1
Eastern	10.2	28.9	1.0	59.9	
Luapula	49.3	12.2	35.9	2.6	
Lusaka	14.6	11.8	27.0	43.0	3.6
Muchinga	59.9	3.6	30.6	5.9	
Northern	9.7	23.8	45.2	21.3	
North-Western	27.0	39.2	22.1	11.7	
Southern	5.5	33.2	9.2	52.1	
Western	54.9	15.3	12.2	17.6	
Zambia	23.3	15.2	23.7	34.3	3.6

3.7 Housing

Provision of minimal housing accounted for 72%, 82.2% and 77.2% for indigenous, broilers and layers, respectively (table 12). The main flooring materials used for broilers and layers were concrete, while for the indigenous chickens, it was the bare earth floor. The roofing materials used for broiler and layer chicken housing were mainly iron sheets with wall and fence materials consisting of burnt bricks and cement blocks. Roofing materials for indigenous chicken housing, on the other hand, were mostly thatched with grass, reeds or stalks with walls and fences of wooden fences and burnt bricks or unburnt mud bricks.

Table 12. Types of Housing for Chicken Rearing

Type of Housing	Chicken Types		
	Indigenous	Broiler	Layer
	%	%	%
None	41.3	4.6	21.9
Confined in sheds	30.7	77.6	55.3
Confined in paddocks	1.2	6.6	2.3
Confined fences	1.4	4.8	5.8
Cage	11.5	3.9	11.3
Basket	8.4	0.8	2.2
Kraal	5.5	1.7	1.1
Total	100.0	100.0	100.0

3.8 Disease Prevalence and Control

It was found that 61.2% of households raising indigenous chicken reported being affected by diseases. Lower numbers were reported from households raising broilers (40.0%) and layers (36.7%), as shown in table 13. Newcastle disease was the highest in indigenous chickens at 78.4% compared to layers at 62.7% and broilers at 38.8% (Table 14). Luapula and Muchinga provinces recorded a high prevalence of Newcastle disease at 70.0% and 60.4%, respectively (Table 15). Gumboro was more prevalent in broiler chickens than layers and indigenous chickens. There were varied levels of confirmation of incidences of diseases by veterinary officers, as indicated in table 16, which could be reflective of the low curative treatments received.

Table 13. Disease Prevalence in Households

Prevalence	Chicken Types					
	Indigenous		Broiler		Layer	
	Number	%	Number	%	Number	%
Yes	821,530.35	61.2	11,862	39.95	1,168	36.7
No	521,285.02	38.8	17,830	60.05	2,016	63.3
Total	1,342,815	100.0	29,693	100.00	3,185	100.0

Table 14. Main Diseases Affecting Chicken Populations

Diseases	Chicken Types		
	Indigenous Chicken	Broiler Chicken	Layers Chicken
	Percent	Percent	Percent
Newcastle Disease (ND)	78.4	38.8	62.7
Infectious Bursal Disease (Gumboro)	7.4	26.2	12.2
Fowl Pox	4.5	2.6	2.2
Other	1.9	15.5	2.6
Don't Know	7.9	16.9	20.3
Total	100.0	100.0	100.0

Table 15. Diseases by Province

Province	Chicken Types											
	Indigenous				Broiler				Layer			
	ND	FP	IBD	Other	ND	FP	IBD	Other	ND	FP	IBD	Other
Central	51.2	5.6	11.6	31.6	47.9	0.1	24.5	27.5	82.8	0.0	0.0	17.2
Copperbelt	63.8	2.8	18.8	14.6	34.0	1.1	26.0	38.9	30.2	0.0	39.2	30.7
Eastern	87.5	4.5	5.6	2.4	36.3	5.7	33.1	24.9	73.3	2.2	18.0	6.4
Luapula	87.8	1.6	6.6	4.1	70.0	6.0	19.0	5.0	100.0	0.0	0.0	0.0
Lusaka	61.1	5.7	10.9	22.3	28.6	2.1	20.6	48.7	27.9	0.0	14.6	57.4
Muchinga	92.1	1.2	3.2	3.5	60.4	0.0	33.5	6.1	95.2	3.2	0.0	1.6
Northern	94.5	0.4	2.0	3.2	42.2	0.0	44.4	13.4	88.0	7.9	4.1	0.0
North-western	90.6	0.6	4.5	4.4	56.4	0.8	24.0	18.8	31.3	0.0	0.0	68.8
Southern	75.0	6.8	9.9	8.3	38.8	6.0	27.9	27.3	6.0	26.8	28.2	38.9
Western	68.9	13.0	4.3	13.9	19.5	35.0	2.7	42.8	65.9	0.0	0.0	34.1

ND = Newcastle disease; FP =Fowl pox; IBD = Infectious bursal disease (Gumboro)

Table 16. Disease Confirmation by an Expert

Veterinary professional	Indigenous chickens	Broiler chickens	Layer chickens
	%	%	%
Yes	11.9	42.7	30.9
No	88.1	57.3	69.1
Total	100.0	100.0	100.0

3.9 Record Keeping

There was no specific request for information on record keeping directed at the chicken types. Rather, the questionnaire was generalized for all livestock. Nevertheless, only 4.3% of households keeping livestock were found to keep livestock records.

4. Discussion

4.1 Chicken Population and Demographics

Our findings that chickens were the most commonly owned type of livestock among most households agreed with the observations made in RALS (2019). Birhanu et al. (2023) also reported that a significant proportion of households in lower income countries accounted for 55%, engaged in poultry farming (mainly chicken). This underscores the importance of chickens in smallholder farming.

Bwalya and Kalinda (2014) reported that the majority of smallholder farmers in Zambia primarily raise indigenous chickens rather than broiler breeds. This is in agreement with our findings. It was also noted that agricultural based provinces raised more indigenous chicken production while the commercial centres focused on broilers and layers. This could be due to the fact that indigenous chickens are well suited to local conditions and require minimum input. By recognizing the prevalent livestock species and their significance in rural households, policymakers can design programs and initiatives that address specific needs and challenges related to livestock management. This targeted approach can improve productivity and enhance rural livelihoods (Machina and Lubungu, 2018).

4.2 Flock Dynamics

Flock dynamics could not be properly analyzed due to the non-collection of required information during the census. For instance, in the indigenous chickens, there were no records on the number lost due to diseases, little or no information on hatched chicks, and chickens received as gifts, slaughtered, bartered, or exchanged. There was limited information on the supply of day-old or point-of-lay chicks for broilers and layers. Hence it was not possible to realistically determine the entry and exit of the flocks. The above scenarios hampered a realistic analysis and supported earlier assertion by Pica-Ciamarra et al. (2014) on the challenges of livestock statistics.

Notwithstanding the above, the negative net flow and reduction in flock size are indicative of underlying issues such as theft and diseases, which need to be mitigated to ensure sustainable chicken production. The reduction in indigenous chicken populations could be attributed to a higher incidence of diseases like Newcastle disease during the rainy season, as Okeno et al. (2012) and DVS (2021) reported. Newcastle disease is known to affect indigenous chickens more severely than other chicken types and may have possibly contributed to the observed reduction.

The decrease in the layer and broiler populations could imply a concomitant drop in supply, highlighting the need for improved breeding programs and management practices for higher production and productivity. It has been reported that there is increased demand for chicken meat during festivities FAO (2014), and it is common for households to slaughter chickens for consumption and as gifts. This could lead to a temporary reduction in the population size of indigenous chickens as the census was carried out over the Christmas period.

The average flock size of 11 chickens reported in this study was the same as an earlier report by Phiri et al. (2017). Comparing the average flock size for indigenous chickens in Zambia to that of other countries indicates that there is room for improvement in the management of chicken populations, given that several authors have reported that households maintain flocks of between 5 to 30 (Nyoni and Masika, 2012).

Understanding the factors influencing flock dynamics is crucial to developing appropriate management practices to improve productivity and profitability. Flock structure is influenced by factors such as production systems, management practices, and feed resources available in subsistence farming (Mtileni et al., 2009). It is therefore suggested that a follow-up census should include more information on disaggregated data (the number of hens, cocks, pullets, cockerels, and chicks) to assist in making informed decisions regarding flock management. It would also have been beneficial if information on the genetic groups of the different chicken types had been collected for analysis.

4.3 Ownership

Our findings on the ownership of indigenous chickens agree with the findings made in RALS (2019), which revealed a higher proportion of livestock ownership observed among ma-headed households than female-headed households. The percentage of female ownership in this study was considerably smaller for broiler and layer production, thus showcasing a gender gap in ownership and management. Exploring the underlying causes and identifying potential obstacles or openings for expanded female ownership in broiler and layer production will require more investigation. Nonetheless, Kitalyi (1998) and Muchadeyi et al. (2004) opined that women, in particular, often undertake various tasks related to indigenous chicken production, including feed distribution, cleaning, watering, and selling eggs and live chickens. The authors further suggested that this may be attributed to lower literacy levels among women, allowing them to stay at home and care for the livestock while men engage in other professional or business activities.

4.4 Purpose of Raising Chickens

Our findings indicated that indigenous chickens were primarily raised for both income generation and consumption as meat, which is consistent with similar studies conducted in areas with moderate to high agricultural potential (Okeno et al., 2012; Wilson et al., 2022). Their short generation intervals, low input requirements and efficient feed conversion into protein make them easily available for sale. They, therefore, serve as the first response to a growing demand and make a convenient cashpoint (El-Yuguda et al., 2007). Furthermore, they are reported to be consumed in a single meal and therefore do not require complex storage facilities, and their products have no cultural or religious taboos (Mahoro et al., 2017; Okeno et al., 2012).

4.5 Production Systems

The traditional production system found to be the most prevailing is consistent with reports from other developing countries, although it included the extensive/free range system (Dana et al., 2010; Mahoro et al., 2017; Okeno et al., 2012). Typically, the traditional system encompasses family poultry, including scavenging chickens and backyard raising. There are variations in the classification of the production system for raising indigenous chickens. FAO (2014) classified production systems into four, namely, small extensive scavenging, extensive scavenging, semi-intensive and intensive production systems, while Bett et al. (2011) classified the systems into free ranging/scavenging, semi-scavenging, semi-intensive and intensive systems, with some systems not having distinctive differences. For this study, the traditional production system is synonymous with the small extensive and free-range/scavenging for FAO (2014) and Bett et al. (2011).

4.6 Management Practices

Management practices for the indigenous chickens were minimal, as little or no effort was made regarding housing, feeding or health care. In certain cases, households adopt a semi-intensive system, where specific groups within the flock receive supplementary feed based on their growth stage. This includes young chicks, productive birds, and sick birds requiring additional nutrition and water. Managing a flock in such systems requires careful attention to balance the diverse needs of different groups within the flock. Alabi et al. (2012) also emphasized that to maximize productivity, it is crucial to meet the optimal requirements of indigenous chickens regarding protein, lysine (an essential amino acid), and energy. Protein levels in the diet were also reported to optimize feed intake and growth (Kingori et al., 2007). In this study, what constituted feeding with supplementation was not clearly elucidated, despite being significant. However, it is assumed that the chickens, through scavenging, would meet their nutritional requirements, but this will require further investigation.

Layer and broiler chickens were predominantly raised in intensive systems, as noted in the results; this was also reported by Wilson et al. (2022) and Mushi et al. (2020). This is because both layer and broiler production systems rely heavily on concentrate feeding offered in an intensive production system. The intensive system offers better control over feeding, protection from predators and thefts, and efficient flock management. Formulated balanced feed is provided to enhance the nutritional intake of the birds and promote optimal growth and productivity.

Okeno et al. (2012) proposed that utilizing indigenous chickens' genetic potential and production environment is economically beneficial in free-range or semi-intensive systems but not in intensive systems. Therefore, strategic interventions such as selective breeding of local chickens, enhancing feeding and housing systems, and regular veterinary services are crucial to optimize the performance of indigenous chicken farming. Odubote (2022) had noted that improvements in management practices can enhance the productivity of indigenous livestock species which can, in turn, result in a rise in household income per annum (Sarkar and Golam, 2009).

4.7 Housing

In this study, the majority of the indigenous chickens reared did not have any housing units, while those housed were in sheds, cages, baskets and kraals. Mahoro et al. (2017), and Okeno et al. (2012) all reported that chickens are mainly housed in kitchens and households at night and left to scavenge during the day. The availability of resources may have influenced the choice of housing or lack thereof (Muchadeyi et al., 2004). Typically, farmers will construct houses from locally available materials. It would therefore be beneficial to determine if this will lead to substantial growth in production levels.

According to Simainga et al. (2011), farmers reportedly secure their indigenous chickens from predators and bad weather by keeping them in undeveloped poultry structures at night, with predation and thefts identified as the main causes of chicken losses. Providing appropriate and adequate housing for chickens is essential for effective management and raising them to marketable age as quickly as possible. Proper housing protects chickens from predators, adverse weather conditions, and disease outbreaks. Housing should provide a conducive environment for egg-laying, brooding, feeding, and general movement, ultimately impacting their growth and productivity (Oloyo and Ojerinde, 2020). Additionally, having good quality housing can improve the overall efficiency of the chicken production system, as it helps to minimize stress and increases the overall health and welfare of the birds. The significant levels of theft and possible mortalities observed in this study could be attributed to the non-provision of housing.

4.8 Disease Prevalence and Control

Our finding that Newcastle disease was the major disease in indigenous chickens, exacerbated by low vaccination practices, agrees with studies undertaken in other developing countries in Africa (Dana et al., 2010; Harrison and Alders, 2010; Moges et al., 2010; Okeno et al., 2012). Limited access to veterinary services and medications was evident in rural areas like Muchinga and Luapula provinces of Zambia. Furthermore, Hernández-Jover et al. (2019) relayed that traditional systems, in comparison to intensive systems, were characterized by minimal disease prevention and major outbreaks, which are usually higher in the hot-dry and wet-rainy seasons.

Sensitization on best practices in chicken husbandry and health should be carried out to mitigate and reduce infections and mortalities, thereby boosting production and productivity to considerable levels (DVS, 2021). Furthermore, it may be beneficial to schedule vaccination programs in dry seasons and thus enabling immune systems to be strengthened before the onset of the wet season (Okeno et al., 2012). There will be a need to propose improvements in the production systems, which will ultimately reduce disease incidence and thus improve production and productivity.

4.9 Record Keeping

The paucity of records in the data collected is of great concern as it hinders effective monitoring and evaluation of the chicken production system. Glatz and Pym (2013) reported that records of production, growth, feed, egg weights, mortalities, treatments given, and treatment response should be maintained to assist investigations of sub-optimal performance and future improvements. The above information is necessary to identify the underlying issues affecting productivity and profitability.

5. Conclusions

Indigenous chickens are the most common type of chickens raised by the majority of smallholder farmers, with higher populations in provinces with high agricultural production. The traditional production system was the most adopted for indigenous chickens at household level, with minimal input in feeding, housing and disease management, while broilers and layers were raised under intensive systems fixated in commercial hubs. Flock ownership was gender balanced for the indigenous chickens, while a notable gender disparity was observed for layer and broilers, with males displaying higher ownership. The majority of the households raised chickens for income generation showing the economic importance in smallholder livelihoods. Newcastle disease was found to be prevalent and possibly responsible for the high mortality reported. The flock dynamics could not be adequately addressed due to inadequate information. Record keeping among farmers was reported to be poor. Most of the technical information required for productivity analysis was not collected in the census, hence there is a need to improve the data collection instrument.

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Author contribution

Dr. IKO came up with the concept for the paper, census data and structure for the manuscript, while MBM performed the statistical analysis. SJH led the preparation of the manuscript. All the authors took part in the preparation and review of the manuscript before submission.

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The data that support the findings of this study is available on request from the corresponding author. The data is not publicly available due to privacy or ethical restrictions.

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Determinants of Smallholder Farmers' About Choices of Sustainable Land Management Practices in West Wollega Zone, Oromia Region, Ethiopia

Addisu Raga[1 & 2], Professor Fekadu Beyene[3], Professor Jema Haji[4 & 5] & Assistant Professor Chanyalew Siyum

[1] Lecturer and program advisor at different area, Ethiopia

[2] PhD student at Haramaya University, Ethiopia

[3] Professor of institutional and resources economics at the School of Rural Development Innovation, Haramaya University, Ethiopia

[4] Professor of agricultural economics at the School of Agricultural Economics, Haramaya University, Ethiopia

[5] Assistant Professor Chanyalew Siyum (PhD)at the School of Rural Development and innovation Research directorate, Ethiopia

Correspondence: Addisu Raga, Haramaya University, Ethiopia. Tel: 251-911-064-348. E-mail: addisusimo@gmail.com

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Abstract

Background: Due attention has recently been given to the choices of sustainable land management practices (SLMPs) to reduce land degradation and improve the livelihood of smallholder farmers in developing countries. A rising number of people believe that Sustainable Land Management is an essential strategy for enhancing food security. For generations, Ethiopia has been regarded as a hotspot of land degradation, posing a severe threat to agricultural productivity leading to widespread rural poverty. Hence, this study aimed at identifying the determinants of smallholder farmers' choice of SLMPs in the West Wollega zone, Oromia region of Ethiopia using the Multivariate Probit (MVP) model.

Results: Results of the MVP model show that the predicted probabilities of adopting organic fertilizer, area closure, soil and water conservation, crop rotation, and compost were 37.2, 35.3, 40.5, 38.3, and 38.5% respectively. The MVP model results also show that the five SLMPs are complementary and the probability that households choose all five SLMPs was 23% which is low. Further, results of the MVP model show that cooperative membership, model farmer contact, farm size, non-farm income, credit, farm experience, perceived soil erosion, social capital, livestock owned, farmland slope, NGO intervention, information access, and training have a significant positive influence while age, family size, and perceived input cost significantly and negatively impacted the choice of SLMPs by households in the study area.

Conclusions: The findings of the study confirm that socioeconomic, household, farm and institutional characteristics of the households have a significant impact on the choices of SLMPs and hence the need to focus on the above-mentioned factors to enhance the choices of SLMPs and reduce land degradation problem in the study area. The results also highlight the significance of environmentally-friendly policies, which include sustainable development, SLMPS plan determination, environmental permits, and incentive programs for managing the sustainability of land management performance in land-use policy within the local context.

Keywords: land degradation, sustainable land management practices, Multivariate Probit model, adoption, and west Wollega zone

1. Background

Land degradation is a global issue affecting rural communities that rely on farmland resources, making them vulnerable to poverty. It lowers agricultural productivity, enhances desertification, biodiversity loss, the cost involved with food and energy security, disturbance of the socioeconomic system, and loss of human livelihoods (Salih et al., 2017). According to Le et al. (2016), over 40% of the world's degraded lands occur in areas with the highest incidence of poverty indicating the linkage between poverty and land degradation. The causes and drivers of land degradation are complex, interactive, and self-reinforcing both across areas and generations (Gebreselassie et al., 2016). As a result, around 1.5 billion people worldwide are affected by land degradation, which covers roughly 23% of the world's land surface and is expanding at a rate of 5 to 10 million hectares per year (Pingali et al., 2014). For instance, due to the adverse effects of land degradation, about a quarter of the world's seven billion people experience food insecurity (FSIN, 2018). From this, soil erosion has been identified as a leading driver of land degradation resulting in desertification in many dryland and non-dryland areas (Haregeweyn et al., 2017; FAO, 2019a; Fenta et al., 2020; Prăvălie et al., 2021).

According to a global meta-analysis synthesis, soil erosion causes a global median loss of 0.3% of annual crop yield, with a total loss of 10% projected for 2050 (FAO, 2019a). This yield loss due to continued soil erosion could be equivalent to removing 4.5 M ha yr-1 of crop production (FAO & ITPS, 2015; FAO, 2019a). Moreover, as per recent projections, the rate of soil erosion will increase by up to 66% globally between 2015 and 2070 (Borrelli et al., 2020).

According to estimates, land degradation affects 46% of Africa's land area, affecting at least 485 million (65%) people and costing USD 9.3 billion per year. This revealed that between 75 and 80% of the continent's farmland appears to be degraded, with annual nutrient losses ranging from 30 to 60 kilograms per hectare (AGNES, 2020). As a result of these hazards, a sizable portion of the $7 billion in agricultural productivity was lost due to land degradation between 2000 and 2012 (David & Michae, 2013).

Similarly, Ethiopia is one of the worst-affected countries with significant land degradation and its negative effects on farm productivity, food security, and the well-being of communities (Berendse et al., 2015; Brevik et al., 2015; Taddese, 2018; Abiye, 2019). The agricultural sector has significant importance in many developing countries' economies and community livelihoods, as it contributes significantly to the country's GDP, creates employment opportunities, and ensures a steady supply of domestic food (Bisht et al., 2020; Dixon et al., 2001). Agriculture is also the primary sector in Ethiopia, where nearly 84% of the population is directly dependent on agriculture, land degradation is a serious issue that must be addressed (Nigussie et al., 2017a). Agriculture, for example, contributes significantly to the country's economic growth (Belachew et al., 2020; Collier & Dercon, 2014). On the other hand, the agricultural sector is still dealing with natural resource depletion, land degradation, soil erosion, climate change, and a lack of modern/productive inputs, to name a few (Belachew et al., 2020; Kagoya et al., 2017). As a result, while this sector faces threats from land degradation, there is no doubt that it is a more pressing issue for Ethiopia's agriculture-based economy and farmers' livelihoods (Nigussie et al., 2017a; Miheretu & Yimer, 2017; Abera et al., 2020).

In this regard, sustainable land management practices (SLMPs) are widely acknowledged as critical to slowing land degradation, preventing desertification, and restoring degraded lands (Eekhout & de Vente, 2022). Researchers, land users, and other stakeholders have been working on issues related to land degradation and the adoption of various SLMPs for decades. As defined by WOCAT (2021), SLMP refers to both technologies and an approach. However, there has been little systematic documentation of the successes or associated challenges. Monitoring and evaluation, in particular at the household level, have received insufficient attention (Studer et al., 2016). Hence, the choices of SLMPs must be documented and shared to provide options for better land use management under varying conditions, to promote practice upscaling and sharing, and to design a sustainable and inclusive policy environment (Mudhara et al., 2016).

Moreover, top-down planning methodologies, a lack of community input, weak institutional frameworks, and a lack of local implementation capacity all contribute to the ineffectiveness of land management practices in achieving the desired results (Tongul & Hobson, 2013). There are also issues with policy enforcement that have contributed to the failure of sustainable land management efforts in various parts of the country to achieve their intended goals. According to the findings of Nkonya et al. (2013) and von Braun et al. (2013), a lack of strong policy action and a low level of evidence-based policy framework are critical challenges to the effectiveness of SLMPs.

To combat and mitigate the interconnected effects of land degradation, the government and non-governmental organizations (NGOs) promoted the SLMP program to reverse the negative effects of land degradation, though progress and success varied across the countryside (Zerihun et al., 2017). This demonstrates and emphasizes the fact that household participation in SLMP is influenced by their geographical location as well as their understanding of the extent of land degradation trends (Tesfa & Mekuriaw, 2014).

Land management practices in Ethiopia, according to studies such as those conducted by Abebaw et al. (2011) and Befikadu & Frank (2015), have fallen far short of expectations, and land degradation, primarily due to soil erosion, remains widespread. Other recent empirical studies in Ethiopia have looked at the adoption of SLMPs and their impact on land degradation in various parts of the country, including Haftu et al. (2019), Senbetie et al. (2017), Paulos and Belay (2017), Tesfaye (2017) and Schmidt & Tadesse (2017). Their findings show that farmers' use of SLMPs remains low, and the country is losing a significant amount of fertile topsoil.

Furthermore, empirical studies have demonstrated the benefits of SLMPs, in increasing productivity and improving smallholder livelihoods (e.g., Haregeweyn et al., 2015; Karidjo et al., 2018). However, the effectiveness of the government's actions to support the scaling up of SLMPs in the country's various agroecological zones requires comprehensive studies conducted in different locations over time. As a result, a more in-depth investigation is required to better understand the factors influencing households' decisions to participate in SLMPs in these various socioeconomic settings: economic, ecological, geographical, and livelihood perspectives.

Typically, a combination of environmental, social, economic, and political factors that are extremely particular to households and the context in which they are implemented have created barriers for smallholder farmers to engage in SLMPs (Bisaro et al., 2011; Cordingley et al., 2015). Due to the failure of one-size-fits-all solutions to address, particularly at the local level, the current study's focus on the factors that influence farm households' participation in SLMPs is very crucial. To this effect, it is critical to investigate what specifically influences households' decisions to adopt SLMPs in the west Wollega zone, Oromia region of Ethiopia, to develop policy options and support systems that could improve smallholder farmers' adoption level to enhance agricultural production and productivity by rehabilitating the degraded lands.

2. Methods

2.1 Description of the Study Areas

This study was conducted in the West Wollega zon

e, which is one of the 20 administrative zones of the Oromia region of Ethiopia. Administratively, the zone has 21 districts, of which 19 are rural and two of them are urban administrations which were further subdivided into 543 kebeles 489 peasant associations, and 54 urban dweller associations. The population size of the zone is estimated as 1,741,567 out of which 864,277 or 49.6% are male, while 877,290 or 50.4% are female (WWZARDO, 2021). The total household size of the sampled districts was about 97,5offrom which 69571 are male and 27,928 are women heads.

West Wollega zone is located between $8^0$12'-$10^0$03'N latitudes and 34008 -$36^0$10'E longitudes, located in the western part of the Oromia region, bordered by Benishangul Gumuz regional state in the North West and North East and Kelem Wollega Zone in the West. In the east it is bordered by East Wollega zone while in the south it is bordered by Gambela Regional state and Illubabor zone. West Wollega zone is found at an altitude ranging from1300 - 2,600 meters above sea level.

The zone has three agro-ecological zones which comprise 15.5% highland, 65.4% midland, and 19.1% lowland. The zone has a bimodal type of rainfall and receives an annual rainfall which ranges between 300 to 2,000 mm, while the average temperature is between 10°C and 30°C. The area of the Zone is estimated to be 1,274,501 hectares (West Wollega Zone, Statistics Office Report, 2021). The total population of the five districts is estimated as 564538 (32.4%) of the total population out of which 287520 are males and 277,018 are females.

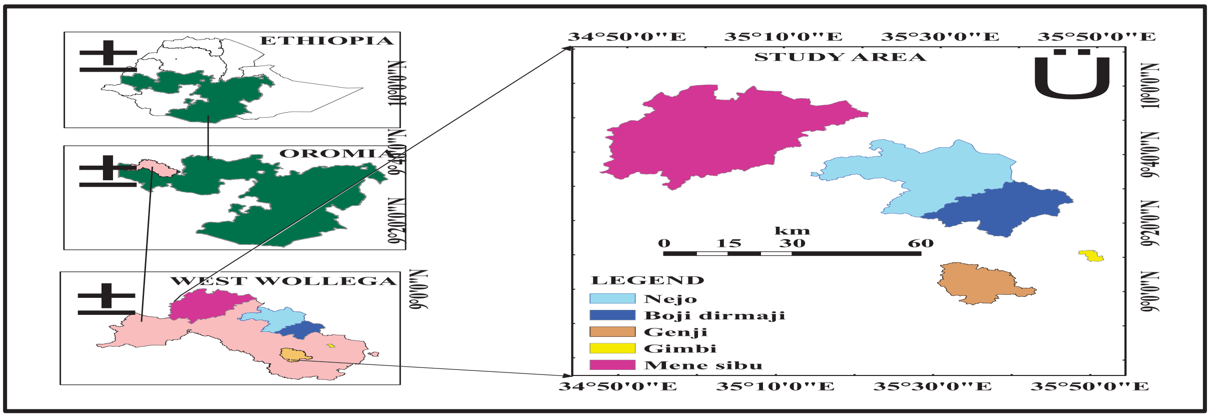

Figure 1. Geographical location of the study area and districts

2.2 Data Types, Sources, Sampling, and Data Collection Methods

2.2.1. Data Types, Sources, and Methods of Collection

The data from primary source were collected from sampled farm household heads using structured questionnaire, key interview and focus group discussion while secondary data were collected from various published documents, zonal agricultural offices, websites, etc through desk review

2.2.2. Sampling Design

A multi-stage sampling technique was used to randomly select 426 households from five districts. The data for this study was gathered using a multi-stage sampling technique to select the study districts, kebeles (It refers to the smallest administrative unit in Ethiopia), and sample households for the study. In the first stage, the zone was stratified based on agro-ecologies and five districts (three from midland and one each from low and highland), namely Ganji, Gimbi, Boji Dirmaji, Nejo, and Mana-Sibu were randomly selected based on probability proportional to size. In the second stage, 15 kebeles were randomly and proportionally chosen from the sample districts those have practices of the SLMP technology. Likewise, the households in each sample kebele were divided into two groups (adopters and non-adopters of SLMPs). In the third stage, using proportionate probability sampling based on the size of the households in each kebele, 426 farm households (201 adopters and 225 non-adopters) were randomly selected from both strata. For this study, the sample size of 426 households was determined using the Cochran (1963) formula.

Table 1. Distribution of sample farm households by districts and kebeles

Districts	Total population	Total number of households	Adopters	Non-Adopters	Sample size
Najo	30,211	2666	63	69	132
Gimbi	18081	1591	36	43	79
Ganji	9842	874	20	23	43
Boji-Dirmaji	10299	918	22	23	45
Mana-Sibu	29067	2577	60	67	127
Total	97,500	8626	201(47.18%)	225(52.82%)	426

Source: Own survey data (2021)

2.3 Data Analysis

Household survey data were first into STATA version 15 and then coded for descriptive and inferential statistics. Descriptive statistics such as frequency, mean and standard deviation were used to describe households' socio-economic, demographic, and institutional characteristics whereas the multivariate probit (MVP) model was used to identify determinants that are likely to influence farmers' choices of SLMPs. MVP model was selected with the justification that the SLMPs themselves and the unobserved error terms might depend on each other and that a household may adopt more than one practice (Yu et al., 2008).

Following Greene (2003), the MVP regression model is specified as:

$$Y^*_{hpj} = X_{hpj}\beta_j + U_{hpj} \qquad j = 1,2,\cdots,m$$

$$Y_{hpj} = \begin{cases} 1\ if Y^*_{hpj} > 0 \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

Where j=1, 2 …, m denotes the SLMPs available, X_{hpj} is a vector of explanatory variables, β_j denotes the vector of the parameters to be estimated, and $U_{hpj}$are random error terms distributed as a multivariate normal distribution with zero mean and unitary variance. It was assumed that a rational farmer has a latent variable,Y^*_{hpj}which captures the unobserved preferences or demand associated with the j^{th} choice of SLM strategies. This latent variable is assumed to be a linear combination of observed household and other characteristics that affect the adoption of SLMPs, as well as unobserved characteristics captured by the stochastic error term. Given the latent nature of the variable $Y^*_{hpj}$the estimation is based on the observable variable Y_{hpj}which indicates whether or not a household adopts a specific SLMP. Since the adoption of several SLMPs is possible, the error terms in equation (1) are assumed to jointly follow a multivariate normal distribution with zero conditional mean and variance normalized to unity.

The off-diagonal elements in the covariance matrix represent the unobserved correlation between the stochastic component of the j^{th} and m^{th} type of SLMPs. This assumption means that equation (1) gives a MVP model that jointly represents the decision to adopt a particular SLMP.

Table 2. Summary statistics and definition of variables used in MVP model

Variable	Description of variables	Mean	S.D
Dependent variable			
Sustainable Land Management Practices (SLMPs)	Adopted SLMPs (1 = yes; 0 = otherwise)	0.47	0.50
Organic fertilizer (OF)	Adopted organic fertilizer (1 = yes; 0 = otherwise)	0.33	0.47
Area closure (AC)	Adopted area closure (1 = yes; 0 = otherwise)	0.32	0.47
Soil and water conservation (SWC)	Adopted soil and water conservation practice (1 = yes; 0 = otherwise)	0.44	0.50
Crop rotation (CR)	Practice crop rotation (1 = yes; 0 = otherwise)	0.41	0.49
Compost (C)	Adopted compost (1 = yes; 0 = otherwise)	0.40	0.49
Independent variables			
Age	Age of the head (years)	43.07	11.17
Family size	Number of members in the household	5.86	0.13
Perceived costs of inputs	1 if fair, 0 if otherwise	0.42	0.49
Farming experience	Number of years into farming	16.00	0.55
Farm size	Size of farmland (ha)	2.12	1.69
Non-farm income	Annual non-farm income in Birr	6568.33	9077.72
Level of education	Years of education of the head	3.91	3.83
Extension contacts	Frequency of contacts per year	5.44	5.95
Access to information	1 if head has access to information, 0 otherwise	0.75	0.43
Access to credit	1 if head has access to credit, 0 otherwise	0.43	0.50
Training	1 if head received training, 0 otherwise	0.28	0.45
Model farmer contact	Number of contacts that the head made with the model farmers per year	8.30	7.82
Social capital	1 if the head has network, 0 otherwise	0.74	0.44
Land slope	1 if flat, 0 otherwise	0.24	0.43
Perceived soil erosion hazards	1 if yes, 0 otherwise	0.34	0.48
Membership in cooperative	1 if yes, 0 otherwise	0.45	0.50
Access to NGOs	1 if NGOs are available in the area, 0 otherwise	0.69	0.46
Livestock	Livestock owned in TLU	11.12	8.39

Source: Authors computation.

Table 3. Test for multicollinearity and heteroscedasticity

Multicollinearity	VIF	
Livestock	4.36	
Model farmer	3.56	
Farm experience	3.20	
Coop membership	3.07	
Access to credit	2.84	
Education level	2.47	
Non-farm income	2.19	
Training	1.85	
Perceived costs of inputs	1.58	
Land size	1.55	
Age	1.49	
Slope type	1.47	
Access to information	1.28	
Access to NGOs	1.27	
Perceived soil erosion	1.22	
Social capital	1.22	
Family size	1.17	
Mean VIF	2.11	
Heteroscedasticity		
Test	χ^2-value	P-value
Breusch-Pagan (BP) test	120.76	0.00

3. Results of the Study

3.1 Descriptive Statistics Results

Descriptive statistics results of the smallholder farmers in the study area are presented in Table 2. Results show that 33% of the farmers have adopted Organic Fertilizer (OF), 32% have adopted Area Closure (AC), 44% have adopted Soil and Water Conservation (SWC), and 41% have adopted Crop Rotation (CR) while 40% of the farmers have adopted Compost (C) as SLMPs in the study areas to reverse effect of land degradation and rehabilitate the degraded farmlands.

3.2 Econometric Model Results

3.2.1 Test for Multicollinearity and Heteroscedasticity

Multicollinearity refers to the presence of linear relationships among the explanatory variables included in the model. In the presence of multicollinearity (independent variables in a model are correlated), the model results in wrong signs of coefficients, high standard errors of coefficients, and high R^2 value even when the parameter estimates are not significant (Wossen et al., 2017). The variance inflation factor (VIF) for each variable was evaluated to check for multicollinearity. If the VIF exceeds 10, that variable is said to be highly collinear and can be excluded from the model. The results of the multicollinearity test are presented in Table 3 above. Results show that the mean value is 2.11 and none of the variables included in the model has VIF greater than 10. This indicates that there is no multicollinearity problem in the dataset and hence all the explanatory variables are included in the model. The result of the heteroscedasticity test is also presented in Table 3. The χ^2-value (120.76) is statistically significant at a 1% probability level, indicating that there exists heteroscedasticity in the dataset. Hence, the robust standard error is used in the analysis.

3.2.2 Model Fitness, Probabilities, and Correlation Matrix from MVP Model

The correlation coefficient among the SLMPs (ρ_{ij}) was determined to assess if these practices are complementary and/or substitutable. The results show that the correlation coefficients of six combined practices, namely ρ_{21} (area closure and organic fertilizer), ρ_{31} (SWC and organic fertilizer), ρ_{41} (crop rotation and organic fertilizer), ρ_{51} (compost and organic fertilizer), ρ_{42} (crop rotation and area closure), and ρ_{43} (crop rotation and SWC) were positive and statistically significant at less than 10% probability levels indicating the complementarity of these practices and that farmers implement multiple SLMPs at a time in the study areas. The rest of the combinations of SLMPS, on the other hand, have proved neither complementarity nor substitutability in their application. Farmers usually construct physical structures on highly depleted land and apply an organic fertilizer to rehabilitate soil fertility (Samuel et al., 2022).

Results presented in Table 4 further assessed the chance of farmers adopting these SLMPs. As a result, the likelihood of implementing organic fertilizer, area closure, SWC, crop rotation, and compost preparation are 37.2%, 35.3%, 40.5%, 38.2%, and 38.5% respectively, indicating the importance of all these practices in choosing to the impacts of land degradation.

Table 4. Model fitness, probabilities, and correlation matrix of SLMPs

Variables	Organic Fertilizer	Area closure	SWC	Crop rotation	Compost
Predicted probability	0.372	0.353	0.405	0.382	0.385
Joint probability of success	0.230				
Joint probability of failure	0.496				
Estimated correlation of SLMPs (Pair-wise correlation coefficients)					
ρ_{21}	0.298**				
ρ_{31}	0.343**				
ρ_{41}	0.344***				
ρ_{51}	0.267*				
ρ_{32}	0.163				
ρ_{42}	0.317***				
ρ_{52}	0.180				
ρ_{43}	0.239**				
ρ_{53}	0.114				
ρ_{54}	0.134				
Likelihood ratio test of $\rho_{21} = \rho_{31} = \rho_{41} = \rho_{51} = \rho_{32} = \rho_{42} = \rho_{52} = \rho_{43} = \rho_{53} = \rho_{54} = 0$:					
chi2(10) = 23.3156 Prob > chi2 = 0.0096					
Number of draws = 5					
Number of observations = 426					
Log likelihood = -492.0966					
Wald chi2(85) = 578.46					
Prob > chi2 = 0.0000					

3.2.3 Parameter Estimates of the MVP Model on the Determinants of Adoption of SLMPs

According to the model results, 13 explanatory variables had a statistically significant effect on SLMPs (use of fertilizer, area closure, SWC, crop rotation, and compost). These include cooperative membership, non-farm income, model farmer contact, perceived costs of inputs, credit access, farming experience, social capital, livestock holding, the slope of the farmland, access to information, and NGO intervention in the village have a significant positive influence in the participation of SLMPs in the study area. However, the age of the household head, and household size, have a significant negative influence. The results on the significant variables are presented below.

Age of the household head: This is an important variable hypothesized to influence the choice of SLMPs in the study area. Age has a significant negative influence on the adoption of SLMPs such as area closure and compost at less than 5% probability levels.

Family size: It has a negative and significant effect on the likelihood of choosing area closure and crop rotation at less than 10% significant levels.

Membership in cooperative: This variable has a positive and statistically significant effect on the adoption of area closure, crop rotation, and compost at less than a 1% significance level and a significant positive impact on SWC at a 10% significance level.

Non-farm income: The total income generated from non-farming activities has a positive and significant effect on the adoption of organic fertilizer and SWC at less than a 1 % significance level while it affects crop rotation at a 10 % level of significance.

Perceived costs of inputs: It is one of the primary factors that are positively impacting the adoption of compost as SLMP for sustaining and reversing the adverse effects of land degradation in the study area.

Access to information: It has a significant positive effect on crop rotation as SLMP at less than 5% significance level. Access to high-quality, relevant, and up-to-date information is critical in the adoption of different agricultural technologies.

Model farmer contact: Model farmer contact has a positive and significant effect on the adoption of organic fertilizer at less than one percent significance level.

Credit access: Credit access by farm households significantly and positively affects the choices of organic fertilizer, area closure, and SWC, at less than 10% significance levels. This finding suggests that farm households with access to credit are more likely to implement these SLMPs for soil fertility management and improved crop production.

Farming experience: It is another important factor related to farm households' choice of SLMPs in the study area. In this study, the household head's farming experience had a positive and significant influence on the adoption of fertilizer, area closure, SWC, crop rotation, and compost at less than 10% significance levels.

Social capital: It is affecting the choice of SLMPs, particularly the use of organic fertilize at less than 1% significance level. Belonging to a specific social group is crucial in a circumstance where there is asymmetric information about various agricultural production and agricultural productivity methods.

Livestock holding: It is used as a proxy for measuring wealth or household asset possession and found to have a positive and significant effect on the decision to adopt area closure, SWC, crop rotation, and compost as SLMPs at less than 1% significance level.

Farm slope: Keeping all other variables constant in the model, the slope of the farmland has a positive and significant influence on the likelihood of adoption of compost as SLMP at 1% level of significance.

Access to NGOs: It has a significant positive impact on the adoption of compost, organic fertilizer, and area closure at less than 10% significance levels. An NGO intervention in the community helps to raise awareness about the importance and role of soil fertility management practices in agricultural productivity improvement.

4. Discussions of the Results

4.1 Descriptive Statistics Results Discussions

The empirical results of the current study demonstrate that a variety of factors affect farmers' decisions regarding the adoption of SLM practices The following discussion examines the key predictors that account for the factors that influence household adoption of SLM practices in the study area. The descriptive statistics results in Table 2 confirmed that the adoptions of organic fertilizer and area closure are the least adopted practices while the remaining three practices received similar attention from the adopters. The mean age of the farmers was found to be 33 years indicating that they are still active and productive. We also found that the average family size, farming experience, size of farmland, income from non-farm activities, years of formal education, extension contacts, contacts with model farmers, and livestock owned are 5.86, 16 years, 2.12 ha, 6568.33 Birr, 5.44, 8.30 and 11.2 TLUs respectively. About 42% of the farmers perceived the costs of inputs are fair, 75% had access to information, 43% had access to credit from formal sources which might have contributed to the adoption of SLMPs, only 28% had received training on natural resource management, 74% had some form of social networks, only 24% had farmland with flat slope, 34% had perceived soil erosion on their lands, about 45% of the farmers belonged to farmers cooperatives, while 75% of them had access to NGOs.

4.2 Econometric Model Results Discussions

The variance inflation factor (VIF) for each variable was evaluated as shown in the table 3 above to check for multicollinearity. And the mean value is 2.11 and none of the variables included in the model has VIF greater than 10. This indicates that there is no multicollinearity problem in the dataset and hence all the explanatory variables are included in the model. The result of the heteroscedasticity test is also presented in Table 3. The χ^2-value (120.76) is statistically significant at a 1% probability level, indicating that there exists heteroscedasticity in the dataset. Hence, the robust standard error is used in the analysis.

The joint probabilities of success or failure of adopting the five types of SLMPs suggested that households were likely to adopt the SLMPs jointly. As indicated in Table 3, the probability of farmers adopting the five SLMPs is 23% indicating that households were less likely to succeed to choose all the selected practices at the same time. That means farmers were unlikely by 73% to succeed in choosing all five SLMPs. The model results of the study on the significant variables are presented and discussed in Table 4 below.

In this particular study, age has a significant negative influence. This means more likely due to the fact that older farmers are more risk averse and young farmers are more willing to seek knowledge from a variety of sources and had long-term plans to preserve SLMPs. This result is consistent with studies conducted by many scholars (Awotide et al., 2014; Milkias & Abdulahi, 2018; Simtowe et al., 2016) who confirmed that older farmers have less updated information on agricultural technologies than younger farmers. This could also be explained by the fact that younger farmers were more likely employed due to better education, greater access to information, and a longer planning horizon for the reasons that some of the SLMPs are more likely to take time labor.

On the contrary, studies such as Beshir (2014), Feyisa (2020), and Amanuel et al. (2018) found a positive and significant effect of age on the adoption of SLMPs and argue that older farmers are better at evaluating the pros and cons of agricultural technologies compared to younger farmers and that younger farmers do not put in more effort, while older farmers with more experience are more likely to adopt the technology.

Different study finding shows that the adoption of SLM practices has been positively correlated with the availability of labour, indicating that households with larger family sizes are more likely to adopt more than their counterparts. However, this current study shows that in the study area, there is a circumstance in which the majority of household members may be responsible for a higher proportion of dependents, primarily children and elders. Therefore, households with larger family sizes but a lower labour force may prefer to spend the majority of their time generating daily income, such as from off/non-farm jobs, in order to pay for their daily needs rather than devoting their time and labour to SLMPs.

Further, this implies that the probability of adoption of these SLMPs decreases with the size of the household members. These results might be related to the fact that households with large family members outlay their income more on consumption rather than investing in SLMPs (Challa & Tilahun, 2014). However, this result contradicted the conducted in Ethiopia who claimed that household size has a positive significant influence on SLMPs (Gebrelibanos & Abdi, 2012; Haftu et al., 2019).

The association cooperative membership variable has a statistically significant positive impact on the adoption of SLMP. This suggests that SLMP-adopting households have higher association membership rates. The association's adoption of SLMP can help farmers who use it by providing them with access to better land fertility maintenance, as would be expected. This outcome is consistent with the conclusions made by Bakhsh et al. (2012).

Hence, the decision of households to adopt SLMP is influenced by their participation in cooperative membership-holding. Households in cooperative groups were discovered to be more likely to adopt SLM practices than non-member households. This result suggests that households that are members of farmers' agricultural cooperatives are more likely to adopt these SLMPs than their counterparts due to the fact that farmers have developed into a vital network that offers different types of assistance to farmers, including financing and technical assistance. This finding is consistent with the findings of Ogada et al. (2014) and Ojo et al. (2019), who discovered that membership in farmers' associations, facilitated the adoption of agricultural technology in Kenya.

Participating of households in off-farm or non-farm activities has an impact on households' decision to adopt SLMP. This could be because households who earn more money from sources other than agriculture are more likely to use SLMPs as they are more likely to overcome the financial barriers required to undertake practices (Ponguane & Mucavele, 2018; Kousar & Abdulai, 2016; Challa & Tilahun, 2014). However, the findings of this study contradict with those of Mekuriaw *et al*. (2018) and Asfaw & Neka (2017), who discovered that participation in non-farm activities have a negative impact on households' willingness to implement SWC on their farmlands.

One of the important factors that restrict the adoption of agricultural technology is the cost of inputs for the adoption of SLMPs. Clearly, the high cost of agricultural technology is a major barrier to adoption, according to many studies. Djibo & Maman's (2019) .Hence, in line with different studies' results to study the determinants of agricultural technology adoption, improved seed adoption is negatively impacted by high input costs while organic fertilizer use is positively impacted. Challa & Tilahun (2014) discovered that household heads' attitudes towards the fairness of the cost of inputs specifically, the cost of improved seed are influenced by the adoption of modern agricultural technology in west Wollega, Gulliso district, Ethiopia.

The perception of the cost of inputs in regard to its affordability and accessibility affects household adoption decisions in the study area. This is more likely because of cost of materials for making compost is less as compared to other inputs like commercial fertilizer for land fertility maintenance. Hence, increased technology adoption suffers as a result of high agricultural input prices, according to Djibo & Maman's (2019) study on factors influencing the use of agricultural technology in Niger.

Access to high-quality, relevant, and up-to-date information is critical in the adoption of different agricultural technologies. This could be because farmers who have regular access to information from a variety of sources are more likely to be informed about potential SLMPs, success stories, and how to overcome land degradation challenges over time (Adjepong et al., 2019; Bekele & Drake, 2003; Mekuriaw et al., 2018).

Model farmer contact has a positive and significant effect on the adoption of SLMPs among households in the study area. This is because model farmer contact increases sharing with practically tested practices, experiences, skills, knowledge, and information that could easily facilitate in promoting perception and the choice of options to look after their plot to reduce hazards of land degradation effectively (Belay et al., 2017). Further, this could be explained by the fact that as farmers to farmers' contact increases their understanding of indigenous knowledge to evaluate their land degradation status and to use SLMPs to improve land fertility maintenance and crop production over time (Alhassan et al., 2018a).

The adoption of SLMPs is more likely promoted as a result of credit services to address any financial constraints for the adoption of these practices. This conclusion is supported by the findings of Haftu et al. (2019), Adeyemo et al. (2017), and Zemenu & Minale (2014) in their respective studies who argue that financial support is an important factor that encourages smallholder farmers to adopt land management practices. On the contrary, to this finding Eleni (2008) and Berhanu et al. (2016) discovered that access to credit hurts the adoption of SWC practices. This further implies that adopting a different SLMP will be more likely if it has financial support or backup. Due to the high capital requirements of implementing SLMP on a farm, having access to financial assistance will motivate the farmers to make investments and adopt sustainable land management practices. The findings of Adeyemo et al. (2017), who discovered that accessing credit facilities encourages the adoption of land management practices, are consistent with this outcome.

Households with years of experience are more likely to have found success with a variety of SLMPs, leading to the adoption of numerous sustainable land management techniques. The result suggests that more experienced farmers understand the value of SLMPs and adopt them more than less experienced farmers. According to Shiferaw & Holden (2008) and Yenealem et al. (2013) experienced farmers are better equipped to identify soil erosion problems than less experienced farmers and have a higher likelihood of taking part in land management initiatives. This finding is also consistent with the findings of Aminu et al. (2018) and Mugisha & Alobo (2012) who discovered that having a substantial level of experience always helps smallholder farmers devise a strategy to deal with land degradation problems through the use of various land management practices.

Being a part of different social groups positively and statistically significantly affected the adoption of all agricultural technologies covered in the study, demonstrating that belonging to different social groups raises the likelihood of adoption. Participation in social groups can improve societal ties. This is because it helps farmers to share information and learn from one another (Feyisa, 2020; Ketema et al., 2016).

In this particular study, it was discovered that livestock ownership as a proxy for wealth or household asset possession measured using TLU had a favorable and significant impact on the choice to adopt the dominant SLM practices. Compared to households with small livestock units, those with large livestock units are more likely to adopt technology. This is so that households with a lot of livestock will be better able to afford and have access to new agricultural technologies. The research by (Abay et al., 2016; Feyisa, 2020) found the same conclusion regarding conformity using technology This further illustrates that households who own large herd sizes have the chance of overcoming the costs of adopting SLMPs as compared to their counterparts. The likelihood of adopting area closure, SWC, crop rotation, and compost is higher for households owning large herd sizes as compared to households owning small herd sizes. This is because households having large livestock will have better financial standing to afford and possess new agricultural technologies (Abay et al., 2016; Feyisa, 2020; Tesfaye & Brouwer, 2016; Senbetie et al., 2017). This was also raised during the focus group discussions, and they confirmed that households with larger sizes of livestock have a greater willingness to adopt SLMPs.

One of the critical factors that affect farmers' choice of adoption of SLMP is limited by slope types among households in the study area. The results imply that owners of gentle farmland are more likely to adopt compost than owners of flat plots. This might be related to the fact that plots with a steeper slope have more runoff water and are therefore more likely to be prone to land degradation. This finding is in line with the findings of Wagayehu (2003) and Haftu et al. (2019), who discovered that gentle slope plots have a significant positive effect on the adoption of various SLM technologies. However, it contradicted, the studies by Asrat & Simane (2017b), Kassie et al. (2009), and Wossen et al. (2015) suggested that farmers invest in adoption strategies in plots with a relatively plane slope than likely to be more vulnerable to any development practices.

The availability and interventions of NGOs in the study area influence the adoption of SLMP among households in the study area. This could be because NGOs provide farmers with training as well as resources on SLMPs in particular, capacitating households through experience sharing and frequent and site-specific extension services.

As a result, because most NGOs provide practical training and materials provision, households will have the opportunity and capacity to participate in the management of their agricultural land by implementing organic fertilizer, area closure, and compost. According to Assefa & Hans-Rudolf (2016), farmers who participated in NGOs' training on NRM projects were more knowledgeable about soil erosion and conservation than those who did not.

Table 5. Multivariate probit simulation results on the determinants choice of SLMPs

Variable	Organic fertilizer		Area closure		SWC		Crop rotation		Compost	
	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
Age	-0.006	0.009	-0.022**	0.009	-0.020	0.015	-0.015	0.010	-0.027***	0.011
Education level	-0.004	0.034	0.013	0.034	0.023	0.048	0.029	0.039	0.023	0.038
Family size	-0.053	0.034	-0.072**	0.034	-0.075	0.051	-0.077*	0.040	0.002	0.041
Model farmer	0.048***	0.017	0.022	0.017	0.013	0.023	0.028	0.020	0.020	0.023
Land size	0.025	0.065	-0.052	0.062	0.161	0.112	-0.065	0.069	0.060	0.075
Access to information	-0.078	0.275	-0.453	0.301	-0.628	0.406	0.728**	0.366	0.429	0.332
Perceived cost of input	-0.070	0.206	0.317	0.209	-0.194	0.348	0.322	0.235	0.541**	0.239
Coop membership	0.218	0.273	1.267***	0.271	0.759*	0.391	0.807***	0.289	0.896***	0.300
Access to credit	0.557**	0.240	0.460*	0.247	1.020***	0.313	0.443	0.286	0.219	0.300
Farm experience	0.024*	0.013	0.033**	0.014	0.040**	0.018	0.036**	0.017	0.002	0.013
Access to NGOs	0.409*	0.239	0.571**	0.251	-0.289	0.376	-0.131	0.262	0.693***	0.253
Training	0.017	0.222	0.338	0.223	0.542	0.341	0.118	0.254	0.214	0.287
Non-farm income	0.000***	0.000	0.000	0.000	0.000***	0.000	0.000*	0.000	0.000	0.000
Soil erosion hazard	0.147	0.192	0.096	0.197	-0.040	0.294	0.085	0.226	-0.242	0.240
Social capital	0.771***	0.256	-0.118	0.258	0.125	0.331	-0.104	0.298	-0.224	0.309
Livestock	0.015	0.012	0.031***	0.012	0.051***	0.018	0.047***	0.014	0.056***	0.014
Slope type	0.208	0.198	0.001***	0.191	0.278	0.298	0.324	0.230	0.715***	0.243
Constant	-2.275***	0.475	-0.954**	0.452	-1.804**	0.733	-1.163**	0.511	-2.176***	0.541

5. Conclusion and Recommendations

Land degradation is the most critical environmental problem limiting agricultural productivity in Ethiopia in general and in the west Wollega zone in particular. Even though. SLMPs contribute significantly to the reduction of land degradation, but farmers' adoption of these practices is low in the study area. Moreover, very limited studies have been conducted on household-level determinants of choice of SLMPs in general and the study area in particular. This shows that in biophysically and socioeconomically diverse countries like Ethiopia, local specific studies provide more information for policymakers to design effective interventions demanded as policy frameworks to minimize the blanket recommendations.

Therefore, this study examined factors that influence the adoption of SLMPs by farm households in the study area. The study used primary cross-sectional data collected from 426 farm households using multistage random sampling methods from five randomly selected districts and fifteen kebeles of the west Wollega zone, Oromia region, Ethiopia. Both quantitative and qualitative data were gathered from household surveys and FGDs respectively. Data were analyzed using descriptive statistics and a Multivariate Probit model. Results show that the rate of adoption of organic fertilizer, area closure, SWC, crop rotation, and compost as SLMPs were 33, 32, 44, 41, and 40% respectively. MVP model results showed a strong correlation between the various SLMPs, demonstrating that households adopted a variety of interdependent SLMPs. The practices were therefore complementary rather than supplementary or having a synergetic effect on one another. Model results also show that the predicted probabilities of adopting organic fertilizer, area closure, soil and water conservation, crop rotation, and compost were 37.2, 35.3, 40.5, 38.3 and 38.5% respectively showing similarity of the importance of these SLMPs to reverse the impact of land degradation and rehabilitate the degraded lands in the study area. Also, the output of the MVP model indicates that the probability that farm households choose all the SLMPS is 23% which is lower.

Further, the results of the MVP model show that 13 explanatory variables had a significant effect on the choice of SLMPs. Family size, agricultural cooperative membership, non-farm income, model farmer contact, credit access, farming experience, social capital, livestock holding, slope of the farmland, access to information and access to NGOs have a significant positive influence while age of the household head and perceived costs of inputs have a significant negative influence on the adoption of SLMPs in the study area.

As a result, the study recommended that local and regional governments develop specific programs to address the constraints, thereby scaling up and encouraging the adoption of SLMPs in the study area. This could be achieved by policy and development interventions that focus on all socio-economic, demographic and institutional factors that influence SLMPs in response to reversing the significant impacts of land degradation in the study area.

Households should use of labor-saving technologies and adopt modern livestock production systems to enhance their adoption rate and reduce the impact of land degradation. Households' access to non-farm income-generating activities and credit has to be prompted through policies strengthening the services of rural microfinance and establishing formal and informal saving institutions for different provision options. In addition, community-based organizations like farmer cooperative groups, NGOs, and different experience-sharing modalities such as model farmers' contacts through preparing different forums like field days should be promoted to improve their adoption rates. Special focus should be given to middle-aged farmers with reach experience in farming will enhance the adoption of SLMPs in the study area. Furthermore, it is critical to advance and update natural resource management and usage regulations by articulating land use and management directives and strengthening the current extension services.

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Authors contributions

Professor Fekadu Beyene (Ph.D.), Professor Jema Haji (Ph.D.), and Assistant Professor Chanyalew Siyum (Ph.D.), all were accountable for the study's design from the outset to the final manuscript writing up. The manuscript was eventually made improvements after numerous revisions made by all authors. And lastly, the final manuscript was read and approved by all authors

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Merging Interest for Sustainability Agenda: Is There a Link between Sustainable Agriculture Practices and Farm Efficiency?

Mahendra Reddy[1]

[1] Graduate School of Business, University of the South Pacific, Suva, Fiji

Correspondence: Mahendra Reddy, Graduate School of Business, University of the South Pacific, Suva, Fiji. E-mail: mahendra.reddy@usp.ac.fj

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Abstract

There is a global movement towards a sustainable agricultural system, given serious concerns for the food security of future generations. However, despite this push, adopting sustainable agriculture practices has been poor, given that their positive effect is not directly evident to the farmers. In countries like Fiji, where the majority of the land is leased, not undertaking sustainable agriculture practices can lead to a crisis of food insecurity and degraded low-quality land returning to the land owners and future generations. This study utilizes the latest Agriculture Census data from Fiji to construct a non-parametric production frontier from which to estimate the levels of efficiency of each farmer. These efficiency scores are then decomposed to farmers engaged in Sustainable Agriculture Practices vis-à-vis those not undertaking any Sustainable Agriculture Practice (SAP). The results from efficiency analysis provide efficiency and productivity scores for each farmer. Further decomposing it by SAPs reveals the marked difference in efficiency and productivity scores between farmers who undertake SAPs and those who do not. The results demonstrate that those farmers who undertake SAP have efficiency and productivity levels substantially higher than those who do not. To push the sustainable agriculture agenda amongst the farmers and landowners, policymakers must demonstrate to the farmers that undertaking SAPs will not only maintain the quality of the foundation input soil but will have a significant positive effect on their farm efficiency, productivity, and thus profitability. By doing so, the interests of all stakeholders are merged, making adopting sustainable agriculture practices easier on all farms.

Keywords: sustainable agriculture, efficiency, productivity, rural households, farms

1. Introduction

The agriculture sector of small developing countries has been the primary source of the growth and development of these countries and their non-agriculture sectors. The surplus created in the agriculture sector was transferred to the non-agriculture sector, excess labor moved to the non-agriculture sector, and well-trained and mature entrepreneurs moved to the urban sector to start expanding the commercial, industrial, and service sectors. However, as these countries' non-agriculture sectors began to grow at a rate higher than the growth rate of the agriculture sector, a misconception arose amongst the urban elite that the agriculture sector was declining and no longer critical. This was further supported by the rapid growth of the urban population, a significant proportion of this growth caused by rural-to-urban migration. Pushed by the urban elite, governments of these small developing countries saw the non-agricultural sector, particularly the tourism sector, as the panacea for the rapid growth and development of the country.

However, several external shocks in the past, such as the global economic crises and their impact on domestic economies through falling tourism receipts and remittances and war, political unrest and their impact on domestic economies, disruptions in the supply chain, and rising oil prices did send silent messages to domestic policymakers that not having complete control of the critical drivers of the country can be catastrophic on its people. Despite these signals, the policymakers pushed by oligarchs continued to allocate increasing amounts of resources to grow urban-based commercial sectors. The last Covid 19 pandemic, which caused incalculable damage to the country, economy, and society, got the policymakers on the drawing board. They realized that small countries' strength lies in their natural resources and primary (agricultural) sectors.

There was a national movement to jump-start the agriculture sector, particularly commercializing it to address food security, exploit the export market, and bring in increasing dollars of foreign currency. Governments started allocating increasing resources to help new farmers enter the agriculture sector and utilize idle land. The government also began to call for commercial agriculture systems so that its primary and processed products could be developed and exported. Over the last two years, the tiny island Pacific countries have seen a surge in commercial farming and ventures targeting export markets. This has raised serious concerns about the sustainability of the critical resources supporting this sector, such as land, water, and natural resources. Environmentalists, Nongovernmental organizations (NGOs), and community leaders have also raised this issue in various forums that a rush to commercialize agriculture could jeopardize the quality of life of future generations. These concerns are peculiar to not only the Pacific but globally as well, which has led the United Nations to coordinate and fund regional and national food systems summits (Sousa, Braganca, da Silva & Oliveira, 2024). Speaking on behalf of the Pacific Island Countries, Fiji's Prime Minister, Hon. Bainimarama, while addressing the UN's Food Systems Summit in New York, noted that climate change, loss of biodiversity, land degradation, and declining productivity of fisheries are some of the significant threats to sustainable agriculture systems and food security in the Pacific region (Pacific Islands Forum Secretariat, 2021).

Therefore, efforts should be made to engage in sustainable agriculture practices. However, this call has not seen many changes in the farming system as commercial farmers see it as a stumbling block to their bottom line, maximizing profits. This issue is much more severe in most Pacific Island countries, where most agricultural land is leased. Commercial farmers are not concerned about the long term as their objective function only covers the lease period and not beyond that as the land will revert to the land owners. Unfortunately, the proponents of sustainable agriculture practices are not merging the interests of all parties. This is necessary for sustainable agriculture practices where cultivation is undertaken on leased land to be practiced. The interest can be merged if sustainability is linked to entrepreneurs' bottom line, productivity, efficiency, and profitability. In this paper, the proponents of sustainability must argue that sustainability is not only about leaving foundation resources of good quality for future generations, but it will also increase farm productivity, efficiency, and profitability. In this paper, we examine the difference in productivity and efficiency of farmers who do not undertake sustainable agriculture practices and compare it to those of farmers who practice different levels of sustainable agriculture practices. The second section of the paper briefly overviews the various problems farmers face in undertaking agriculture, which will degrade the land quality over time. The paper's third section will provide details on the theoretical basis of efficiency studies. The fourth section provides information on the methodology, the fourth section provides results and discussion, and the last section provides a summary and policy implications.

2. Sustainability and Sustainability Challenges

The agriculture sector worldwide is facing several challenges that could severely inhibit its ability to increase its production and productivity in the future to feed the rising global population. While intensive agriculture systems has been praised as a panacea for enhancing food security, some researchers, for example, McMichael and Schneider (2011) have noted that in the longer run, it destroys the capacity of agro-ecosystems for food production. These problems and challenges include climate change; a high rate of biodiversity loss; land degradation through soil erosion, compaction, salinization, and pollution; depletion and pollution of water resources (Velten, Leventon, Jager & Newig, 2015; Beus & Dunlap, 1999; Rosset & Altieri, 1997; Thrupp, 2000; Ogaji, 2005 and Peters, 2010). Some researchers argue that there should be a trade-off between economic growth and ecological and environmental balance, though it will be challenging and costly (Sharmiladevi, 2023). In light of these problems and challenges, the Brundtland Report in 1987, while presenting the overarching concept of sustainable development, a development that meets the needs of the present generation without compromising the needs of the future generation, also talks about the importance of sustainable agriculture and its role in sustainable development. Since then, much interest has been generated amongst all players linked to the agriculture sector, including policymakers and those contributing to policymakers from outside the government circles (Latruffe et al., 2016). Researchers have also attempted to establish a steady definition of sustainable agriculture but have failed. Chopra (1993) argues that organic farming methods, maintaining soil integrity, and related ecological systems are the core of sustainability. FAO (1989) defines sustainable agriculture as the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving national resources. The 1990 U.S. Farm Bill notes Sustainable agriculture as an "integrated system of plant and animal production practices having a site-specific application that will, over the long term: (i) satisfy human food and fiber needs; (ii) enhance environmental quality; (iii) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; (iv) sustain the economic viability of farm operations; and (v) enhance the quality of life for farmers and society as a whole." (U.S. Congress, 1990). Appleby (2005) survey the definition of Sustainable agriculture and notes that in general, these definitions argue for an agriculture system that is "ecologically sound, economically viable, and socially just". He further argues that most definitions are biased towards crop agriculture mostly and ignore livestock agriculture. He calls for adding "humane" agriculture to the definition of sustainable agriculture.

Noting all the definitions of sustainability presented above, it is clear that maintaining soil structure, quality, fertility, and integrity is the core of any sustainable agriculture system. China, a country that has coped much blame for not giving due regard to environmental protection in the face of speeding up economic growth to tackle poverty, has now made enormous strides in supporting its labor-intensive small rural farms to undertake sustainable agricultural practices while making a remarkable achievement of feeding 22% of world's population with 9% of worlds arable land (Yu & Wu, 2018).

Fiji's ecological stock and its biodiversity have also contributed to the sustainability of Fiji's agriculture sector. The rich biodiversity has contributed significantly to the prosperity of the rural farmers and their farming activities in numerous ways. It supplements the households with many non-timber products, enhancing the productivity of the household members working on the farm. Materials from the biodiversity have been used to improve soil fertility. The biodiversity has also indirectly contributed to retaining soil water and moisture and replenishing groundwater for agricultural use. A large volume of work also links agriculture to the environment. This link and the importance of strengthening it was discussed at length at the 9th International Conference on Sustainable Agriculture and Environment (ICSAE-9) on 24-25 August 2022 in Surakarta, Indonesia, over the period 24-25 August 022.

However, this rich biodiversity now faces enormous threats due to the combined effects of commercial logging activities and habitat destruction, waterways and environmental contamination, over-exploitation of natural resources, introduction of exotic species such as African tulips in Fiji, and climate change. River bank erosion has contributed to the washing away of large chunks of inland arable agricultural land. Coastal erosion and saltwater intrusion have reduced the quality of arable land along the coastal areas. Changing climate patterns have witnessed extreme flooding and droughts, thus affecting the agricultural production of small farmers who do not have access to technology to deal with extreme weather conditions. Farmers' practices on their farms have been a significant cause of concern, given their impact on soil quality, microorganisms, and the environment. At a community meeting with farmers, the former Minister for Agriculture, Waterways, and Environment voiced his concern and urged the farmers to undertake sustainable agriculture practices. He noted, "One issue that has been bothering the Ministry is the lack of sustainable agriculture practices practiced at the farm level. We need to ensure that the agriculture practices undertaken by farmers are sustainable, meaning that they are not undertaken in a manner that is detrimental to the environment, the soil, and our groundwater" (Reddy, 2022, p. 1).

Therefore, sustainable environment and ecosystem management cannot be confined to the natural resource area or the protected forests but must be thoroughly championed in the agricultural areas at the farm level. Studies in other countries, such as the African region, also suggest that policymakers should make a concerted effort to support on-the-ground mitigation strategies and support sustainable agriculture practices (Amankwah, 2023). Furthermore, given that Fiji is at the forefront of climate change impacts, Climate Smart Agriculture (CSA) practices need to be adopted to minimize the negative impact of climate change. CSA practices are now becoming more widely recognized as a sustainable solution to the effects of climate change on agriculture (Brohm & Klein, 2020 and Chandra, McNamara, & Dargusch, 2018). However, their interests must be merged to sell the notion of sustainable agriculture to the farmers, households, landowners, and input suppliers. All the parties must see a stake in it instead of just emphasizing the need to protect the interest of future generations. The stake referred to here can be aptly summarized as the financial sustainability and viability of all stakeholders' core business. Bobitan, Dumitrescu & Burca, (2023) argue that the long-term sustainability of agricultural enterprises requires financial sustainability, which can be related to productivity and efficiency gains. This argument is supported by Solís, Bravo-Ureta and Quiroga, (2009), who use an input-oriented stochastic distance frontier simultaneously with a technical efficiency effects model and demonstrate that improvements in technical efficiency are financially beneficial to farm households while at the same time contributing to environmental sustainability.

3. The DEA Method of Efficiency Measurement

This study uses the Data Envelopment Analysis (DEA) method to estimate each farmer's efficiency level. There are several advantages to using this method over measuring efficiency using a stochastic frontier production, cost, or profit function. Firstly, this method does not require data on input and output prices. This is a significant advantage for cross-sectional data because the prices of inputs do not vary at a point in time; hence, parametric stochastic frontier functions cannot be estimated. Secondly, this method does not require the specification of a functional form of the production, cost, and profit functions. In the parametric stochastic approach, we must assume and specify the relevant technology's functional form. Lastly, the distance function utilized in this non-parametric does not require behavioral assumptions such as profit maximization, cost minimization, or revenue maximization.

The DEA approach has been widely used in applied economic analysis for both agriculture and non-agricultural sectors. Some of the recent studies of efficiency and productivity growth in the agriculture sector include studies by Ali, Neda & Mahdi, (2018), Gunes and Guldal (2019), Chaubey, Sharanappa, Mohanta, Mishra, and Mishra. (2022), and Galluzzo, (2018). Some of the recent studies of efficiency analysis for the non-agriculture sector include studies on the banking industry by Antunes, Hadi-Vencheh, Jamshidi, Tan, & Wanke, (2022); studies on income diversification and bank efficiency by Alhassan (2015); measurement of the environmental performance of green funds by Allevi, Basso, Bonenti, Oggioni & Riccardi, (2019); examination of capital, risk, and efficiency by Altunbas, Carbo, Gardener, & Molyneux, (2007); assessment of Chinese high-tech industries by An, Meng, Xiong, Wang & Chen, (2020); measurement of efficiency in the education sector by Aparicio, Ferrera & Ortiz, (2019); measurement of efficiency in the banking sector by Defung, Salim, & Bloch. (2016); and, measurement of efficiency and profitability of the banking sector by Eling and Jia (2019).

Estimating the efficiency of individual decision-making units index is based on the Farrell measure of technical efficiency (Farrell, 1957) and Shephard's (1970) distance function. The output distance function for a given output vector y and input vector x for a period t technology is defined as:

$$dt(y,x) = St\} \tag{1}$$

Where St represents technology in period t, the distance function can be defined as the minor factor by which output can be deflated so as to be feasible with input vector x. This concept of distance function can be illustrated using Figure 1.

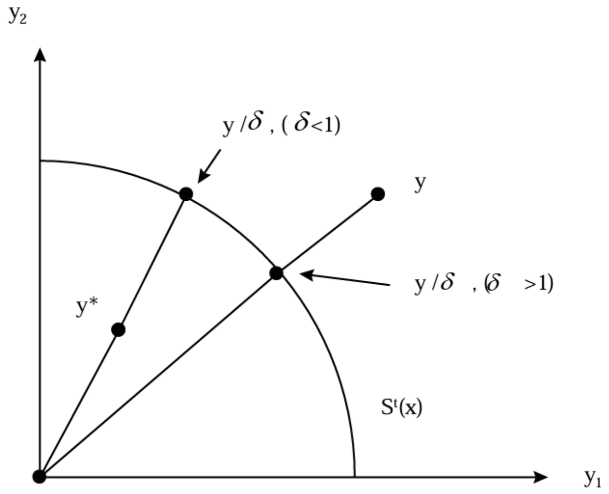

Figure 1. Illustration of Distance Function

Observations can lie above (y) or below (y*) with given technology S^t. δ is greater than one for "y" and less than one for "y*", given the same input vector x. Since y_t is assumed to be optimal for x_t in S^t (technology in period t), $d^t(y_t,x_t)=1$. Equivalently, if y_s is optimal for x_s, then $d^s(y_s,x_s)=1$.

DEA is a non-parametric mathematical programming approach to frontier estimation. Detailed discussion of the DEA methodology is provided in Seiford and Thrall (1990), Lovell (1993), Ali and Seiford (1993), Lovell (1994), Charnes *et al*. (1995), and Seiford (1996). DEA was first advanced by Charnes, Cooper and Rhodes (1978), and led to a large number of papers extending its application.

The output-oriented measure of Farrell technical efficiency between years (s) and (t); that is, the efficiency change is equivalent to the ratio of the Farrell technical efficiency in period (t) to the Farrell technical efficiency in period (s).

$$\text{Efficiency change} = \frac{d^t(y_t, x_t)}{d^s(y_s, x_s} \tag{2}$$

In Figure 2, the firm produces at points D and E in periods s and t, respectively. In both periods, the firm is operating below the technology for that period. Therefore, the efficiency change can be described in the following equation (3) as:

$$\text{Efficiency change} = \frac{y_t / y_c}{y_s / y_a} \tag{3}$$

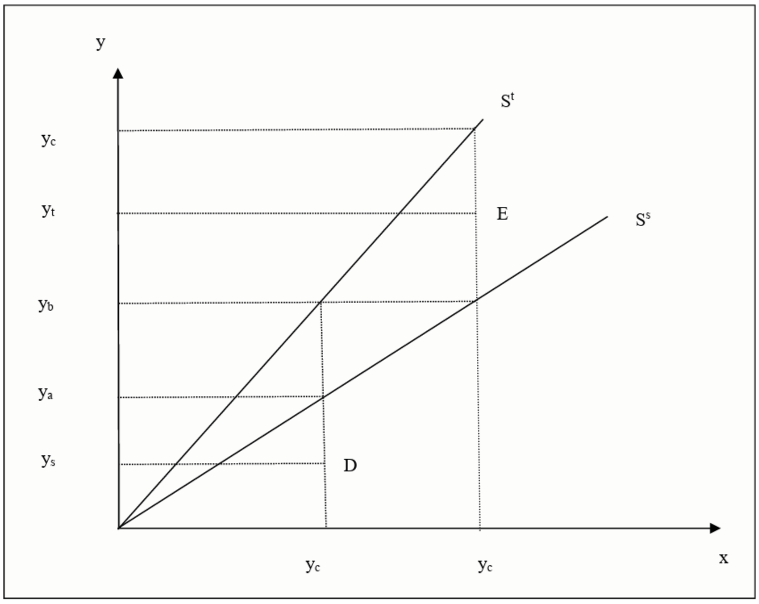

Figure 2. Illustration of Efficiency Change Measurement

4. Data and Empirical Model Estimation

4.1 Data Source

This study will utilize the latest Fiji Agriculture Census (FAC) 2020 data. The FAC 2020 was designed, pilot-tested, and administered under the purview of the author of this paper. In 2019, the survey instrument, the survey questionnaire, was designed, pilot tested, and enumerators selected and trained. The questionnaire had thirteen sections: Section 1: Household Composition; Section 2: Housing Particulars; Section 3: Land; Section 4. Crops on Farm Land; Section 5: Livestock; Section 6: Forestry; Section 7: Fishing; Section 8: Aquaculture; Section 9: Climate Change and Challenges; Section 10: Equipment; Section 11: Agriculture Services; Section 12: Food Security; and, Section 13: Labor.

Fiji Agriculture Census was undertaken from 10 to February 29, 2020, covering 70,991 agricultural households in the rural sector and selected peri-urban boundary areas where agricultural activities are commonly practiced. This comprises 99.1% of the households interviewed in rural and peri-urban areas where agriculture is commonly practiced. This was the first time that all four sub-sectors of agriculture: crop, livestock, fisheries, and forestry were covered on a complete enumeration basis. For this survey, a *household* is defined as a small group of persons who share the same living accommodation, contribute their income and wealth to acquire certain goods and services, and share the same eating arrangement. An "agricultural household" is defined as a household where the main economic activity identified is farming, i.e. it practices any agricultural activity (such as crop, livestock, fisheries, and forestry) during the reference period of the 2020 Fiji Agriculture Census (2020FAC). For this study, 4544 farmers' data were used as not all farmers provided data on the Labor and Capital variables. Hence only these farmer's data were utilized.

4.2 Empirical Model

The Efficiency change is computed by estimating the component distance functions of equation (2). Based on a constant return to scale technology, the production frontier was estimated for all crop output measured in tons of crop harvested and four inputs: Sustainable Agriculture practices, Land, Labor, and Capital. The inputs are defined as follows:

X1 = Sustainable Agriculture (SA) practice measured the number of practices carried on the farm over the last 12 months from 0= No SA practices to 5= 5 SA practices from the list below.

(i) Agroforestry on farm

(ii) Planting climate-resilient crop

(iii) Use of Ministry-recommended agriculture inputs only

(iv) Undertaking crop rotation

(v) Planting of Mucuna cover (nitrogen fixing) before the next crop.

(vi) Undertaking contour Farming

(vii) Use of organic manure

X2 = Land area under cultivation (in ha);

X3 = Labour is measured in terms of the number of full-time labor engaged on the farm;

X4 = Capital is measured in terms of the dollar value of farm equipment and machinery.

The descriptive statistics of the variables are provided in Table 1 below.

Table 1. Descriptive Statistics of Variables

Variable	Mean	Stdev	Minimum	Maximum
Crop Output	81.04	682.79	0.1D-04	23543.0
Land Area	14.25	205.82	0.1D-05	8890.9
Sustainable Agr Practices	1.77	1.26	0.0	5.0
Capital	5107.84	12149.52	100	75000
Labor	1.21	0.63	1.0	12.0

5. Results and Discussion

The results from DEA measuring each farm's output-oriented technical efficiency (converted to percentages) are presented in Table 2 below, alongside results for partial productivity. The results demonstrate that farms with no sustainable agriculture practice have much lower productivity and efficiency, 5.5 tons per ha and 45.9%, respectively. Those farms engaging in Sustainable agriculture practices have much higher productivity and efficiency, 14.1 tons per ha and 67.7% efficiency, respectively.

Table 2. Partial Productivity and Efficiency by Level of Sustainable Practice

Sustainability Category	Partial Productivity (tons/ha)	Technical Efficiency (%)
Full Sample Average	12.549 (4.941)	63.8 (0.265)
Category 0 (No SAP)	5.492 (2.049)	45.9 (0.184)
Category 1-5 (SAP undertaken)	14.080 (3.956)	67.7 (0.264)
Category 1 (One SAP)	12.156 (2.892)	74.2 (0.277)
Category 2 (Two SAP)	12.762 (2.400)	79.0 (0.286)
Category 3 (Three SAP)	16.229 (3.397)	51.3 (0.126)
Category 4 (Four SAP)	17.663 (5.735)	63.9 (0.223)
Category 5 (Five SAP)	18.964 (5.647)	69.9 (0.225)

Note: Figures in parenthesis are standard deviations.

While the average productivity for farms undertaking sustainable agriculture practices is 14.1 tons per ha, the productivity increases as the farms adopt an increasing number of sustainable agriculture practices. For example, for farms employing only one sustainable agriculture practice, their partial productivity is 12.2 tons per ha, much higher than those not undertaking any sustainable agriculture practice, 5.5 tons per ha. However, for farmers undertaking five sustainable agriculture practices, their productivity is 18.9 tons per ha. A similar trend is observed for the technical efficiency of farms. Those farms undertaking only one sustainable agriculture practice have an efficiency score of 74.2%. While this is much higher than the farms where no sustainable agriculture practices are undertaken, 45.9%. However, as farmers undertake more sustainable agriculture practices, their efficiency of production increases. As observed, those farmers who undertake five sustainable agriculture practices have a farm efficiency score of 69.9%. This result is very revealing and has significant policy implications for promoting sustainable agriculture at the farm level. Every rational farmer would aim to maximize profit. One of the ways this can be achieved without changing the technology is by raising efficiency. This study demonstrates that farmers can raise profitability by raising farm efficiency. One of the ways farm efficiency can be raised is by undertaking sustainable agriculture practices. If this becomes the farming system, all stakeholders will benefit the current and future generations.

6. Summary and Policy Implications

This study utilizes farm-level data to examine if sustainable agriculture practices contribute to improvements in the efficiency of the farms. There is a global movement towards a sustainable agricultural system, given severe concerns for the food security of future generations. However, farmers and landowners in developing countries, dependent firmly on the agriculture sector for growth and development at the micro and macro level, have kept the sustainable agenda on the back burner as their interest is maximum production and maximum profit. They do not see any link between sustainable agriculture and maximum production and profit. In countries like Fiji, where the majority of the land is leased, not undertaking sustainable agriculture practices can lead to a crisis of food insecurity and degraded low-quality land returning to the land owners and future generations. Therefore, we need to merge the interests of all these stakeholders.

The findings from this study demonstrate that farmers can substantially increase their farm productivity and efficiency by undertaking sustainable farming practices. With the efficiency and productivity gain, these farmers will have significantly higher profits vis-à-vis those farms not undertaking any sustainable agriculture practice. Therefore, by demonstrating this finding to the different stakeholders within the agriculture sector, we can merge the interests of all stakeholders towards sustainable agriculture. Lastly, this study also calls for a significant change in the discourse on sustainability, from a shift from issues with supply change bottlenecks, the commodity to product development, over-emphasis on the needs of future generations to focus more on the farm, on the current generation of farmers, the farming activities, support packages and training on sustainable practices and providing ownership to them on these sustainable technologies.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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Between Professionalism and Amateurism in the Use of the Agricultural Training Videos: Lessons Learnt from Experimental Auctions in Benin

Gérard C. Zoundji[1], Espérance Zossou[2], Dossou S. Wilfilas Awanvoeke[2] & Simplice D. Vodouhè[2]

[1] Ecole de Sociologie Rurale et de Vulgarisation Agricole, Université Nationale d'Agriculture, Porto-Novo, Bénin

[2] Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Bénin

Correspondence: Gérard C. Zoundji, Ecole de Sociologie Rurale et de Vulgarisation Agricole, Université Nationale d'Agriculture, 01 BP 55 Porto-Novo, Bénin. Tel: 229-9772-7273. E-mail: gezoundji@gmail.com

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Abstract

Agriculture training videos (ATV) facilitate the wider dissemination of agricultural technologies and encourage farmers to adapt the learnings to their conditions. However, producing quality video is expensive as well as challenging for notable number of agricultural extension organizations across many Africa countries. This paper compares farmers' willingness to pay (WTP) for two distinct video quality levels—a cheap, amateurish video and a costly, professionally produced video. Using stratified random sampling, 91 farmers were selected for the experimental auction sessions. These farmers were chosen from a database that was compiled by the Ministry of Agriculture developed in 2021, with a total population of 382 vegetable farmers. Data were analyzed using Student's t-test and Tobit model. 97% of farmers who attend the experimental auction sessions, agreed to pay for the ATV and results show a significant difference of 0.063 USD between the two videos, and in favor of professional video. Farmers' WTP for ATV is influenced by education, access to funding, images clarity, type of character in videos, understanding level of message and language spoken. Video quality is very important in the learning process in rural areas and support the promotion of professional videos. However, amateur videos can be used in agricultural training if financial support are not available for professional videos production.

Keywords: agricultural extension, agricultural training video, experimental auctions, willingness to pay, Benin Republic

1. Introduction

Agricultural training videos (ATV) are a useful and effective extension channel for reaching marginalized farmers and disseminating agricultural information (Van Mele, 2011). ATV facilitates the sharing of agricultural extension related information with large audiences by triggering farmers' innovation, ingenuity and imagination to adapt basic principles of improved technologies to local context (Bentley et al., 2022). Using ATV as extension tools, which are based on farmers' experiences and combine visual and verbal communication methods is suitable for knowledge development (Zoundji et al., 2018a; Goller et al, 2021). Several studies showed that when the ATV are made available to farmers at the right place, they find their own way to watch them, even if there is no electricity (Van Mele et al., 2016; Zoundji et al., 2016). The effectiveness of ATV in the process of producing and using technological, organizational and institutional innovations has been demonstrated by several studies (Zossou et al., 2017; Zoundji et al., 2018b; Bentley et al., 2022). Based on the "professional" videos created by audiovisual experts, these studies have demonstrated the benefits of ATVs by encouraging farmers to carry out their own basic research and adapt the technologies. However, the production of "professional" videos is quite costly (Songhaï, 2015; Zoundji et al., 2016) and mostly dependent on development funding.

For instance, Benin, Mali, Egypt, Kenya, Uganda, and Malawi were among the countries where the Swiss Agency for Development and Cooperation's "Videos for Farmers" project assisted in the production and distribution of several ATVs (Bentley et al.,2014). Additionally, the International Maize and Wheat Improvement Centre and the Cereal Systems Initiative for South Asia were assisted by the United States Agency for International Development and the Bill and Melinda Gates Foundation to produce the "Save More, Grow More, Earn More" video in Bangladesh (Bentley et al., 2015). The International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT) funded the creation of the production of the "Fighting Striga" videos in Mali (Zoundji et al., 2018b), while AfricaRice funded the development of the parboiling rice video in Benin (Zossou et al., 2012).

Given that only development organizations have invested in the "professional" videos, ensuring their sustainable production and wide distribution remains a challenge, particularly given the current global context of reduced development aid and financial assistance (IARAN and CaLP, 2019). Consequently, it could be a good idea to expand the scope of video production beyond financial aid or development aids and seek for the kinds of films whose production costs are reasonable and for which farmers would be happy to split the cost in order to ensure the long-term viability of using videos as an agricultural extension tool. This article's goal is to determine if making an "amateur" video on the same subject may have the same effect on the farming community as a "professional" film while spending less on production. In order to achieve this, we examined the farmers' willingness to pay (WTP) for three different types of ATV on the same topic. The first video referred to as the "reference video" was used as a benchmark for contrasting it with other kinds of videos. This video was created with a low budget cell phone, and as a result, it has extremely poor image clarity, sound quality, message content, and structure.

A second video, dubbed an "amateur video" had low production expenses since it was produced by an amateur cameraman who disregarded many "professional video", requirements such as graphics, visual effects, and background music. The third video is referred to as a "professional video" or "high-quality video" meaning that it includes information from scientists and farmers' backed up with pertinent, coherent and steady quality audio visuals effect that sequences of farmers at work (Van Mele, 2018).

In order to attract the audience's or farmers' attention and encourage learning, professional videos need to have high-quality audio and visuals, a strong narrative framework, and a relevant message (Salm et al., 2018; Vilppola et al., 2022). These kinds of videos were made using the zooming-in, zooming-out (ZIZO) technique, in which narrators and farmers explain cutting-edge technologies and the science behind them in simple easy to understand everyday language (Van Mele, 2006).

In order to capture the impact of the above three ATV on farmers' preferences, experimental auctions is used to elicit the willingness to pay which is defined as the maximum price a customer would be willing to pay, under normal market conditions, to acquire a product or service (Robin et al., 2008). In the context of this study, the WTP is the amount derived from farmers' preferences for acquiring each type of ATV on different formats such as DVDs, mobile phones and public screenings. Several methods have been developed in marketing and economics to measure consumer WTP (Le Gall-Ely, 2009). This study used experimental economics, in particular the Vickrey auction, as it protects the measurement of WTP from hypothetical bias, the Warm Glow effect and strategic bias and limits measurement bias (Robin et al., 2008). The experimental method thus enables better control of the environment in which this measurement is carried out. In order to examine economic behaviors or phenomena in recognized, regulated, and repeatable situations, many authors (Robin 2017, Yildirim 2022) claim that experimental economics is first and foremost a research methodology that replicates a real economic environment.

2. Method

2.1 Study Area and Sampling

This study was conducted in the Municipalities of Kpomassè and Ouidah, located in the southern part of Benin and belong to the Guinea zone, which extends from the Atlantic coast and stretches between 1°45' and 2°24'E and 6°15'and 7°00'N to the west and 6°15' and 7°30'N to the east (Akoègninou et al., 2006). These municipalities are among the major tomato producing areas in Atlantic department of Benin (MAEP, 2020). According to same author, total production of tomato in 2012 was 244,742 tons, with 113,373 tons for the Atlantic department production, or 46.32% of total production. The municipalities of Kpomassè and Ouidah produced about 64% of the total production of tomato in the Atlantic department and were selected because the agricultural training videos used in this study are focused on the tomato conservation techniques. In addition, two villages from each municipality were selected. Villages of Kpodji and Houéyogbé of the municipality of Kpomassè and villages of Gbéhonou and Gakpé of the municipality of Ouidah were selected for this study because of their importance of tomato production.

Ninety-one vegetable producers were chosen from four selected villages for the experimental auction sessions using the stratified random sampling method and a simple random draw (Rondeux, 2021). This figure was selected since the experimental auction approach is expensive and the project has limited resources. These producers were randomly chosen from a database that was compiled by the Ministry of Agriculture developed in 2021, with a total population of 382 vegetable producers.

2.2 Data Collection

Data on farmers' WTP were collected using the Vickrey (1961) auction sessions method. Each study village had one session. As a result, the reference video (benchmark), the "amateur" video, and the "professional" video were the three different kinds of videos that were used during the various sales sessions. Each sales session comprised five stages, as per Zossou's (2022) planned stages:

Stage 1. Introduction

This stage consisted of explaining the basic rules to be followed throughout the session in the farmers' local language. Farmers were also promised travel expenses worth 500 FCFA (0.8 USD). This pretext is often used in Africa to detach donations from their context of payment for services or gifts. It also slightly reduces the bias associated with participation fees (Lusk and Shogren, 2007).

Stage 2. Training with biscuits

Following Shogren et al (1994), biscuits were used to familiarize participants with the procedure. Each participant was given the benchmark "Glucose" biscuit and asked to give their WTP for two other types of biscuit, "Chic Choc" and "Rich". An actual sale of a randomly chosen biscuit was carried out. The training was followed by discussions and questions-answers to help participants understand the procedure.

Stage 3. Individual bids

We asked each participant if they would rather have the video on a mobile phone, DVD, or projection. Next, we asked them to select their favorite alternative video (amateur or professional) based on its comparison to the reference video they had received as a donation on the desired medium. If the individual chose the reference video, we asked the individuals if they would still prefer this video if the other two types of videos in comparison were at the same price. If they answer in the affirmative, we consider their WTP to be less than 0. If they answered negatively, then we consider their WTP is equal to 0. If the alternative video is chosen, we ask the individual to submit a price to be added to the price of the reference video (the price of the reference video for the DVD medium is 0.64 USD, 0.32 USD for the projection and 0.16 USD for the mobile phone) to have the preferred video on the chosen medium. The value provided is then considered as the individual's WTP. The total price is only obtained by adding the added value to the prices of the reference video according to each medium. Responses were recorded privately for each individual.

Stage 4. Surveys

We asked each participant to complete an independent questionnaire to gather precise information on their appreciation of the characteristics of the videos, as well as socio-economic information. This survey was carried out after all the auctions, to avoid revealing information about the aims of the study (Corrigan and Rousu, 2008).

Stage 5. Closing

We randomly selected one type of video and one type of medium (DVD or Mobile phone) that has been sold. This was deducted from the entry fee of the winner who bought at the second-best price.

2.3 Data Analysis

Once the WTP had been determined, the WTP amounts were compared using Student's t-test. A one-factor ANOVA test at 5% was then carried out to determine whether there was a significant difference between WTP depending on the type of support. The factors influencing these amounts were then identified using a Tobit model. In general, the Tobit model is written as:

$$Y_i^* = X_i\theta + \varepsilon_i$$

Where Y_i^* is a latent variable used to approximate the maximum value that individual i is willing to pay. θ is a vector of model parameters to be estimated, X_i is a vector of explanatory variables and ε_i is an error term independently and identically distributed according to a normal distribution with zero mean and constant variance σ^2.

Let Y_i be the actual amount that individual i is willing to pay:

$$Y_i = \begin{cases} Y_i^* & si\, Y_i^* > 0 \\ 0 & si\, Y_i^* \leq 0 \end{cases}$$

Tobit model is used to estimate the parameters θ and σ^2 from observations of Y_i and X_i.

3. Results and Discussion

3.1 Socio-economic Characteristics of Participants in Experimental Auction Sessions

Tomato farming is the main activity that occupies both men and women of all age groups. The average age of respondents was 43, with 20 years' farming experience, including 11 years in tomato farming. In terms of education, 38% of respondents were uneducated and 62% educated. All the respondents had farming either as their main activity (94%) or as a secondary activity (6%). This finding is similar to the study of Shaw et al (2019), who showed that agriculture employs more than 50% of the population in sub-Saharan Africa. However, to improve their incomes, respondents engage in other activities such as livestock rearing, fishing, processing, and trading. Tomato production accounts for an average 53% of annual household income. It is important to note that only 44% of respondents belong to a farmer group (Table 1). This low percentage could be explained by the scarcity of support projects in these areas.

Table 1. Respondents sociodemographic characteristics (n=91)

Variables	Definition	Mean (std. Dev.)
Age	Age in years	43.15 (11.76)
Education	1= Not instructed; 2= No formal schooling; 3= Primary school, 4= Secondary school; 5= University level	2.47 (1.27)
Main activity	1= agriculture ; 0= non agriculture activity	0.94 (0.23)
Experience in farming (year)	Years of farming experience	20.31 (10.29)
Experience in tomato growing (year)	Years of experience in tomato growing	10.98 (6.01)
Share of annual income	1=10%, 2=20%, 3=30%, 4=40%, 5=50%, 6=60%, 7=70%, 8=80%, 9=90%	53.24 (21.37)
Association membership	1= yes ; 0= no	0.44 (0.50)

3.2 Willingness to Pay for the Agricultural Learning Videos

Among farmers who attend the experimental auction sessions, 97% agreed to pay for the agricultural training videos. This result shows the interest that farmers have in agricultural training videos. This is in line with the results of Zoundji et al. (2016; 2018b), who highlighted that farmers were willing to pay for the ATV and use it for the knowledge development in vegetable farming. It also supports Okry et al. (2014)'s study, which found that farmers were prepared to spend money on learning new skills. The calculation of the average WTP did not take into account the zeros (number of non-consenters) and this explains the non-zero minimum values. It should also be noted that these values are the amounts to be added to the prices of the reference video. Table 2 summarizes the descriptive statistics for WTP for each medium and video. It shows that the respondents (34%) who chose the DVD medium agreed to pay an average of 232 FCFA (0.385 USD) for the “amateur” video and 317 FCFA (0.526 USD) for the “professional” video. Those (40%) who chose video screenings agreed to pay an average of 187 FCFA for amateur videos and 198 FCFA (0.328 USD) for professional videos. The respondents (26%) who chose to have the various videos on their mobile phones agreed to pay an average of 183 FCFA for the “amateur” video and 214 FCFA (0.355 USD) for the “professional” video. We found no significant difference between the average WTP for the “amateur” video, whatever the medium (p=0.34). For the average WTP for professional video, there is a significant difference (p=0.005) between offers for DVD and the other two medium (projection and mobile phone). We can therefore conclude that farmers in the study areas prefer to have videos on DVD. These results confirm those of Zoundji et al (2016) who observed that most farmers agreed to pay 2,000 FCFA (3.516 USD) for a DVD, which was made within the professional standard video production.

Table 2. Descriptive statistics of willingness to pay for agricultural learning videos

Parameters	**WTP for amateur videos**			**WTP professional videos**		
	DVD	Projection	Mobile phone	DVD	Projection	Mobile phone
Number of farmers	32	33	23	30	35	23
Minimum price (FCFA)	50	50	50	50	25	50
Maximum price (FCFA)	600	500	600	800	500	600
Mean price (FCFA)	232.5**	187.12**	182.95**	317.5**	197.72**	213.63**
Standard deviation	157.99	119.26	142.55	194.7	119.95	138.47

Note: Reference price of video on DVD is 400 FCFA, 200 FCFA for the projection and 100 FCFA for the mobile phone; Fixed exchange rate: 1 USD = 603 FCFA;

** denote significant differences at the 5% level based on ANOVA test.

3.3 Quality of Videos Assessment

Farmers' perceptions of the different videos were gathered based on certain characteristics of the videos, namely the quality of the images, the length, the type of character used, the language spoken and the level of understanding of the message. Table 3 shows that most respondents (62%) found "very good" the image quality of professional videos, unlike amateur videos, where around 51% of respondents found "good" the quality of image. As for the length of the videos, 53% of respondents considered this characteristic to be 'long' for the professional video and 'average' for the amateur video. Concerning the type of character in the videos, 67% of respondents considered this to be 'very satisfactory' for professional videos, unlike amateur videos, where 57% considered the type of character to be 'satisfactory'. The spoken language in the videos remains a key factor in the farmers' appreciation of the videos. This characteristic (language) is judged to be "understandable" by most of the respondents for both amateur and professional videos. According to the respondents, the level of understanding of the message conveyed is higher for professional video (72%) than for amateur video. Thus, both amateur and professional videos are of interest to farmers. Each farmer focuses on the characteristic that seems most important to them, which explains the different levels of appreciation from one characteristic to another and from one video to another.

Table 3. Quality videos assessment by farmers (n= 91)

Characteristics of videos		**Videos assessment by farmers (%)**	
		Amateur video	**Professional video**
Quality of images	Very good	47.25	62.64
	Good	36.26	51.65
	Poor	1.1	1.1
Video duration	Long	14.29	52.75
	Medium	81.32	47.25
	Short	4.39	0
Type of character	Very satisfied	40.66	67.03
	Satisfied	57.14	32.97
	Not satisfied	2.2	0
	Very understandable	48.35	39.56
Language	Understandable	49.45	57.14
	Not understandable	2.2	3.3
Level of understanding	Good	43.96	72.53
	Fair	53.84	25.27
	Poor	2.2	2.2

3.4 Comparative Analysis of Willingness to Pay for Amateur and Professional Videos

Using Student's t-test, this study compared the average WTP offers for amateur and professional videos. The results of this test show a significant difference (p=0.0048) between the two videos if we take the WTP amounts as a whole, i.e. ignoring the WTP per medium. This difference is 38 FCFA (0.063 USD). However, the results note that there is no significant difference between the offers depending on the medium. This study can therefore conclude that video medium (DVD, projection, mobile phone) does not influence farmers' interest in a particular type of video. Thus, "amateur" videos interest farmers in the same way as "professional"videos.

Table 4. Comparison of average WTP for the two videos, by medium

Parameter	**DVD**		**Projection**		**Mobile phone**		**Together (DVD, Proj. & Mobile phone)**	
	Amateur	Professional	Amateur	Professional	Amateur	Professional	Amateur	Professional
Mean	232.5	317.5	187.12	197.72	182.95	213.63	202.01	240.51
Std. Dev.	157.99	194.66	119.26	119.95	142.55	153.47	138.47	165.49
Mean difference	85		10.60		30.68		38.50	
Probability (diff Moy=0)	0.1202		0.6689		0.5088		0.0048**	

** significant at the 5% level

3.5 Determinants Affecting Willingness-to-pay Amounts

The factors influencing the amount of consent to pay for the purchase of agricultural training videos were examined using the Tobit model. This revealed the socio-economic factors and factors relating to the videos that have a significant influence on the amount of WTP by the respondents. Analysis of the Table 5 reveals that WTP is influenced by factors such as: level of education, access to funding, clarity of images, type of character in the videos, level of understanding of the message contained in the videos and language spoken. Thus, when the farmer is literate (educated), he is more willing to give a higher amount for the videos. This is in line with Sodjinou et al. (2015) and Otieno (2020) who argue that education level enhances farmers' ability to efficiently allocate resources or input for more knowledge on the sustainable farming and forest management in Benin. This is also confirmed in Burkina Faso through the results of Sigue et al. (2019), who showed that the level of education is one of the determinants of the amount of WTP for farmers using the "microdose" technology. The level of education therefore has a considerable effect on the farmers' WTP.

The results also show that respondent access to microfinance services has a positive influence on the amount of WTP. Thus, access to microfinance services is essential and constitutes a significant factor to agricultural activities. Therefore, more the farmers have access to a source of finance, more they are willing to give a higher amount for the acquisition of agricultural videos. Our results are in line with those of Ayedun et al (2017) who showed in Northern Nigeria that maize and groundnut farmers' access to credit positively influenced their willingness to pay for organic products for aflatoxin control. Regarding to the intrinsic factors of videos, the study shows that, except for the length of the videos, factors such as the quality of the images, the type of character, the level of understanding of the message and the language spoken in the videos have a significant and positive influence on the respondents WTP. As a result, the perception that the quality of the images is good increases farmers' WTP. Thus, farmers accepted to pay 107 FCFA (0.177 USD) for a marginal unit of image quality of the videos. The "farmer to farmer video" technique lowers the technical complexity of best practices so that farmers can increase their WTP by observing farmers from similar socioeconomic backgrounds performing the tasks they are being educated to perform. This clarifies the beneficial impact the character type has had on the farmers' WTP amount. This promotes the buying of videos. Farmer WTP is also influenced by understanding the message presented in the videos portray.

When producers have a high level of understanding of the technology, they are more willing to increase their amount. This was highlighted by Jimmy et al (2016) who showed that the positive effect of perception, facilitated the understanding and use of soybean processing technology in Benin by women after watching ATV. Understanding the message contained in the videos is an important factor in the farmers' decision making to acquire a training video. The study revealed that the language spoken in the video has an influential factor. This confirms the generally accepted idea that producers learn and are more interested when the video is in their own language. This result is in line with the study of Zoundji et al. (2018a), who showed that agricultural training videos in the vernacular represent an enormous potential for farmers to increase the rate of dissemination of agricultural innovations. Bentley et al (2013), postulates that dissemination can be negatively influenced when viewing is done without understanding the language. It is therefore obvious that not understanding the language of the video makes it difficult to grasp the content of the message and therefore discourages the desire to purchase the video.

Table 5. Determinants of WTP using Tobit regression model

Variable	**Coefficients**	**Bootstrap standard deviation**	**P>z**
Intrinsic factors of the videos			
Quality of images	106.68	21.763	0.000***
Type of character	27.16	13.717	0.048**
Message understanding	44.92	19.799	0.023**
Duration (length of the videos)	4.51	13.604	0.740
Language spoken in the videos	26.85	8.614	0,002***
socioeconomic factors of the farmers			
Gender	-28.25	23.612	0.231
Age (year)	0.00	0.892	1.000
Education (year)	25.54	5.108	0.000***
Experience in farming (year)	0.04	0.871	0.964
Association membership	11.19	13.504	0.407
Access to micro finance service	44.86	10.397	0.000***
_CONS	-125.64	38.161	0.001
LR chi-deux	404.94		
Prob > chi-deux	0.000***		
Log likelihood	466.20		

*** significant at the 1% level; ** significant at the 5% level

4. Conclusion

Videos for agricultural training are a great resource for farmers learning about new agricultural technologies these days. This study used Vickrey's experimental auction method to compare farmers' willingness to pay (WTP) in order to evaluate their capacity to distinguish between amateur and professional video quality. Given that farmers are interested in both “amateur” and “professional” videos, the study found no significant difference in the WTP amounts between them. The factors that define the WTP and have a significant impact on the farmers' decision-making process are the degree of education, availability of finance services, characteristics of characters, image quality, language used in the video, and comprehension level. The study also showed that most farmers accepted to pay around 0.177 USD for a marginal unit of video image quality. These amounts are respectively 0.045 USD, 0.075 USD and 0.028 USD for a marginal unit of satisfaction linked to the type of character, the level of understanding of the message and the language spoken in the videos. These results show that video quality is very important in the learning process in rural areas and support the promotion of professional videos. However, because extension and agricultural advisory organizations lack the funding necessary to create high-quality or “professional” movies, it's possible that they will instead make use of “amateur” recordings, which have a big influence on how widely and quickly agricultural advances are adopted. With less development aids and financial help available in around the world today, amateur videos which are significantly less expensive to make than professional videos are an appropriate option.

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Authors contributions

Dr. Zoundji and Dr. Zossou were responsible for study design and revising. M. Awanvoeke was responsible for data collection. Dr. Zoundji and Dr. Zossou drafted the manuscript with input from M. Awanvoeke and Prof. Vodouhe revised it. All authors read and approved the final manuscript.

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Data sharing statement

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Open access

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